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Final report

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AutoRess: Resource efficient and circular electric cars

by:
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Abstract: AutoRess

In the project AutoRess, options for reducing the impact of passenger car transport in Germany on climate and resource use were analysed. 10 technical and non-technical topics for additional GHG and material savings were defined and then analysed in depth. They were selected based on a systematic analysis of key levers along all life cycle phases of passenger cars. Each selected topic addresses a specific aspect of the transport system that can be influenced by technological, social or political measures. Three levers were identified that have a particularly strong impact on the goals: reduction of vehicle and battery dimensions, longer vehicle and battery lifetime, and higher quantities of recycled materials. A vision for a resource-efficient vehicle was developed and criteria were analysed to fullfill this vision. This vision is based on purely battery-powered electric cars. They are considered resource-efficient if, over their entire life cycle, they require as few primary raw materials as possible, consume as little energy as possible, emit as few greenhouse gases as possible, are as durable as possible, and their components can be returned to the material cycle as completely as possible and without downcycling at the end of their life. Based on the model results and developed criteria measures and instruments were identified, described and evaluated. Selected measures are Bonus-malus system based on vehicle dimensions, a statutory lifetime guarantee for the entire vehicle, company car taxation based on maximum values for CO_2 emissions (PCF) or maximum raw material consumption, minimum requirements for the energy density of batteries, recycled content targets for plastics and steel an the introduction of EPR scheme to finance proper ELV treatment operations. All together were combined to form a Circular Economy Roadmap for vehicles.

Kurzbeschreibung: AutoRess

Im Projekt AutoRess wurden Optionen zur Verringerung der Auswirkungen des Pkw-Verkehrs in Deutschland auf das Klima und den Ressourcenverbrauch analysiert. Es wurden 10 technische und nicht-technische Themen für zusätzliche Treibhausgas- und Materialeinsparungen definiert und anschließend eingehend analysiert. Sie wurden auf der Grundlage einer systematischen Analyse der wichtigsten Hebel entlang aller Lebenszyklusphasen von Pkw ausgewählt. Jedes ausgewählte Thema befasst sich mit einem bestimmten Aspekt des Verkehrssystems, der durch technologische, soziale oder politische Maßnahmen beeinflusst werden kann. Es wurden drei Hebel identifiziert, die einen besonders starken Einfluss auf die Ziele haben: Reduzierung der Fahrzeug- und Batterieabmessungen, längere Lebensdauer von Fahrzeugen und Batterien sowie höhere Mengen an recycelten Materialien. Es wurde eine Vision für ein ressourceneffizientes Fahrzeug entwickelt und Kriterien zur Erfüllung dieser Vision analysiert. Diese Vision basiert auf rein batteriebetriebenen Elektroautos. Sie gelten als ressourceneffizient, wenn sie über ihren gesamten Lebenszyklus hinweg so wenig Primärrohstoffe wie möglich benötigen, so wenig Energie wie möglich verbrauchen, so wenig Treibhausgase wie möglich ausstoßen, so langlebig wie möglich sind und ihre Komponenten am Ende ihrer Lebensdauer so vollständig wie möglich und ohne Downcycling in den Materialkreislauf zurückgeführt werden können. Auf Grundlage der Modellergebnisse und der entwickelten Kriterien wurden Maßnahmen und Instrumente identifiziert, beschrieben und bewertet. Ausgewählte Maßnahmen sind ein Bonus-Malus-System auf der Grundlage der Fahrzeugabmessungen, eine gesetzliche lebenslange Garantie für das gesamte Fahrzeug, die Besteuerung von Firmenwagen auf der Grundlage von Höchstwerten für CO_2-Emissionen (PCF) oder maximalen Rohstoffverbrauch, Mindestanforderungen an die Energiedichte von Batterien, Ziele für den Recyclinganteil von Kunststoffen und Stahl sowie die Einführung eines EPR-Systems zur Finanzierung einer ordnungsgemäßen Behandlung von Altfahrzeugen. All diese Maßnahmen wurden zu einer Roadmap für die Kreislaufwirtschaft für Fahrzeuge zusammengefasst.

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List of abbreviations

Abbreviation	Explanation
ABS	Acrylonitrile Butadiene Styrene
ATF	Authorised Treatment Facility
BMS	Battery Management System (BMS)
BEV	Battery-electric vehicle
PHEV	PlugIn Hybrid Electric vehicle
HEV	Hybrid-electric vehicle
CCU	Carbon Capture and Utilization
CFRP	carbon fiber reinforced polymer
COP	Conference of the Parties
CPA	Statistical Classification of Products by Activity
CRF	Common reporting format
CRMA	Critical Raw Materials Act
DERA	Deutsche Rohstoffagentur (German Mineral Resources Agency)
DSG	Direct-Shift Gearbox
EC	European Commission
ELV	End-of-life vehicle
EnVKV	Energieverbrauchskennzeichnungsverordnung
EoL	End-of-life
EU-ETS	EU Emissions Trading Scheme
F-gases	Fluorinated greenhouse gases
FTIP	Federal Transport Infrastructure Plan
GHG	Greenhouse gas
HBEFA	Handbook of emission factors
HEV	Hybrid-electric vehicle (not externally chargeable)
HGV	Heavy goods vehicle
ICAO	International Civil Aviation Organization
ICE	Internal combustion engine
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre

Abbreviation	Explanation
KBA	German federal motor transport authority (Kraftfahrtbundesamt)
KRA	Kumulierter Rohstoffaufwand (cumulative raw material use)
KSBV	UBA-study Klimaschutzbeitrag des Verkehrs bis 2050 [UBA, 2016a]
LCO	Lithium-Cobalt
LFP	Lithium-Iron-Phosphate battery
LIB	Lithium-Ionen-Batterien
Na-Ion	Sodium-Ion battery
NaWaRo	Renewable raw materials
NCA	Nickel-Cobalt-Aluminium battery
NDC	Nationally Determined Contributions (in Paris-Agreement)
NEDC	New European Driving Cycle
NMC	Nickel-Mangan-Cobalt battery
N_2O	Nitrous oxide (laughing gas)
NO_x	Nitrogen oxides
PA	Polyamide
PCF	Product carbon footprint
PE	Polyethylene
PHEV	Plug-In hybrid vehicle
PJ	Petajoule (energy measuring unit)
PP	Polypropylene
PtG	Power-to-Gas (any power-based gaseous fuels)
PtL	Power-to-Liquid (any power-based liquid fuels)
PU	Polyurethane
RDE	Real Driving Emissions
RIR	Recyclate input rate
RMC	Raw material consumption
SCR	Selective catalytic reduction
SEI	Solid Electrolyte Interphase
SLI	Starting/lighting/ignition battery
SoH	State of Health
SUV	Sports Utility Vehicle
TWh	Terawatt hours (measuring units for energy)

Abbreviation	Explanation
UNFCCC	United Nations Framework Convention on Climate Change
WLTP	Worldwide Harmonized Light-Duty Vehicles Test Procedure

Summary

The Paris Agreements and the Climate Protection Plan 2050 set clear CO_2 reduction targets in the transport sector. Yet these targets can only be met with an ambitious mobility transition to electric vehicles. Electric vehicles are characterised by special components such as te electric drive motors, batteries, fuel cells and power electronics. The **AutoRess** project analysed technical and non-technical options for reducing the impact of transport on climate and resource use across all vehicle life-cycle phases. Based on these analyses, suitable instruments and measures were developed and evaluated, and a definition of and criteria for a resource-efficient vehicle were developed. These were combined to form a Circular Economy Roadmap for vehicles. In different workshops, the results were then fed back to the project advisory board, external experts and internal UBA experts. The research project was conducted by Oeko-Institut e.V. together with partners ifeu gGmbH, Mehlhart Consulting and team ewen from November 2022 to August 2025.

In-depth analysis of technical and social options

In the AutoRess project, we analysed greenhouse gas (GHG) emissions and primary material savings potentials for different mainly technical options in Germany's car transport sector, taking into account all life-cycle phases of the vehicles.

As a starting point for assessing future GHG and material savings potentials in the vehicle life cycle, it was first necessary to evaluate how the various influencing factors and the resulting GHG emissions and material requirements will develop without additional interventions ("current drivers"). The systemic analysis of direct and indirect factors influencing GHG emissions and raw material consumption identified 10 technical and social options (see table). These were analysed in-depth to assess additional potential ("additional drivers"). The current status quo, development trends with current drivers and fields of action for additional drivers to reduce GHG emissions and material requirements were researched and discussed in expert workshops.

Overview of analysed technical and social options

Option	Analysed approaches
1. Alternative powertrains	Different battery technologies and cell materials (LFP, solid-state NMC, Na-Ion); variation in battery capacities
2. Vehicle downsizing	Shift in new car registrations towards smaller vehicles
3. Lightweight construction	Use of lightweight materials, in particular aluminium, in various vehicle components; lightweight construction of battery housings
4. Design for circularity	Car designs that increase longevity or the amount of components that can be reused/ repurposed
5. Reuse and repurpose of EV batteries	Higher shares of re-used and re-manufactured spare parts
6. Repair and remanufacturing of car body	Higher shares of "high repairability and reuse potential"
7. Recycled content of battery materials	Changes in return rates of battery materials from battery recycling; effect of graphite recycling

Option	Analysed approaches
8. Recycled content of metals (Fe, Cu, Al, regardless of battery system)	Different rates for recycled metal content in the vehicle body (battery excluded)
9. Recycling of Plastics	Plastic recycling; use of non-fossil plastic sources
10. End of Life	Higher shares of dismantled materials prior to shredding, higher share of material recovery of glass and higher share of high-quality recycling of steel, aluminium, and copper

Modelling

A detailed model of car transport in Germany was developed for AutoRess, which incorporated all stages of the vehicle life cycle. This model was used to derive comparable GHG and material savings potentials for all 10 options up to year 2045. For each option, up to five variants were modelled and the bandwidth of GHG and material effects was estimated. tThe calculation model mapped the car transport system in Germany in five-year steps in from 2020/21 to 2045 across all life cycle phases, taking into account and linking all relevant influencing factors. Status quo and trend developments of all influencing factors relevant to GHG emissions and material requirements awere adopted from existing analyses or additionally derived. The effects of the analysed options on the various influencing factors are recorded, and the resulting changes can be compared directly in the model with the trend development..

The number of new registrations was taken from the 2024 projection report. It is projected that, between 2025 and 2030, 3.1 to 3.2 million new passenger cars will be registered in Germany annually, with the proportion of battery electric vehicles increasing continuously. After 2030, it is foreseen that the number of annual new registrations will decrease to 2.8 million vehicles in 2035 and 2.6 million vehicles after 2040. From 2035 onwards, it is expected that only BEVs will be newly registered (see following figure, right side).

Vehicle dimensions, weights, and engine power have risen steadily over the past few decades. This growth is expected to continue in the coming years. The AutoRess model is based on the average unladen weights of new vehicle registrations in 2021, with a further weight increase of 1.2% per year until 2030.

The battery capacities of electric cars are assumed to average 61 kWh (gross capacity), increasing to 88 kWh by 2030. Cell chemistry is expected to shift from NMC622 batteries in 2021 to NMC811 batteries from 2030 onwards, and a partial switch to lithium iron phosphate (LFP) batteries is also taken into account.

In the calculation of the specific GHG emissions from automotive production, the increasing shift to renewable energies in the EU was considered in the electricity supply. However, the long-term defossilization of global material supply was not taken into account.

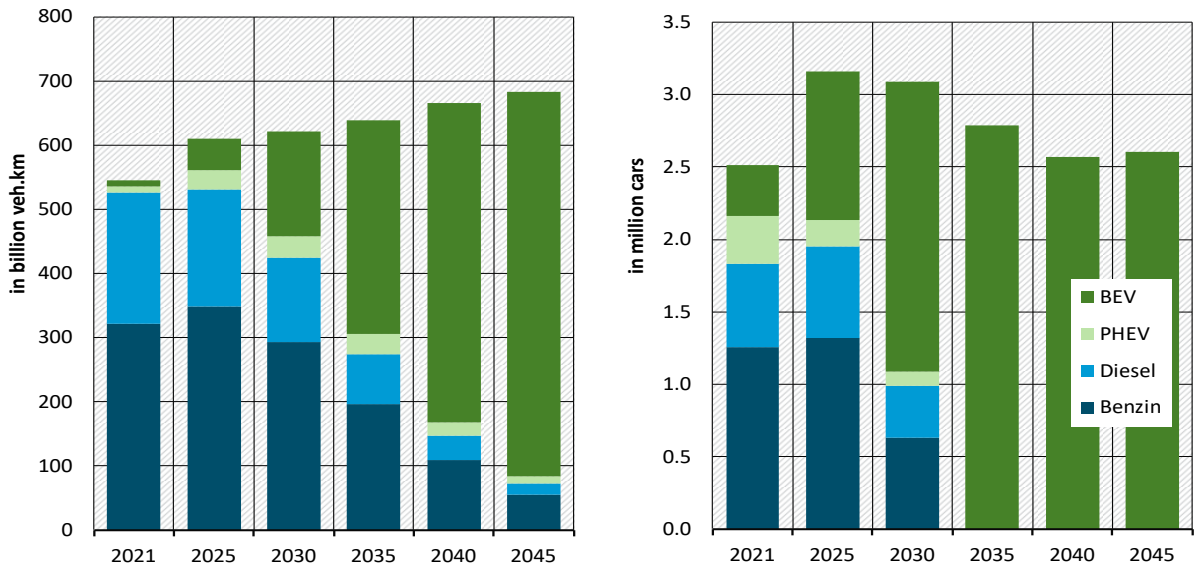
The average percentage material compositions of the vehicle glider and powertrain remain constant in all years.

The use phase includes energy consumption and the resulting greenhouse gas emissions from motor vehicle operation, as well as emissions and material requirements from motor vehicle maintenance and repair.

It is expected that, from 2021 to 2030, passenger car mileage (see following figure, left side) will increase by 14%, with the share of mileage covered by battery electric passenger cars rising to 26%. Even after 2030, passenger car mileage will likely continue to rise steadily, reaching a level in

2045 that is 10% higher than in 2030. Battery electric cars will account for 88% of mileage in 2045.

Annual mileage (left) and new registrations (right) of cars in Germany by drive concept



Source: based on the "with existing measures scenario" (MMS) of the 2024 Projection Report

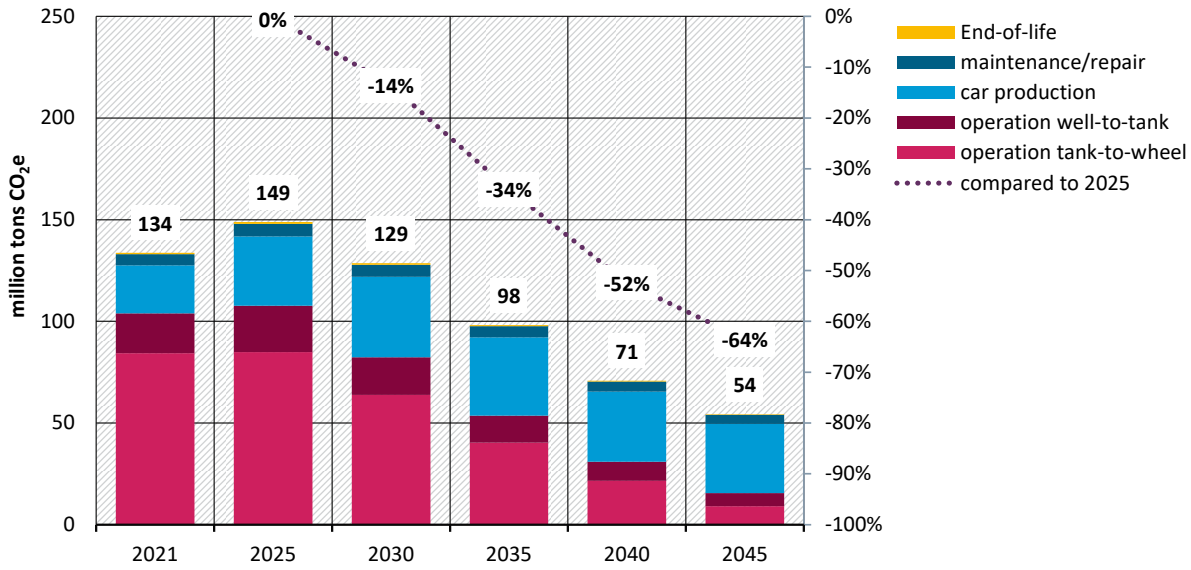
Greenhouse gas emissions and material demand in passenger car transport in Germany

In the reference scenario, it is foreseen that GHG emissions from passenger car traffic in Germany will fall by 4%, from 134 million tons to 129 million tons by 2030. This trend will likely continue, decreasing by almost 60% to 54 million tons by 2045. This drop is expected as a result of increasing electromobility and the decarbonization of the electricity supply.

In contrast, the model foresees that emissions from automobile production will initially rise from 24 million tons of CO_2e to 40 million tons of CO_2e between 2021 and 2030, before falling again to 34 million tons of CO_2e by 2045. The increase in production emissions until 2030 is due in equal measure to the higher annual number of new registrations and the rising share of new registrations of electric cars. From 2030 to 2035, the number of annual new registrations of electric cars are foreseen to continue to increase but will decline after 2035. At the same time, specific emissions from automobile production will likely decline after 2030 as renewable energies are increasingly used in production processes. At the same time, specific emissions from automotive production will decline after 2030 as renewable energies are increasingly used in production processes.

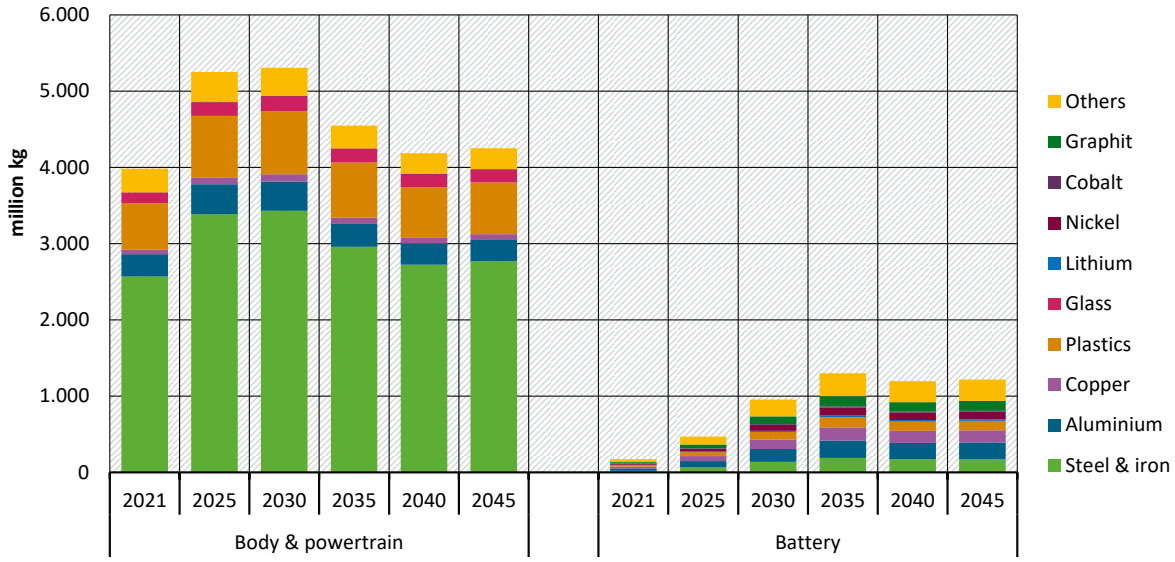
The total annual material requirements for automotive production (see below) were calculated per material group and categorised as either gliders & powertrains or batteries. The material requirements for gliders & powertrains were mainly determined using the total number of new registrations and the increase in vehicle weight. In the model, the shift in new registrations toward electric cars was reflected above all in the sharp increase in material requirements for batteries. The material requirements for gliders & powertrains are dominated by steel and iron as well as aluminium and plastics, which together account for approximately 88% of the weight. Other weight-relevant material groups include copper and glass. Together steel, aluminium and plastics account for 42% of the material requirements in batteries. Copper, nickel, and graphite represent a significant proportion, at 8%-14% each. In contrast, the cell materials lithium and cobalt have a low presence in the overall material balance, each accounting for 1%-3% of the total weight.

Model of GHG emissions of car transport in Germany including all phases of the life cycle



Source: own calculations, ifeu

Model of annual material demand for new passenger cars in Germany



Source: based on annual new registrations in the "with existing measures scenario" (MMS) of the 2024 Projection Report

Material impacts for new car production

The comparison of the impacts of the 10 technical and social options focuses on material requirements for producing new vehicles. Changes in material requirements for vehicle maintenance and repair were addressed in individual options.

The material demand in all powertrains is expected to fall slightly by 2035 and 2045 compared to 2025 despite the increase in vehicle sizes. The reason for this is the decrease in annual new registrations assumed in the trend development.

In contrast, the demand for battery materials will rise sharply, driven by the ramp-up of electromobility and the additional trend towards increasing battery sizes.

Approaches that focus on the entire vehicle (e.g. “downsizing”, “design for circularity: longevity”) have a proportional effect on all material groups, whether due to reduced new registrations or reduced vehicle sizes and accompanying reduced battery sizes.

Options that focus on electromobility, such as “alternative powertrains”, “reuse/repurpose batteries” and “recycled content battery”, only affect the demand for battery materials. Depending on the approach examined, all battery materials can be proportionally affected (e.g. change of battery capacities, repurpose of batteries), but significant differences can also arise between individual battery materials. Adopting different battery technologies (e.g. solid-state, sodium ion) reduces demand for certain materials while increasing demand for others.

Some options only affect selected material groups, in particular for “lightweighting” (steel, aluminium) and “plastics recycling/renewable” (plastics). Options that deal with the decommissioning of cars (plastics recycling, end of life) were seen to have no effect on the total material demands in car production.

In most cases, the options examined are expected to lead to a reduction in annual material requirements. However, in the “Alternative powertrains” and “Lightweighting” options, there is also a partial increase in individual material requirements if the reduction in one material is accompanied by a shift to other materials. In one variation of the “lightweighting” option, a possible reduction in vehicle lifetime was also included. In the model, this results in an increase in the annual number of new registrations and thus in total material requirements.

Primary material demands depend on the total material demand and on the recycled content in the material used. This was also reflected in the changes in primary material demands due to the different technical and social options. Total material demands for new cars change due to:

- Number and size of new cars (e.g. downsizing, remanufacturing) or vehicle components (e.g. battery size), and
- Material composition of vehicles (battery cell materials, aluminium lightweighting).

Recycled content in the total material used depends on:

- Closed-loop recycling: amount of recovered material in vehicle recycling depending on
  (1) number, size and material composition of decommissioned cars,
  (2) share of decommissioned cars and components, which are sent for recycling, and
  (3) material-specific recycling efficiency.
- Effects of closed-loop recovered materials on the overall recycled content:
  (a) increase of overall recycled content or
  (b) higher closed-loop share within an overall unchanged recycled content.

Vision of a resource-efficient vehicle

The AutoRess project developed a vision for a resource-efficient vehicle. The vision was based on purely battery-powered electric cars, which are considered resource-efficient and suitable for the circular economy if they meet the following conditions:

- The **least amount possible of primary raw materials** is consumed over the entire lifecycle.
- The **least amount possible of greenhouse gases** are emitted over the entire lifecycle.
- The **least amount possible of energy** is consumed over the entire lifecycle.
- The **vehicle’s life span is as long as possible.**

- The **vehicles' components can be recycled** in the most efficient way possible without the need for downcycling.
- Additional **negative environmental as well as social impacts are minimized.**

The modeling activities carried out in the AutoRess project on resource use and GHG emissions in the automotive industry in 10 selected subject areas identified three levers that have a particularly strong impact on the goals:

- **Reduction of vehicle and battery dimensions**
- **Longer vehicle and batteries lifetime**
- **Higher quantities of recycled materials**

Criteria for a resource-efficient vehicle

The results from the model were combined with expert knowledge and further research to formulate criteria that could fulfil the requirements of a resource-efficient vehicle.

To meet these requirements, the ideal battery-electric vehicle for urban transport would be less than 2.4 m long and 1.4 m wide. For interurban transport for a family with luggage, it would be less than 5.0 m long and less than 2.0 m wide. The ideal vehicle would be made entirely from secondary materials, have a service life of 20 years, and be optimized in terms of repairability. This requires would require all vehicle parts, especially those that can break or wear out quickly, to be easily accessible and replaceable. This total modularity would also promote the recyclability of the components and materials used in the vehicle by facilitating the dismantling of parts before the body is shredded at the end of its service life. Software and hardware upgrades are guaranteed for the vehicle's entire service life.

Measures

Based on the results from the model and the developed criteria for a resource-efficient vehicle, the necessary measures and instruments to implement these targets were derived and developed. These measures were classified, evaluated and prioritised according to specific criteria, such as current status of implementation of the measure, life cycle phase, affected stakeholders, impact mechanism, time horizon, geographical level of action, and level of obligation. The following measures were considered a priority.

- **Bonus-malus system based on vehicle size:** In a bonus-malus system, buyers of smaller cars receive a bonus, while those who purchase larger cars must pay a penalty that also increases with size. One-time payments when purchasing a car have a greater impact than annual vehicle taxes. Proposed values for the bonus are less than 2.4 m in length and 1.4 m in width for a battery electric vehicle for city traffic, and less than 5.0 m in length and less than 2.0 m in width for a family with luggage for interurban traffic.
- **Taxation of company cars:** An estimated 20% to 25% of new registrations in Germany are company cars that are also used privately (UBA 2021). The reason for the attractiveness of the car as a salary component is low taxation: for employees, the taxable monetary benefit is significantly cheaper than the cost of a privately purchased car. Companies can deduct the purchase of cars for business purposes as operating expenses without a maximum price limit and regardless of the vehicles' CO_2 emissions. Under this measure, resource-efficient electric cars, e.g. those with small dimensions, are taxed less than other vehicles.

- **Environmental bonus in car insurance:** With regard to a car's CO_2 emissions, many car insurance companies now offer environmental discounts when insuring an environmentally friendly vehicle. One example from Germany is R+V, offering an Environmental bonus of 10% discount on the insurance premium for electric and hybrid cars and 5% for cars with low CO_2 emissions (up to 95 g/km). Further environmental discounts of this kind may be introduced in the near future.
- **Promotion of sustainable vehicles in public procurement guidelines.** The Federal Environment Agency's "Guide to Environmentally Oriented Procurement" is supplemented by recommendations for vehicles. These cover sustainable aspects throughout the entire life cycle of vehicles, including compliance with due diligence obligations in the raw material value chains, the use of recycled materials in production, reparability during use, and recyclability during disposal.
- **Minimum service life warranty for vehicles:** Introduction of a statutory lifetime warranty for the entire vehicle based on realistically achievable service lives; a warranty of 20 years is proposed. Wearing parts are excluded from this.
- **Minimum values for the energy density of batteries:** This measure sets minimum requirements for the energy density of traction batteries. The Battery Regulation defines energy conversion as a functional unit, which already provides an incentive in this direction – with fixed limits. These limits could become even more significant. Limits for battery weight per car could be achieved by limiting battery capacity and increasing energy densities.
- **Minimum service life warranty for batteries:** A mandatory minimum warranty for batteries of 300,000 km or 20 years is specified. Currently, there are no legal obligations for further incentives for long warranty periods for batteries, except for the general 2-year product warranty and the requirements for traction batteries for M1 and N1 vehicles in the Euro 7 Regulation (Annex II: 5 years and 100,000 km), as well as voluntary manufacturerguarantees.
- **Replacement and removal of parts and components:** Vehicle manufacturers will be required to provide detailed instructions on how to replace and remove vehicle parts and components. Vehicles must be designed in such a way that components with reuse potential can be removed when the vehicles are disposed of. This also applies to drive batteries and electric motors. This measure is part of the proposal for a new End-of-Life Vehicles Regulation presented by the EU Commission on 13 July 2023.
- **Minimum service life warranty for spare parts:** A mandatory minimum warranty of two years for spare parts will be established. This measure is part of the proposal for a new end-of-life vehicle regulation presented by the EU Commission on 13 July 2023.
- **Software update warranty:** Vehicle manufacturers will be required to provide software updates over a longer period of time. These must be guaranteed for the lifetime of the vehicle, i.e. for 20 years.
- **Access to information on EV battery repair and maintenance:** Vehicle manufacturers will be required to provide affordable access to software updates and spare parts for 20 years to support EV battery reconditioning activities. A right to repair ensures that independent repair shops have access to the information, tools, and parts necessary for the repair and maintenance of EV batteries without legal or technical restrictions.

- **EPR system for financing the proper treatment of end-of-life vehicles:** In order to ensure adequate financing for the prescribed treatment of end-of-life vehicles and to offer recycling companies incentives to improve quality, an EPR system is being introduced in which vehicle manufacturers are made responsible for financing the treatment of end-of-life vehicles in accordance with Extended Producer Responsibility (EPR).
- **Setting a recycled content target for steel:** Introduction of a target for the use of recycled steel in vehicle production. One challenge here is the quality of steel scrap from vehicle shredding plants. Contaminants such as copper reduce the quality of recycled steel and currently prevent a higher recycling rate in the production of high-quality flat steel products. A legal minimum target for the recycled steel content in vehicles would shift the market for recycled steel towards higher quality. According to calculations, a recycled content of 25% by 2030 and 30% by 2035 would be achievable with a closed recycling loop.
- **Requirements for shredder and post-shredder plants:** Copper in particular is a contaminant in steel recycling that reduces the quality of recycled steel. In order to ensure high quality of the recovered steel, a maximum value of 0.1% copper in the steel fraction is set for vehicle shredder plants. The main aim here is to separate copper particles that enter the steel fraction during the shredding process. However, the intrinsic copper contained in the steel alloy cannot be separated at an economically viable cost.
- **Setting recycling targets for glass and plastics:** Cars contain many different materials, but these are treated differently at the end of their service life. Steel, aluminum, and copper are largely recovered, but other materials are not. Since certain materials such as plastics and glass account for only a small proportion of the vehicle's weight, they are often disposed of and only recovered after shredding, which leads to a reduction in the quality of the recovered material. This measure sets recycling targets for glass and plastics.

Circular Economy Roadmap for vehicles

In the last project phase a strategic roadmap for the circular economy for vehicles as part of the transport and energy transition in the transport sector was developed. This roadmap aims to demonstrate which measures and instruments can make a significant contribution to reducing greenhouse gas emissions and resource consumption and in which timeframe by which stakeholders these can be achieved. The following table shows these prioritized measures and instruments.

Strategic roadmap for the circular economy for vehicles

Option	Level of action	Timeframe	Addressed stakeholders	Effectiveness	Feasibility
Bonus-malus system based on vehicle size	Germany	short (up to 5 years)	car buyers	medium	high
Taxation of company cars	Germany	short (up to 5 years)	car buyers	medium	high
Environmental bonus in car insurance	Germany	short (up to 5 years)	car insurances	medium	high

Option	Level of action	Timeframe	Addressed stakeholders	Effectiveness	Feasibility
Promotion of sustainable vehicles in public procurement guidelines	Germany	short (up to 5 years)	public procurement	low	high
Minimum service life guarantee for vehicles	European Union	medium (5 to 10 years)	car manufacturers	high	low
Minimum values for the energy density of batteries	European Union	medium (5 to 10 years)	battery manufacturers: car manufacturers	high	low
Minimum service life guarantee for batteries	European Union	medium (5 to 10 years)	battery manufacturers: car manufacturers	high	low
Replacement and removal of parts and components	European Union	medium (5 to 10 years)	car manufacturers	high	low
Minimum service life guarantee for spare parts	European Union	medium (5 to 10 years)	Repair workshops; remanufacturers	medium	high
Software update guarantee	European Union	medium (5 to 10 years)	car manufacturers	medium	high
Access to information on EV battery repair and maintenance	European Union	medium (5 to 10 years)	car manufacturers	medium	high
EPR system for financing the proper treatment of end-of-life vehicles	European Union	medium (5 to 10 years)	car manufacturers	high	high
Setting a recycled content target for steel	European Union	medium (5 to 10 years)	car manufacturers	medium	medium
Requirements for shredder and post-shredder plants	European Union	medium (5 to 10 years)	schredders; Post Shredders	high	high
Setting recycling targets for glass and plastics	European Union	medium (5 to 10 years)	ATFs; shredders; post shredders; recyclers	medium	high

Zusammenfassung

Die Pariser Vereinbarungen und der Klimaschutzplan 2050 setzen auch im Verkehrssektor klare CO_2-Reduktionsziele. Diese können nur mit einer ambitionierten Umstellung auf Elektrofahrzeuge erreicht werden. Elektrofahrzeuge zeichnen sich durch spezielle Komponenten wie den elektrischen Antriebsmotor, die Batterie, die Brennstoffzelle oder die Leistungselektronik aus. Im Projekt AutoRess wurden technische und nicht-technische Optionen zur Verringerung der Auswirkungen des Verkehrs auf das Klima und den Ressourcenverbrauch über alle Phasen des Fahrzeuglebenszyklus hinweg analysiert. Auf dieser Grundlage wurden geeignete Instrumente und Maßnahmen entwickelt und bewertet sowie eine Definition und Kriterien für ein ressourceneffizientes Fahrzeug erarbeitet. All dies wurde zu einer Roadmap für die Kreislaufwirtschaft für Fahrzeuge zusammengefasst.

Die Ergebnisse wurden in verschiedenen Workshops an den Projektbeirat sowie an externe Experten und interne UBA-Experten zurückgemeldet. Das Projekt wurde vom Öko-Institut e. V. zusammen mit der ifeu gGmbH, Mehlhart Consulting und team ewen von November 2022 bis August 2025 durchgeführt.

Eingehende Analyse technischer und sozialer Optionen

In AutoRess wurden die Treibhausgasemissionen und Primärmaterial-Einsparpotenziale im deutschen Pkw-Sektor für verschiedene, vorwiegend technische Optionen unter Berücksichtigung aller Lebenszyklusphasen der Fahrzeuge analysiert.

Als Ausgangspunkt für die Bewertung des zukünftigen Treibhausgas- und Materialeinsparpotenzials im Fahrzeuglebenszyklus muss zunächst bewertet werden, wie sich die verschiedenen Einflussfaktoren und die daraus resultierenden Treibhausgasemissionen und Materialbedarfe ohne zusätzliche Eingriffe entwickeln werden („aktuelle Treiber“). Als Ergebnis der systemischen Analyse direkter und indirekter Faktoren, die die Treibhausgasemissionen und den Rohstoffverbrauch beeinflussen, wurden 10 technische und soziale Optionen (siehe Tabelle) ausgewählt. Diese wurden anschließend eingehend analysiert, um zusätzliches Potenzial („zusätzliche Treiber“) zu bewerten. Der aktuelle Status quo, Entwicklungstrends mit aktuellen Treibern und Handlungsfelder für zusätzliche Treiber zur Reduzierung von Treibhausgasemissionen und Materialbedarf wurden in Expertenworkshops diskutiert.

Übersicht über die analysierten technischen und sozialen Optionen

Option	Analysierte Ansätze
1. Antriebswechsel	Verschiedene Batterietechnologien und Zellmaterialien (LFP, Festkörper-NMC, Na-Ion); Variation der Batteriekapazitäten
2. Verringerung der Fahrzeuggröße	Verlagerung der Neuzulassungen hin zu kleineren Fahrzeugen
3. Leichtbau	Verwendung von Leichtbaumaterialien, insbesondere Aluminium, in verschiedenen Fahrzeugkomponenten; Leichtbauweise von Batteriegehäusen
4. Kreislauforientiertes Design	Autodesigns, die die Langlebigkeit oder die Menge der wiederverwendbaren/wiederverwertbaren Komponenten erhöhen
5. Reparatur und Wiederaufbereitung von E-Fahrzeug-Batterien	Höherer Anteil wiederverwendeter und wiederaufbereiteter Ersatzteile

Option	Analysierte Ansätze
6. Reparatur und Wiederaufbereitung der Fahrzeugkarosserie	Höherer Anteil an „hoher Reparaturfähigkeit und Wiederverwendungspotenzial“
7. Rezyklateinsatz von Batterierohstoffen	Veränderungen der Rücklaufquoten von Batteriematerialien aus dem Batterierecycling; Auswirkungen des Graphitrecyclings
8. Rezyklateinsatz von Metallen (Fe, Cu, Al, antriebsunabhängig)	Unterschiedliche Anteile an recyceltem Metall in der Fahrzeugkarosserie (ohne Batterie)
9. Kreislaufführung von Kunststoffen	Kunststoffrecycling; Verwendung nicht-fossiler Kunststoffquellen
10. Altfahrzeugentsorgung	Höherer Anteil an vor dem Schreddern demontierten Materialien, höherer Anteil an Materialrückgewinnung aus Glas und höherer Anteil an hochwertigem Recycling von Stahl, Aluminium und Kupfer

Modellierung

Für AutoRess wurde ein detailliertes Modell des Autoverkehrs in Deutschland erstellt, das alle Phasen des Fahrzeuglebenszyklus umfasst. Anhand dieses Modells wurden für alle 10 Optionen vergleichbare Treibhausgas- und Materialeinsparpotenziale bis 2045 abgeleitet. Für jede Option wurden bis zu 5 Varianten modelliert und die Bandbreite der Treibhausgas- und Materialeffekte abgeschätzt. Im Berechnungsmodell wird das System des Autoverkehrs in Deutschland im Zeitraum 2020/21 bis 2045 in 5-Jahres-Schritten über alle Lebenszyklusphasen hinweg abgebildet, wobei alle für Treibhausgasemissionen und Materialbedarf relevanten Einflussfaktoren berücksichtigt und miteinander verknüpft werden. Status quo und Trendentwicklungen für diese Einflussfaktoren wurden aus bestehenden Analysen übernommen oder zusätzlich abgeleitet. Die Auswirkungen der analysierten Optionen auf die verschiedenen Einflussfaktoren wurden erfasst und die sich daraus ergebenden Veränderungen im Vergleich zur Trendentwicklung direkt im Modell ermittelt.

Die Zahl der Neuzulassungen wurde dem Projektionsbericht 2024 entnommen. In den Jahren 2025 und 2030 werden jährlich 3,1 bis 3,2 Millionen neue Personenkraftwagen zugelassen, wobei der Anteil batterieelektrischer Fahrzeuge kontinuierlich steigt. Nach 2030 gehen die jährlichen Neuzulassungen auf 2,8 Millionen Fahrzeuge (2035) und 2,6 Millionen Fahrzeuge (ab 2040) zurück. Ab 2035 werden nur noch BEV neu zugelassen (nachfolgende Abbildung, rechts).

Die Fahrzeugabmessungen, Gewichte und Motorleistungen sind in den letzten Jahrzehnten stetig gestiegen. Dieses Wachstum wird sich voraussichtlich auch in den kommenden Jahren fortsetzen. Das AutoRess-Modell basiert auf den durchschnittlichen Leergewichten der Neuzulassungen im Jahr 2021, mit einer weiteren Gewichtszunahme von 1,2 % pro Jahr bis 2030.

Die Batteriekapazitäten von Elektroautos werden mit durchschnittlich 61 kWh (Bruttokapazität) angenommen, die bis 2030 auf 88 kWh steigen. Die Zellchemie verlagert sich von einem großen Anteil NMC622-Batterien im Jahr 2021 hin zu mehr NMC811-Batterien ab 2030, wobei auch eine teilweise Umstellung auf Lithium-Eisenphosphat-Batterien (LFP) berücksichtigt wurde.

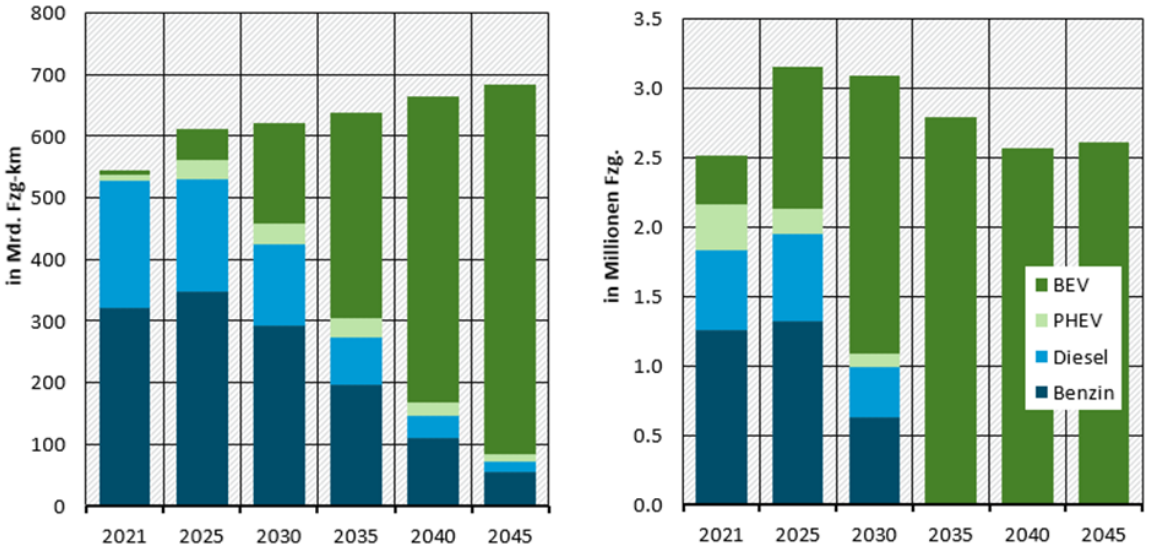
Bei der Berechnung der spezifischen Treibhausgasemissionen aus der Automobilproduktion wurde die zunehmende Umstellung auf erneuerbare Energien für die Stromversorgung in Europa berücksichtigt, nicht jedoch die langfristige Defossilisierung der globalen Materialversorgung.

Die durchschnittlichen prozentualen Materialzusammensetzungen des Fahrgestells und des Antriebsstrangs bleiben in allen Jahren konstant.

Die Nutzungsphase umfasst einerseits den Energieverbrauch und die daraus resultierenden Treibhausgasemissionen während des Betriebs von Kraftfahrzeugen und andererseits die Emissionen und den Materialbedarf durch Wartung und Reparatur.

Von 2021 bis 2030 steigt die jährliche Gesamtfahrleistung von Pkw in Deutschland (siehe nachfolgende Abbildung, linke Seite) um 14 %, wobei sich der Anteil der mit batterieelektrischen Pkw zurückgelegten Kilometer auf 26 % erhöht. Auch nach 2030 steigt die Kilometerleistung von Personenkraftwagen stetig weiter an und erreicht bis 2045 ein Niveau, das 10 % über dem von 2030 liegt. Batterieelektrische PKW werden 2045 88 % der Kilometerleistung ausmachen.

Jährliche Fahrleistung (links) und Neuregistrierungen (rechts) von Pkw in Deutschland



Quelle: auf Grundlage des “with existing measures scenario” (MMS) des 2024 Projektions-Berichts

Treibhausgasemissionen und Materialbedarf im Pkw-Verkehr in Deutschland

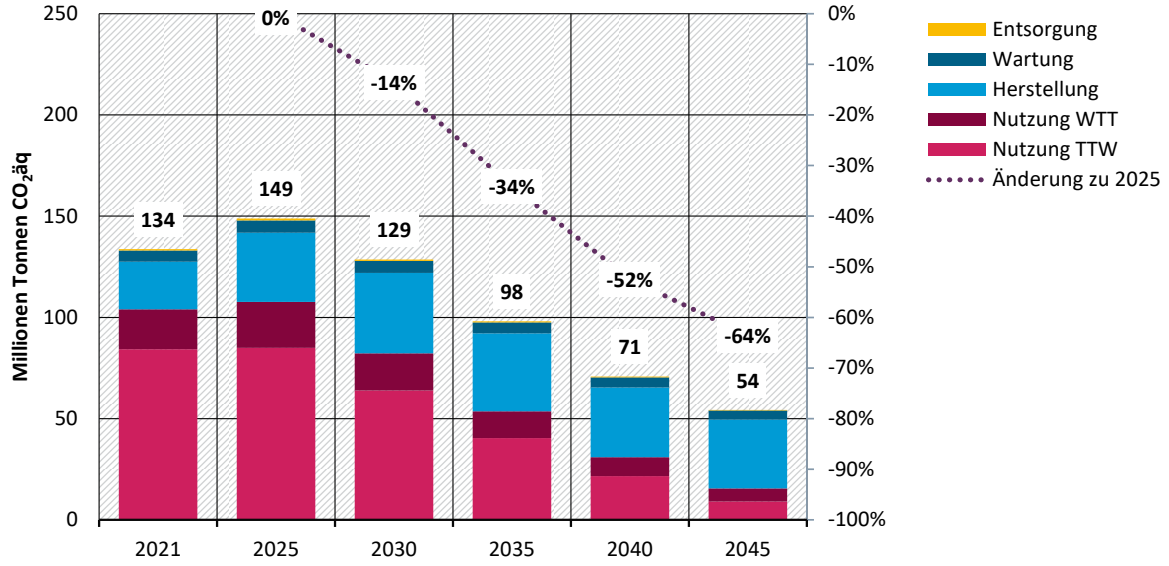
Im Referenzszenario sinken die Treibhausgasemissionen aus dem Pkw-Verkehr in Deutschland bis 2030 um 4 % von 134 Millionen Tonnen auf 129 Millionen Tonnen, bis 2045 jedoch aufgrund der zunehmenden Elektromobilität und der Dekarbonisierung der Stromversorgung um fast 60 % auf 54 Millionen Tonnen (siehe Abbildung unten).

Im Gegensatz dazu werden die Emissionen aus der Automobilproduktion zwischen 2021 und 2030 zunächst von 24 Millionen Tonnen CO_2e auf 40 Millionen Tonnen CO_2e steigen, bevor sie bis 2045 wieder auf 34 Millionen Tonnen CO_2e sinken. Der Anstieg der Emissionen bis 2030 ist gleichermaßen auf die höhere jährliche Zahl der Neuzulassungen und den steigenden Anteil der Neuzulassungen von Elektroautos zurückzuführen. Von 2030 bis 2035 wird die Zahl der jährlichen Neuzulassungen von Elektroautos zunächst weiter steigen, nach 2035 jedoch zurückgehen. Gleichzeitig werden die spezifischen Emissionen aus der Automobilproduktion nach 2030 sinken, da in den Produktionsprozessen zunehmend erneuerbare Energien zum Einsatz kommen.

Der jährliche Gesamtmaterialbedarf in der Automobilproduktion (siehe Abbildung unten) wurde nach Materialgruppen berechnet, differenziert nach Fahrgestellen und Antriebssträngen sowie Batterien. Der Materialbedarf für Fahrgestelle und Antriebsstränge wird hauptsächlich durch die Gesamtzahl der Neuzulassungen und die Zunahme des Fahrzeuggewichts bestimmt. Die Verlagerung der Neuzulassungen hin zu Elektroautos spiegelt sich vor allem in dem starken

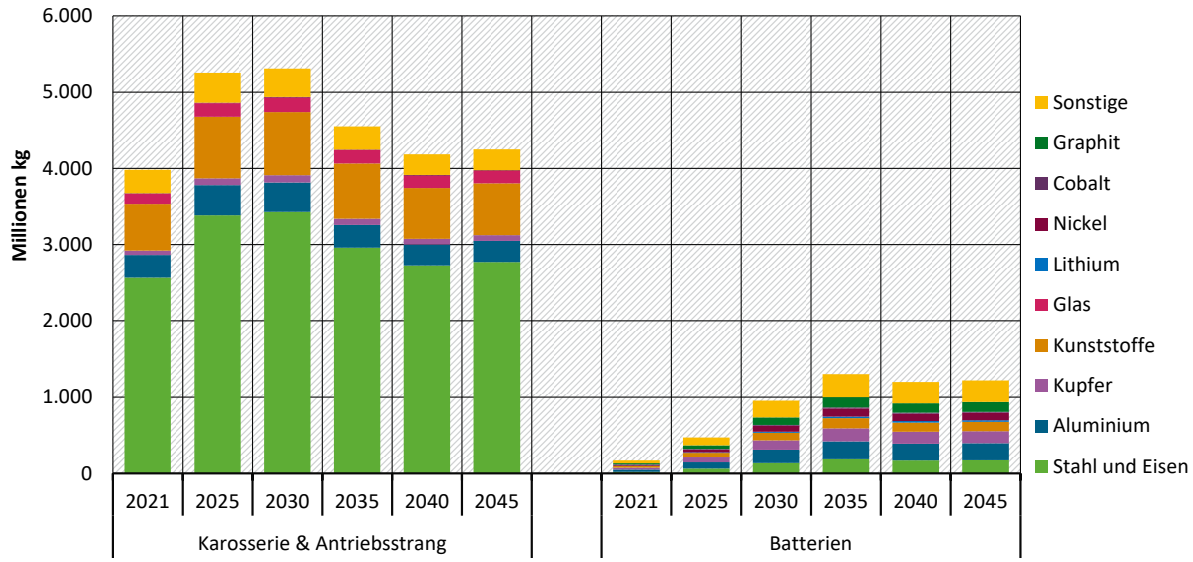
Anstieg des Materialbedarfs für Batterien wider. Der Materialbedarf für Fahrgestelle und Antriebe wird von Stahl und Eisen sowie Aluminium und Kunststoffen dominiert. Zusammen machen diese etwa 88 % des Gewichts aus. Weitere gewichtsrelevante Materialgruppen sind Kupfer und Glas. Stahl, Aluminium und Kunststoffe machen zusammen auch 42 % des Materialbedarfs in Batterien aus. Kupfer, Nickel und Graphit haben ebenfalls bedeutende Anteile von jeweils 8 bis 14 %. Im Gegensatz dazu sind die Zellmaterialien Lithium und Kobalt in der Gesamtmaterialbilanz mit jeweils 1 bis 3 % des Gesamtgewichts nur gering vertreten.

Treibhausgasemissionen des Pkw-Verkehrs in Deutschland einschl. aller Lebenszyklus-Phasen



Quelle: Eigene Berechnungen, ifeu

Jährlicher Rohstoffbedarf des Pkw-Verkehrs in Deutschland (Neuwagen)



Quelle: auf Grundlage des jährlichen Neuregistrierungen und des “with existing measures scenario” (MMS) des 2024 Projektions-Berichts

Materialauswirkungen bei der Neuwagenproduktion

Der Vergleich der Auswirkungen der zehn technischen und sozialen Optionen konzentriert sich auf den Materialbedarf bei der Neuwagenproduktion. Veränderungen beim Materialbedarf für die Wartung und Reparatur von Fahrzeugen wurden jeweils in einzelnen Optionen behandelt.

Der Materialbedarf aller Antriebsarten wird bis 2035 und 2045 trotz der Zunahme der Fahrzeuggrößen gegenüber 2025 leicht zurückgehen. Grund dafür ist der in der Trendentwicklung angenommene Rückgang der jährlichen Neuzulassungen.

Demgegenüber wird der Bedarf an Batteriematerialien aufgrund des Ausbaus der Elektromobilität und des zusätzlichen Trends zu größeren Batterien stark ansteigen.

Optionen mit Fokus auf das gesamte Fahrzeug (z. B. „Downsizing“, „Design for Circularity: Langlebigkeit“) wirken sich aufgrund reduzierter Neuzulassungen oder aufgrund reduzierter Fahrzeuggrößen und damit einhergehender reduzierter Batteriegrößen proportional auf alle Materialgruppen aus.

Ansätze mit Schwerpunkt auf Elektromobilität („alternative Antriebe“, „Wiederverwendung / Umnutzung von Batterien“, „Batterien mit recycelten Inhaltsstoffen“) wirken sich nur auf die Nachfrage nach Batteriematerialien aus. Je nach untersuchter Vorgehensweise können alle Batteriematerialien proportional betroffen sein (z. B. Änderung der Batteriekapazitäten, Umnutzung von Batterien), es kann jedoch auch zu erheblichen Unterschieden zwischen einzelnen Batteriematerialien kommen. Eine Änderung der Batterietechnologie (Festkörper, Natrium-Ionen) reduziert die Nachfrage nach ausgewählten Materialien, erhöht aber gleichzeitig die Nachfrage nach anderen.

Einige Optionen wirken sich nur auf ausgewählte Materialgruppen aus, insbesondere auf Leichtbau (Stahl, Aluminium) und Kunststoffrecycling/erneuerbare Kunststoffe.

Optionen, die sich mit der Stilllegung von Autos befassen (Kunststoffrecycling, Ende der Lebensdauer), haben keinen Einfluss auf den Gesamtmaterialbedarf in der Automobilproduktion.

In den meisten Fällen führen die untersuchten Optionen zu einer Verringerung des jährlichen Materialbedarfs. Bei den Optionen „Antriebswechsel “ und „Leichtbau“ kommt es jedoch auch zu einem teilweisen Anstieg des Bedarfs an einzelnen Materialien, wenn die Reduzierung eines Materials mit einer Verlagerung auf andere Materialien einhergeht. Unter „Leichtbau“ wurde in einer Variante auch eine mögliche Verkürzung der Fahrzeuglebensdauer berücksichtigt. Im Modell führt dies zu einem Anstieg der jährlichen Neuzulassungen und damit des Gesamtmaterialbedarfs.

Der Primärmaterialbedarf hängt vom Gesamtmaterialbedarf und vom Recyclinganteil im verwendeten Material ab. Dies spiegelt sich auch in den Veränderungen des Primärmaterialbedarfs aufgrund der verschiedenen technischen und sozialen Optionen wider.

Der Gesamtmaterialbedarf für Neufahrzeuge ändert sich aufgrund von

- Anzahl und Größe der Neufahrzeuge (z. B. Downsizing, Wiederaufarbeitung) oder Fahrzeugkomponenten (z. B. Batteriegröße)
- Materialzusammensetzung der Fahrzeuge (Batteriezellenmaterialien, Aluminium-Leichtbauweise)

Der Rezyklat-Anteil am gesamten Materialverbrauch hängt ab von:

- Geschlossener Recyclingkreislauf: Menge an zurückgewonnenem Material beim Fahrzeugrecycling in Abhängigkeit von
- Anzahl, Größe und Materialzusammensetzung der ausgemusterten Fahrzeuge,
- Anteil der ausgemusterten Fahrzeuge und Komponenten, die dem Recycling zugeführt werden, und
    - materialspezifischer Recyclingeffizienz
- Auswirkungen von geschlossenen Kreisläufen für zurückgewonnene Materialien auf den Gesamtanteil an recycelten Materialien:
- Erhöhung des Gesamtanteils an recycelten Materialien oder
- höherer Anteil geschlossener Kreisläufe bei insgesamt unverändertem Anteil an recycelten Materialien.

Vision eines ressourceneffizienten Fahrzeugs

Das AutoRess-Projekt hat eine Vision für ein ressourceneffizientes Fahrzeug entwickelt. Diese Vision basiert auf rein batteriebetriebenen Elektroautos. Diese gelten als ressourceneffizient und für die Kreislaufwirtschaft geeignet, wenn sie die folgenden Bedingungen erfüllen

- Über den gesamten Lebenszyklus werden so wenig Primärrohstoffe wie möglich verbraucht.
- Über den gesamten Lebenszyklus werden so wenig Treibhausgase wie möglich ausgestoßen.
- Über den gesamten Lebenszyklus wird so wenig Energie wie möglich verbraucht.
- Die Lebensdauer des Fahrzeugs ist so lang wie möglich.
- Die Komponenten der Fahrzeuge können auf möglichst effiziente Weise recycelt werden, ohne dass Downcycling erforderlich ist.
- Zusätzliche negative ökologische und soziale Auswirkungen werden minimiert.

Die im Rahmen des Projekts „AutoRess“ durchgeführte Modellierung des Ressourcenverbrauchs und der Treibhausgasemissionen in der Automobilindustrie in 10 ausgewählten Themenbereichen hat drei Hebel identifiziert, die einen besonders starken Einfluss auf die Ziele haben:

- Reduzierung der Fahrzeug- und Batteriegrößen
- Längere Lebensdauer für Fahrzeuge und Batterien
- Höhere Mengen an recycelten Materialien

Kriterien für ein ressourceneffizientes Fahrzeug

Anhand der Ergebnisse des Modells in Kombination mit Expertenwissen und weiteren Forschungsergebnissen wurden Kriterien formuliert, um die Anforderungen an ein ressourceneffizientes Fahrzeug zu erfüllen.

Um die Anforderungen zu erfüllen, sollte ein ideales batterieelektrisches Fahrzeug für den Stadtverkehr weniger als 2,4 m lang und 1,4 m breit sein, für den Überlandverkehr für eine Familie mit Gepäck weniger als 5,0 m lang und weniger als 2,0 m breit. Es sollte vollständig aus Sekundärmaterialien hergestellt werden, eine Lebensdauer von 20 Jahren haben und auch hinsichtlich der Reparaturfähigkeit optimiert sein. Dies erfordert, dass alle Fahrzeugteile (insbesondere solche, die schnell kaputt gehen oder verschleißen können) leicht zugänglich und austauschbar sind. Diese vollständige Modularität fördert auch die Recyclingfähigkeit der im Fahrzeug verwendeten Komponenten und Materialien, da sie die Demontage von Teilen vor der Verschrottung der Karosserie am Ende ihrer Lebensdauer erleichtert. Software- und Hardware-Upgrades sind für die gesamte Lebensdauer des Fahrzeugs garantiert.

Maßnahmen

Auf Grundlage der Ergebnisse der Modellierung und der entwickelten Kriterien für ressourceneffiziente Fahrzeuge wurden Maßnahmen und Instrumente abgeleitet und entwickelt, die zur Umsetzung dieser Ziele erforderlich sind. Die Maßnahmen wurden nach bestimmten Kriterien (z. B. aktueller Stand der Umsetzung der Maßnahme, Lebenszyklusphase, betroffene Interessengruppen, Wirkungsmechanismus, Zeithorizont, geografische Ebene der Maßnahme, Verbindlichkeit) klassifiziert, bewertet und priorisiert. Die folgenden Maßnahmen wurden als vorrangig eingestuft.

- Bonus-Malus-System basierend auf der Fahrzeuggröße: In einem Bonus-Malus-System erhalten Käufer kleinerer Autos einen Bonus, während diejenigen, die größere Autos kaufen, eine Strafe zahlen müssen, die mit der Größe steigt. Einmalzahlungen beim Kauf eines Autos haben eine größere Wirkung als jährliche Kfz-Steuern. Die vorgeschlagenen Werte für den Bonus liegen bei weniger als 2,4 m Länge und 1,4 m Breite für ein batterieelektrisches Fahrzeug für den Stadtverkehr und bei weniger als 5,0 m Länge und weniger als 2,0 m Breite für eine Familie mit Gepäck für den Überlandverkehr.

- Besteuerung von Firmenwagen: Schätzungsweise 20 bis 25 % der Neuzulassungen in Deutschland sind Firmenwagen, die auch privat genutzt werden (UBA 2021). Der Grund für die Attraktivität des Autos als Gehaltsbestandteil ist die geringe Besteuerung: Für Arbeitnehmer ist der steuerpflichtige geldwerte Vorteil deutlich günstiger als die Kosten für ein privat gekauftes Auto. Unternehmen können den Kauf von Autos für geschäftliche Zwecke ohne Höchstpreis als Betriebsausgaben absetzen.

- Umweltbonus in der Kfz-Versicherung: Im Hinblick auf die CO_2-Emissionen eines Autos bieten viele Kfz-Versicherungen mittlerweile Umweltrabatte an, wenn ein umweltfreundliches Fahrzeug versichert wird. Ein Beispiel aus Deutschland ist die R+V: Umweltbonus: 10 % Rabatt auf die Versicherungsprämie für Elektro- und Hybridautos und 5 % für Autos mit geringen CO_2-Emissionen (bis zu 95 g/km). Weitere Umweltrabatte dieser Art könnten in naher Zukunft eingeführt werden.

- Förderung nachhaltiger Fahrzeuge in den Richtlinien für die öffentliche Beschaffung. Der „Leitfaden zur umweltorientierten Beschaffung" des Umweltbundesamtes wird durch Empfehlungen für Fahrzeuge ergänzt. Diese umfassen nachhaltige Aspekte über den gesamten Lebenszyklus von Fahrzeugen, einschließlich der Einhaltung der Sorgfaltspflichten in den Rohstoffwertschöpfungsketten, der Verwendung von recycelten Materialien in der Produktion, der Reparierbarkeit während der Nutzung und der Recyclingfähigkeit bei der Entsorgung.

- Mindestlebensdauergarantie für Fahrzeuge: Einführung einer gesetzlichen Lebensdauergarantie für das gesamte Fahrzeug auf der Grundlage realistisch erreichbarer

Lebensdauern; vorgeschlagen wird eine Garantie von 15 Jahren. Verschleißteile sind davon ausgenommen.

- Mindestwerte für die Energiedichte von Batterien: Diese Maßnahme legt Mindestanforderungen für die Energiedichte von Antriebsbatterien fest. Die Batterieverordnung definiert die Energieumwandlung als Funktionseinheit, was bereits einen Anreiz in diese Richtung darstellt – mit festen Grenzwerten könnte dies noch bedeutender werden. Grenzwerte für das Batteriegewicht pro Fahrzeug könnten durch eine Begrenzung der Batteriekapazität und eine Erhöhung der Energiedichte erreicht werden.
- Mindestlebensdauergarantie für Batterien: Es wird eine obligatorische Mindestgarantie für Batterien von 300.000 km oder 20 Jahren festgelegt. Derzeit gibt es keine gesetzlichen Verpflichtungen für weitere Anreize für lange Garantiezeiten für Batterien, mit Ausnahme der allgemeinen 2-jährigen Produktgarantie und der Anforderungen für Traktionsbatterien für M1- und N1-Fahrzeuge in der Euro-7-Verordnung (Anhang II: 5 Jahre und 100.000 km) sowie freiwilliger Herstellergarantien.
- Austausch und Ausbau von Teilen und Komponenten: Fahrzeughersteller müssen detaillierte Anweisungen zum Austausch und Ausbau von Fahrzeugteilen und -komponenten bereitstellen. Fahrzeuge müssen so konstruiert sein, dass Komponenten mit Wiederverwendungspotenzial bei der Entsorgung der Fahrzeuge ausgebaut werden können. Dies gilt auch für Antriebsbatterien und Elektromotoren. Diese Maßnahme ist Teil des Vorschlags für eine neue Altfahrzeugverordnung, den die EU-Kommission am 13. Juli 2023 vorgelegt hat.
- Mindestlebensdauergarantie für Ersatzteile: Es wird eine verbindliche Mindestgarantie von zwei Jahren für Ersatzteile eingeführt. Diese Maßnahme ist Teil des Regelungsvorschlags der EU-Kommission. Teil des Vorschlags für eine neue Altfahrzeugverordnung, den die EU-Kommission am 13. Juli 2023 vorgelegt hat.
- Garantie für Software-Updates: Fahrzeughersteller werden verpflichtet, über einen längeren Zeitraum Software-Updates bereitzustellen. Diese müssen für die gesamte Lebensdauer des Fahrzeugs, d. h. beispielsweise für 20 Jahre, garantiert werden.
- Zugang zu Informationen über die Reparatur und Wartung von EV-Batterien: Fahrzeughersteller werden verpflichtet, 20 Jahre lang einen erschwinglichen Zugang zu Software-Updates und Ersatzteilen bereitzustellen, um die Aufarbeitung von EV-Batterien zu unterstützen. Ein Recht auf Reparatur gewährleistet, dass unabhängige Werkstätten ohne rechtliche oder technische Einschränkungen Zugang zu den Informationen, Werkzeugen und Teilen haben, die für die Reparatur und Wartung von EV-Batterien erforderlich sind.
- EPR-System zur Finanzierung der ordnungsgemäßen Behandlung von Altfahrzeugen: Um eine angemessene Finanzierung für die vorgeschriebene Behandlung von Altfahrzeugen sicherzustellen und Recyclingunternehmen Anreize zur Qualitätsverbesserung zu bieten, wird ein EPR-System eingeführt, bei dem die Fahrzeughersteller gemäß der erweiterten Herstellerverantwortung (Extended Producer Responsibility, EPR) für die Finanzierung der Behandlung von Altfahrzeugen verantwortlich gemacht werden.
- Festlegung einer Recyclingquote für Stahl: Einführung eines Ziels für die Verwendung von recyceltem Stahl in der Fahrzeugproduktion. Eine Herausforderung dabei ist die Qualität des Stahlschrotts aus Fahrzeugverschrottungsanlagen. Verunreinigungen wie Kupfer mindern die Qualität von Recyclingstahl und verhindern derzeit eine höhere Recyclingquote bei der Herstellung hochwertiger Flachstahlprodukte. Eine gesetzliche Mindestquote für den

Recyclingstahlanteil in Fahrzeugen würde den Markt für Recyclingstahl in Richtung höherer Qualität verschieben. Berechnungen zufolge wäre ein Recyclinganteil von 25 % bis 2030 und 30 % bis 2035 mit einem geschlossenen Recyclingkreislauf erreichbar.

- Anforderungen an Schredder- und Nachschredderanlagen: Insbesondere Kupfer ist ein Verunreinigungsstoff im Stahlrecycling, der die Qualität von recyceltem Stahl mindert. Um eine hohe Qualität des zurückgewonnenen Stahls zu gewährleisten, wird für Fahrzeugschredderanlagen ein Höchstwert von 0,1 % Kupfer in der Stahlfraktion festgelegt. Das Hauptziel besteht dabei darin, Kupferpartikel abzutrennen, die während des Schredderprozesses in die Stahlfraktion gelangen. Das in der Stahllegierung enthaltene intrinsische Kupfer kann jedoch nicht zu wirtschaftlich vertretbaren Kosten abgetrennt werden.
- Festlegung von Recyclingzielen für Glas und Kunststoffe: Autos enthalten viele verschiedene Materialien, die jedoch am Ende ihrer Lebensdauer unterschiedlich behandelt werden. Stahl, Aluminium und Kupfer werden weitgehend zurückgewonnen, andere Materialien hingegen nicht. Da bestimmte Materialien wie Kunststoffe und Glas nur einen geringen Anteil am Fahrzeuggewicht ausmachen, werden sie oft entsorgt und erst nach der Zerkleinerung zurückgewonnen, was zu einer Verringerung der Qualität des zurückgewonnenen Materials führt. Mit dieser Maßnahme werden Recyclingziele für Glas und Kunststoffe festgelegt.

Roadmap für die Kreislaufwirtschaft im Fahrzeugbereich

Im letzten Kapitel wird eine strategische Roadmap für die Kreislaufwirtschaft im Fahrzeugbereich als Teil der Verkehrs- und Energiewende im Verkehrssektor entwickelt. Diese Roadmap soll aufzeigen, welche Maßnahmen und Instrumente einen wesentlichen Beitrag zur Reduzierung der Treibhausgasemissionen und des Ressourcenverbrauchs leisten können und in welchem Zeithorizont und durch welche Akteure diese erreicht werden können. Die folgende Tabelle zeigt diese priorisierten Maßnahmen und Instrumente.

Roadmap für die Kreislaufwirtschaft für Fahrzeuge

Option	Ebene	Zeitrahmen	Adressat	Wirksamkeit	Umsetzbarkeit
Bonus-Malus-System basierend auf der Fahrzeuggröße	Deutschland	kurzfristig (bis 5 Jahre)	Fahrzeugkäufer	mittel	hoch
Besteuerung von Firmenwagen	Deutschland	kurzfristig (bis 5 Jahre)	Fahrzeugkäufer	mittel	hoch
Umweltbonus in der Kfz-Versicherung	Deutschland	kurzfristig (bis 5 Jahre)	Versicherungs-unternehmen	mittel	hoch
Förderung nachhaltiger Fahrzeuge in Richtlinien für die öffentliche Beschaffung	Deutschland	kurzfristig (bis 5 Jahre)	Öffentliche Beschaffung	niedrig	hoch
Mindestlebensdauergarantie für Fahrzeuge	Europäische Union	mittelfristig (5 bis 10 Jahre)	Fahrzeughersteller	hoch	niedrig

Option	Ebene	Zeitrahmen	Adressat	Wirksamkeit	Umsetzbarkeit
Mindestwerte für die Energiedichte von Batterien	Europäische Union	mittelfristig (5 bis 10 Jahre)	Batterie- und Fahrzeughersteller	hoch	niedrig
Mindestlebensdauergarantie für Batterien	Europäische Union	mittelfristig (5 bis 10 Jahre)	Batterie- und Fahrzeughersteller	hoch	niedrig
Austausch und Entfernung von Bauteilen und Komponenten	Europäische Union	mittelfristig (5 bis 10 Jahre)	Fahrzeughersteller	hoch	niedrig
Mindestlebensdauergarantie für Ersatzteile	Europäische Union	mittelfristig (5 bis 10 Jahre)	Werkstätten, Wiederaufbereiter	mittel	hoch
Garantie für Software-Updates	Europäische Union	mittelfristig (5 bis 10 Jahre)	Fahrzeughersteller	mittel	hoch
Zugang zu Informationen über die Reparatur und Wartung von EV-Batterien	Europäische Union	mittelfristig (5 bis 10 Jahre)	Fahrzeughersteller	mittel	hoch
EPR-System zur Finanzierung der ordnungsgemäßen Behandlung von Altfahrzeugen	Europäische Union	mittelfristig (5 bis 10 Jahre)	Fahrzeughersteller	hoch	hoch
Festlegung eines Ziels für den Rezyklatanteil von Stahl	Europäische Union	mittelfristig (5 bis 10 Jahre)	Fahrzeughersteller	mittel	mittel
Anforderungen an Schredder- und Post-Schredderanlagen	Europäische Union	mittelfristig (5 bis 10 Jahre)	ATFs; Betreiber von Schredder- und Post-Schredder-Anlagen	hoch	hoch
Festlegung von Recyclingzielen für Glas und Kunststoffe	Europäische Union	mittelfristig (5 bis 10 Jahre)	ATFs; Betreiber von Schredder- und Post-Schredder-Anlagen, Recycler	mittel	hoch

1 Background

Triggered by the Paris Agreement the Federal Climate Protection Act (in the following abbreviated by KSG) set high CO_2 reduction requirements in the transport sector besides others. The RESCUE study has shown what resource-conserving and greenhouse gas-neutral transport should look like by 2050 (Purr et al. 2019). For the two basic strategies, namely substitution of technologies or products and avoidance, the study recommends the following measures in the transport sector, which are primarily characterized by efficiency, sufficiency, and consistency:

- Substitution
  - Phasing out pure combustion engines (cars & trucks)
  - Introducing battery-electric drives for cars & trucks
  - Establishing an infrastructure for overhead line trucks (not pursued further in Germany for cost reasons)
  - Market launch of post-lithium-ion batteries
- Avoidance
  - Shifting freight transport to rail and inland waterways thus avoiding road freight transport
  - Phasing out domestic air traffic
  - Strengthening electric vehicles and creating structures for short distances
  - Increasing energy efficiency
  - Increasing material efficiency and recycling
  - Implementation of an efficient sector coupling
  - Expansion of research & development
  - Global partnerships for a technology and knowledge-based economy

With the increasing market penetration of electric drive concepts in the transport sector, the demand for critical raw materials is increasing significantly (Dehoust et al. 2020; European Commission 2020; Grohol, Veeh 2023). In the foreseeable future, this can only be met to a limited extent through recycling from closed-loop recycling.

The primary extraction of many of these critical raw materials is associated with significant environmental and social impacts (e.g. cobalt, nickel, lithium, and rare earths). Moreover, the production of various components out of these materials often requires a high energy input (e.g. the production of batteries). At the same time, the environmental impact of the use phase will decrease in medium and long term due to the increasing electrification of transportation and the rising share of renewable energies in electricity generation. While the use phase currently has a much higher environmental impact than the vehicle production, this ratio will shift more and more towards the production side. However, other metals that are used in large quantities in vehicles, such as copper, aluminium, and steel, also have a relevant environmental impact in their primary production (in mining, ore processing, smelting, and refining).

Project objective

Against this background, the AutoRess project analysed technical and non-technical options across all vehicle life cycle phases (resource extraction, vehicle design, vehicle production, use and vehicle disposal at end-of-life) to reduce the impact of the transport sector on climate change and resource consumption. In addition, suitable instruments and measures were developed and evaluated afterwards together with experts and stakeholders.

The findings were used to implement a roadmap for an optimized circular economy for vehicles as part of the transport and energy transition.

The overarching approach is intended to identify mutual interactions, reduce conflicting objectives, and develop an optimal set of measures and instruments. A high market dynamic as well as the pressure to innovate and the uncertainties regarding technical development are to be taken into account.

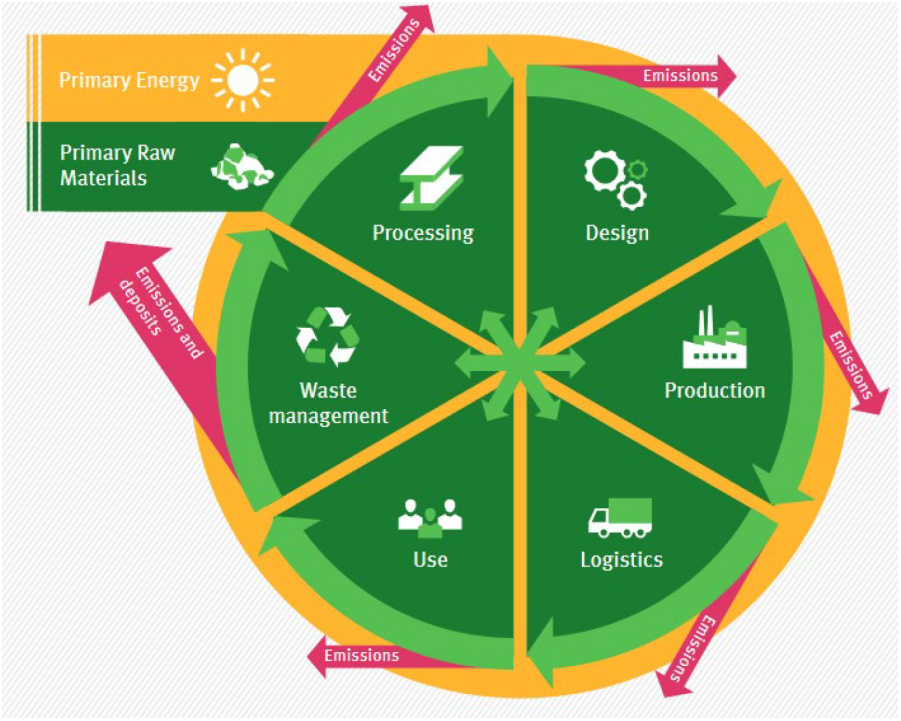
2 Systemic analysis: Core assumptions and their contribution to reduction of greenhouse gas emissions and resource consumption

In AutoRess, at first (key) measures for reducing GHG emissions and limiting the use of raw materials along the life cycle phases of motor vehicles were identified. This was the basis for the selection of technical and social options to be further developed in the course of the project. A general overview of the raw material consumption and GHG emissions of motor vehicles, in particular passenger cars, is given in chapter 2.1. This is followed by an examination of the factors directly affecting the transport sector (chapter 2.2) with regard to greenhouse gas emissions in all life-cycle stages and material requirements in vehicle production. For this purpose, current scenarios and their assumptions of future developments are analysed and compared. Indirect influencing factors (chapter 2.3) primarily affect vehicle production (including preliminary products and material supply), maintenance and disposal. They are also analysed with regard to the potential savings in raw material consumption and greenhouse gas emissions.

The project will take a life cycle perspective for the entire vehicle (including the vehicle body and drive-specific components such as the engine, transmission and battery), taking into account aspects of the circular economy. A distinction is made between the following stages or phases (see Figure 1):

- Extracting, processing and production of raw materials
- Design of vehicles including drive types, substitution, lightweighting, choice of materials, dismantlability, etc.
- Production (vehicle parts, preliminary products, final assembly of passenger cars)
- Logistics, including procurement of raw materials and preliminary products
- Use phase of vehicles including effects of different transport demand and modal splits, including repairs, etc.
- Disposal, including remanufacturing and recycling

Figure 1: Life cycle phases of product- and technology-centered closed-loop management



Source: (UBA 2020)

2.1 Overview of raw material consumption and greenhouse gas emissions from today's motorised transport

2.1.1 Raw material consumption

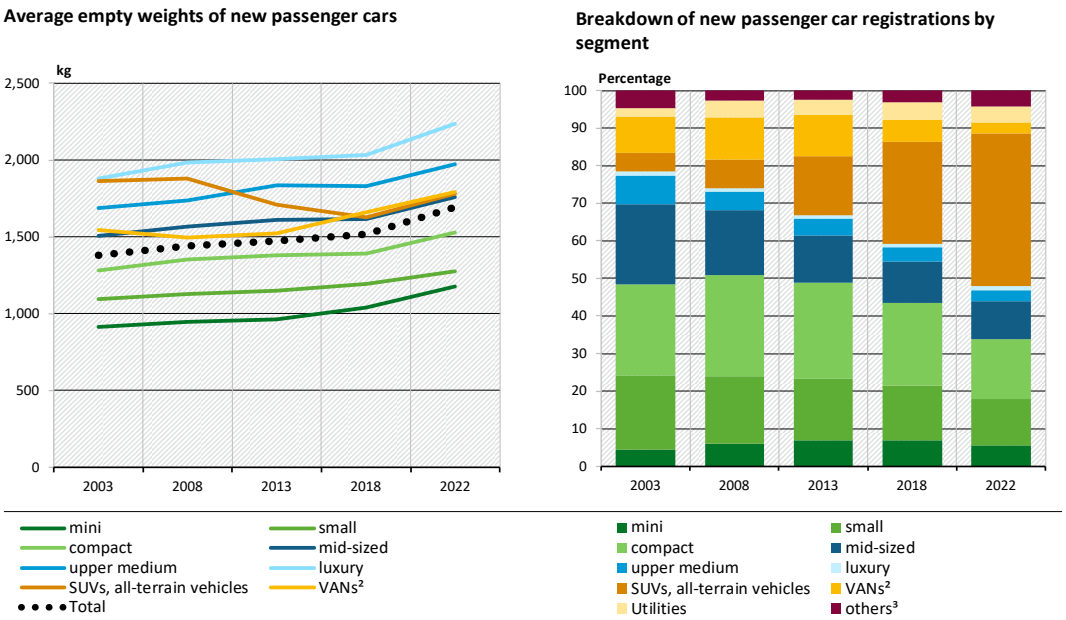
2.1.1.1 Development of vehicle weights and material composition for passenger cars

Development of vehicle sizes of new car registrations in the past

In the past, there has been a continuous increase in the weight of new passenger cars and a shift between vehicle segments (KBA 2024). Since 2019, the impact of rising new registrations of BEVs has also become apparent, as they add additional weight due to their batteries. These developments can be observed not only in Germany, but also in other countries. A study by the Global Fuel Economy Initiative (GFEI) also shows similar trends (GFEI 2023) for other car markets worldwide. Interestingly, the trend towards “SUVcation” does not necessarily lead to larger cars in terms of car footprint, but primarily to an increase in vehicle weight, as many models are growing in height.

The average empty weight of new cars in Germany has increased by around 23% since 2003, from 1,381 to 1,696 kg (KBA 2024). Main reasons for this are increasing empty weights within all segments - from small cars to the luxury class (Figure 2, left) as well as a shift in the number of new registrations from smaller vehicle classes (small cars, compact cars) to larger segments (SUVs, all-terrain vehicles) (Figure 2, right). The contribution of increasing shares of new SUV registrations to the increasing vehicle weights cannot be assessed with certainty, as the SUV vehicle segment at the KBA comprises a wide range of models from mini SUVs to large models comparable to the upper mid-size class.

Figure 2: Development of the average empty weights of new passenger cars and the percentage breakdown of new registrations by segment in Germany since 2003



Source: own illustration Oeko-Institut / ifeu, based on (KBA 2024)

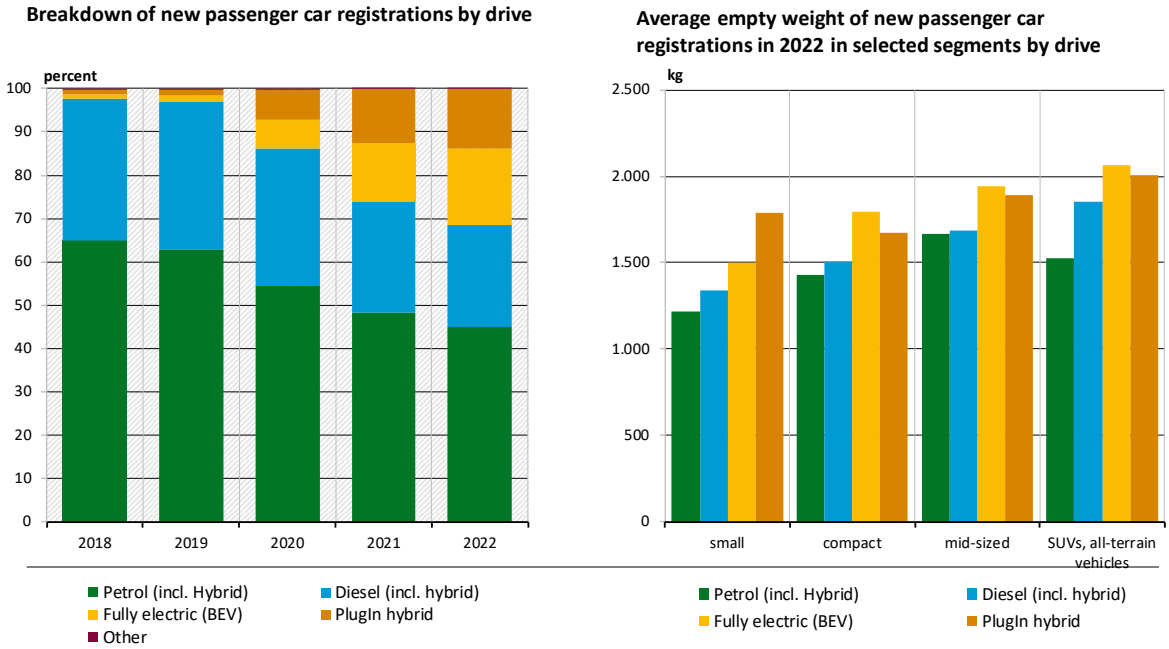
Notes: [1]The classification of passenger car models by segment is carried out by the Kraftfahrt-Bundesamt on the basis of visual, technical and market-oriented characteristics for vehicles registered from 1990 onwards. M1 vehicles including special purpose vehicles (e.g. motorhomes and ambulances).

[2] small and large vans

[3] including sports cars and motorhomes

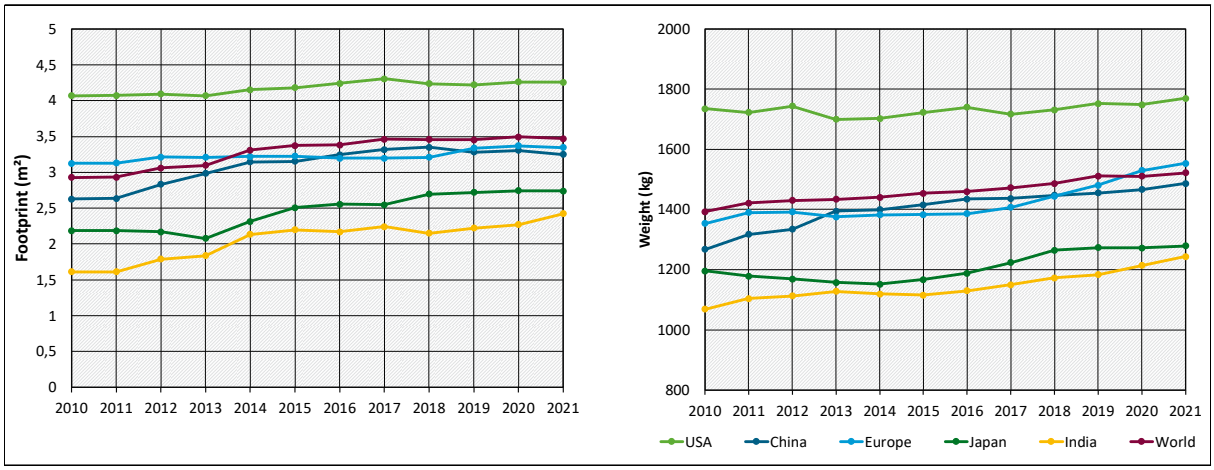
After 2018, the statistics also reflect the increasing proportion of new registrations of electric cars. The weight of the combustion engine powertrain (engine, transmission, exhaust gas aftertreatment) is eliminated in these vehicles. Nevertheless, they are significantly heavier than cars with a combustion engine, mainly due to the battery. According to analyses in (Biemann et al. 2024), a typical electric car has an average usable battery capacity of 55 kWh (or a gross capacity of 60.5 kWh), which corresponds to a weight of 400 kg at a standard market energy density of 150 Wh/kg. Figure 3 shows the average empty weights of new passenger car registrations in 2022 for selected segments, broken down by drive type. Diesel cars are heavier than petrol cars in the same segment. Above all, however, electric cars in all segments are on average several 100 kg heavier than comparable petrol or diesel cars.

Figure 3: New registration shares of different powertrain concepts 2018-2022 (left); average empty weights of new car registrations in 2022 for selected segments (right)



Source: own illustration Oeko-Institut / ifeu, based on (KBA 2024)

Figure 4: Development of vehicle footprints and empty weights of new vehicles in various global vehicle markets



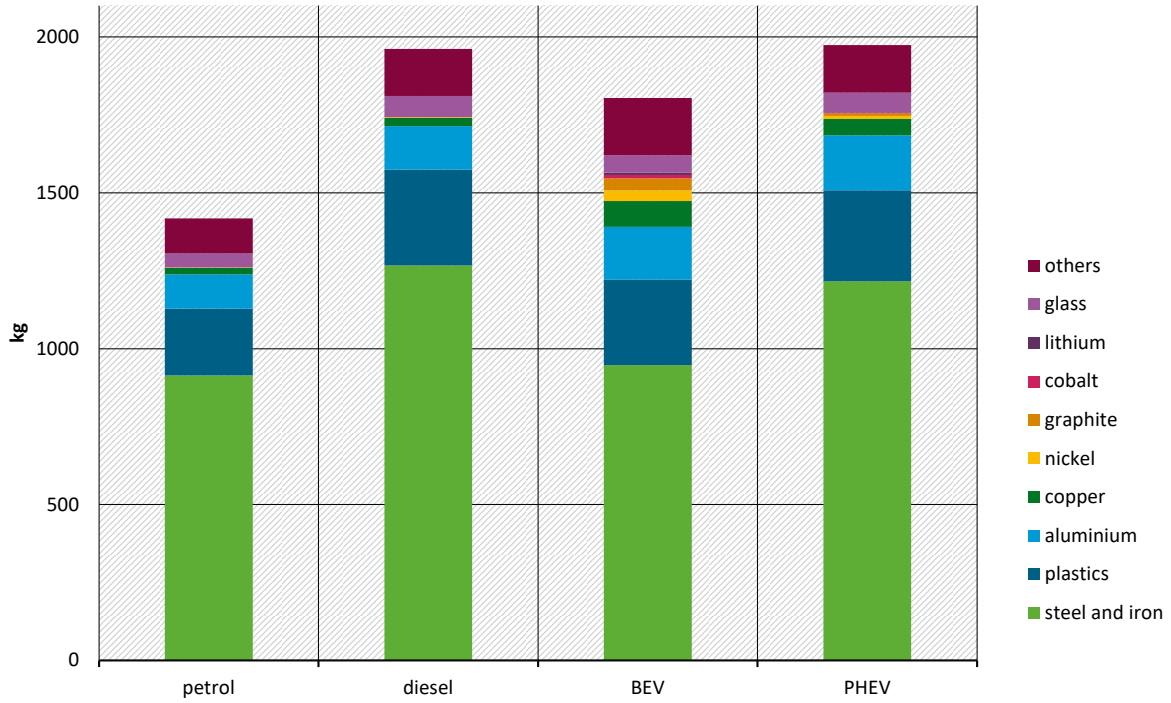
Source: own illustration Oeko-Institut / ifeu, based on (GFEI 2023)

Similar developments as in Germany can be seen in the vehicle markets in Europe and worldwide (GFEI 2023). While vehicle weights and footprints have risen equally in the past, footprints have tended to stagnate in recent years as weight has continued to increase, see Figure 4. This could be explained by the trend towards SUVs: Here, the spectrum ranges from small SUVs, some of which use the same platform as the manufacturer's small car models, to very large all-terrain vehicles. The share of new SUV registrations is rising continuously worldwide. At the same time, there are clear differences between the vehicle markets. In North America, SUVs currently account for over 75% of new registrations, a significant proportion of which are large SUVs. In Japan and India, on the other hand, the vehicle market is still very much dominated by small cars (GFEI 2023).

Material composition of new passenger cars

Across all drive systems and size classes, a car is primarily made of steel and cast iron, followed by plastics and rubber, various other metals such as aluminium and copper, glass and textiles (Figure 5). Critical raw materials such as platinum or cobalt are used in smaller quantities. Even if the composition of individual cars differs, it is clear that the proportion of steel has fallen across all vehicles in recent years and the proportion of other metals and plastics has increased (Zimmermann et al. 2022). Particularly relevant here are raw materials that are required in batteries and are considered critical. According to the EU definition, critical raw materials are those that are processed in economically relevant sectors on the one hand and whose supply is subject to risks on the other. The EU maintains a list of critical raw materials, which is updated every three years. Examples of critical raw materials that are used in conventional or electric cars include cobalt, lithium and platinum (Grohol, Veeh 2023).

Figure 5: Material composition of medium-sized new passenger cars in Germany in 2022



Source: own figure Oeko Institut/ ifeu

Note: Across all new registrations, the average new diesel car in 2022 had a higher unladen weight than a new BEV car. BEVs are heavier than diesel cars within the individual segments (see Figure 3). However, new diesel passenger cars are disproportionately sold in heavier segments compared to battery electric passenger cars.

2.1.1.2 Raw material consumption: Cumulative raw material expenses (KRA) and raw material consumption (RMC)

The vehicle weight or material composition is not identical to the raw material expenditure required for the production of a car, as the pure vehicle weight does not include the raw material expenditure for the preliminary products (production waste, offcuts, mine tailings, etc.). Two raw material indicators that address this shortcoming include cumulative raw material consumption (KRA) and raw material consumption (RMC). The indicators have different areas of application and also differ slightly in their calculation.

The **cumulative raw material expense (KRA)** accounts for all raw material quantities used for the provision (including production and transportation) of a product along the value chain,

including energy raw materials. However, materials and mixtures of materials that are not used economically (such as unused extraction) are not taken into account. The KRA is largely used in the context of life cycle assessments and refers to a specific functional unit, for example to show the raw material expenditure of various alternative products (e.g. means of transport). The quantity of the KRA per se does not contain any information on the assessment of raw material use (e.g. critical or not, ecological consequences of raw material extraction).

Raw material consumption (RMC) is a material flow indicator that estimates the mass of raw materials used along the value chain of all goods and services that flow into final consumption in a country. The RMC is also referred to as the "material footprint". It is calculated from the total quantity of primary raw materials extracted domestically (domestic extraction) plus the cumulative raw material content of imports in raw material equivalents (RME) minus the raw material content of exports in RME. If only domestic extraction and imports in RME are considered, this is referred to as raw material input (RMI).

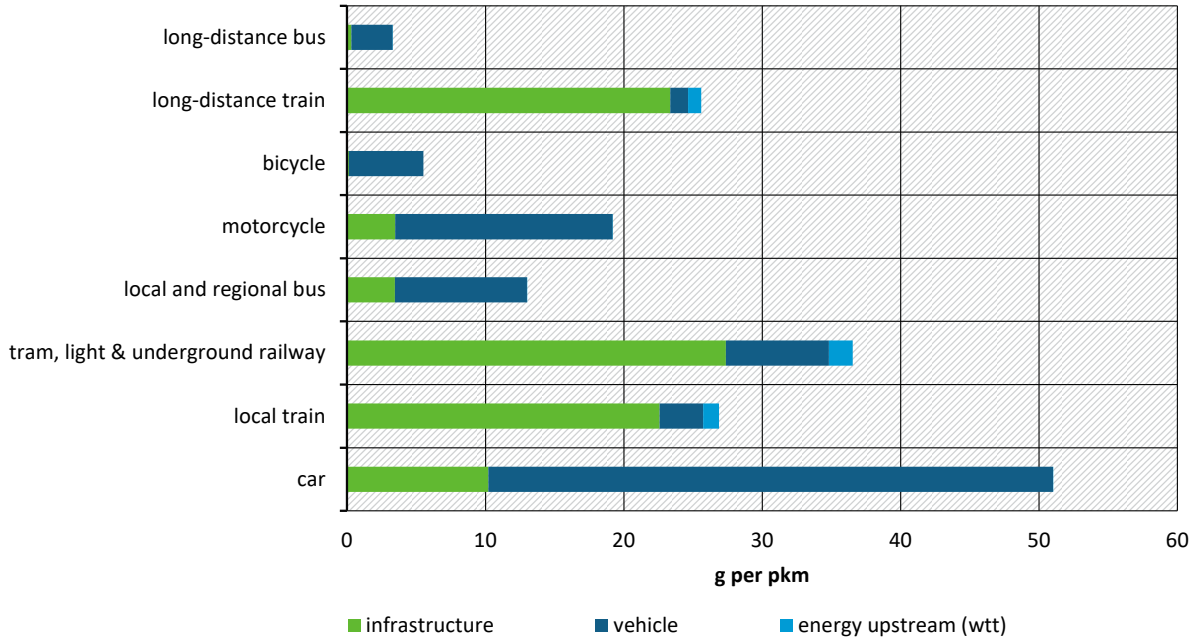
The RMC is published by Destatis from the perspective of last domestic use by commodity group (Destatis 2021a). The last domestic use includes all commodities required for domestic consumption (by households, non-governmental organizations and the state) and domestic investment (equipment and other facilities, buildings, changes in inventories and net acquisition of valuables). The RMC thus describes a utilization variable (not a consumption variable). In contrast to the KRA, it is calculated top-down in life cycle assessments using environmental economic accounting methods and is therefore not product or service-specific.

KRA and RMC of vehicle production

The KRA results of a life cycle assessment comparison of different means of transport are shown in Figure 6 for metals and Figure 7 for non-metallic minerals. The calculations are based on a large number of assumptions and allocations, which are described in detail in (Allekotte et al. 2020).

- In 2017, around 41 g of metals were used per passenger kilometer (pkm) by car in vehicles and around 11 g in infrastructure. Compared to passenger cars, for example, less metal is used per passenger kilometer in rail transport in vehicles, but more in infrastructure.
- Non-metallic minerals are mainly used for the infrastructure. Figure 7 shows that around 47 g of non-metallic minerals were required for the infrastructure and only around 5 g for the vehicle itself per pkm in a passenger car in 2017.

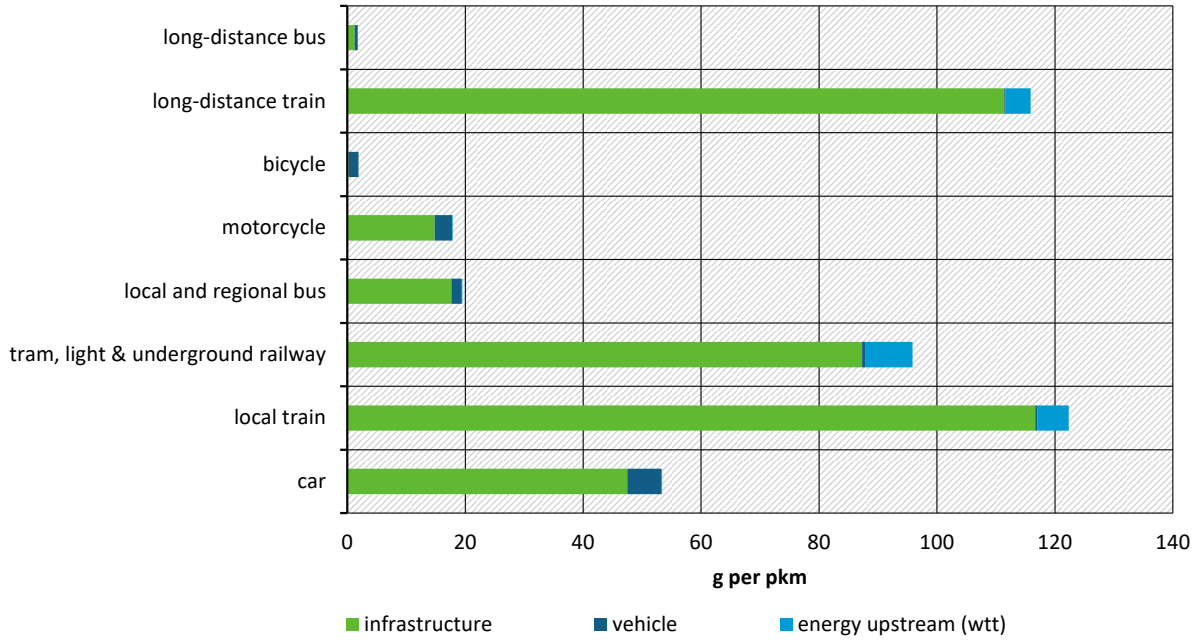
Figure 6: Cumulative raw material expenditure of metals in passenger transport 2017



Source: (Allekotte et al. 2020)

Note: The quantity of the KRA accounts for all raw material quantities used for the provision of a product along the value chain. However, it does not contain any information on the assessment of raw material use that can vary greatly for different raw materials (e.g. critical or not, ecological consequences of raw material extraction). Accordingly, a higher KRA is not synonymous with higher environmental impacts.

Figure 7: Cumulative raw material expenditure for non-metallic minerals in passenger transport 2017



Source: (Allekotte et al. 2020)

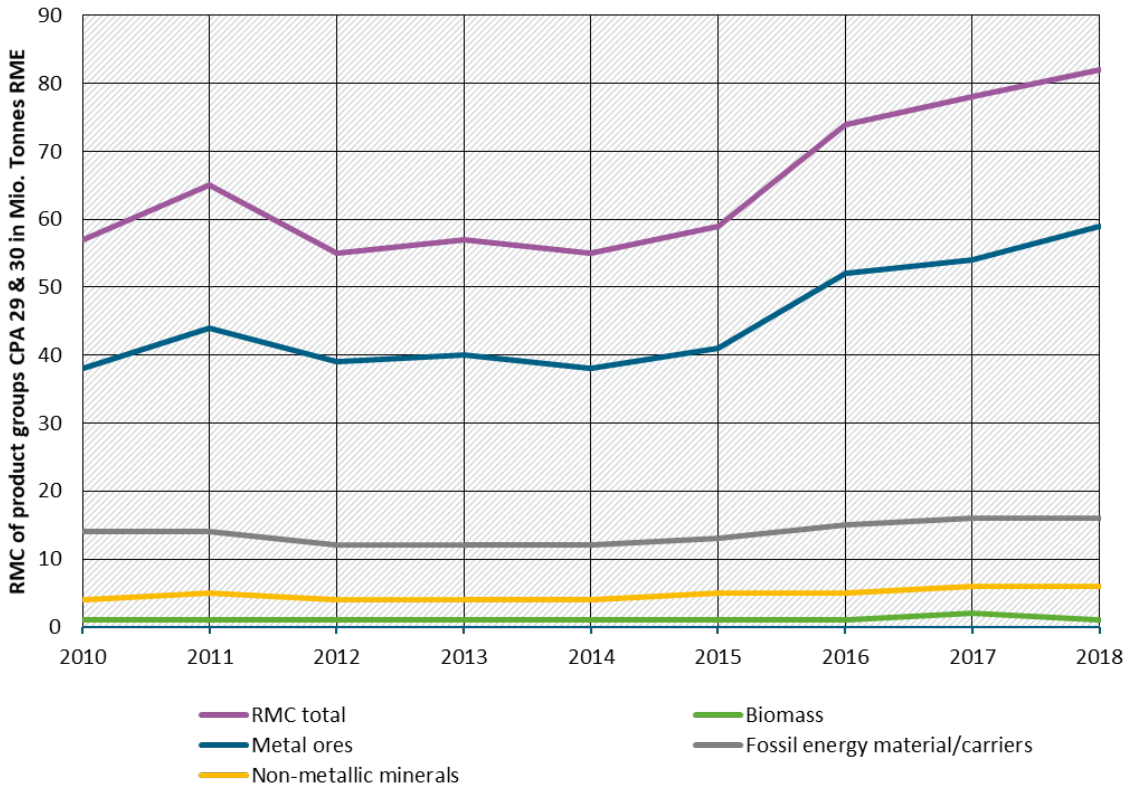
Note: The quantity of the KRA accounts for all raw material quantities used for the provision of a product along the value chain. However, it does not contain any information on the assessment of raw material use that can vary greatly for different raw materials (e.g. critical or not, ecological consequences of raw material extraction). Accordingly, a higher KRA is not synonymous with higher environmental impacts.

Figure 8 shows the RMC from the perspective of the last domestic use of the economic sectors "Manufacture of motor vehicles and parts" (statistical classification of products by activity (CPA)[1] 29: includes passenger cars, trucks and other commercial vehicles) and "Other transport equipment" (CPA30: includes ships, rail vehicles, aircraft and other vehicles). Both groups of goods describe the entire "construction of vehicles" for subsequent vehicle use in Germany, including imported vehicles. A separate presentation of the individual goods groups or more detailed presentations within the goods groups are not available. In terms of volume, passenger cars dominate vehicle construction, so it can be assumed that the relative developments shown are essentially due to the development of passenger car production.

In 2010, a total of 57 million tons of raw material equivalents (RME) were demanded domestically from the "vehicle construction" goods group. After a period of stagnation, demand has increased since 2015. In 2018 (the most recent year available), a total of 82 million tons of RME were in demand domestically. The "vehicle construction" goods group accounted for 6.2% of total German raw material consumption (RMC) in 2018.

Vehicles are mainly made of metals, which is why metal ores dominate the RMC "Vehicle construction" with 72% in 2018. This is followed by fossil energy materials with approx. 20% (2018), which are used in vehicle production in the form of plastics or for intermediate inputs. Other mineral raw materials, e.g. glass, have a share of around 7% (2018). The proportion of biotic raw materials, e.g. for textiles in vehicle construction (belts, seat covers), is around 1%.

Figure 8: RMC from the perspective of the last domestic use of the goods group "vehicle construction" in Germany



Source: own figure Oeko-Institut / ifeu, based on(Destatis 2021a)

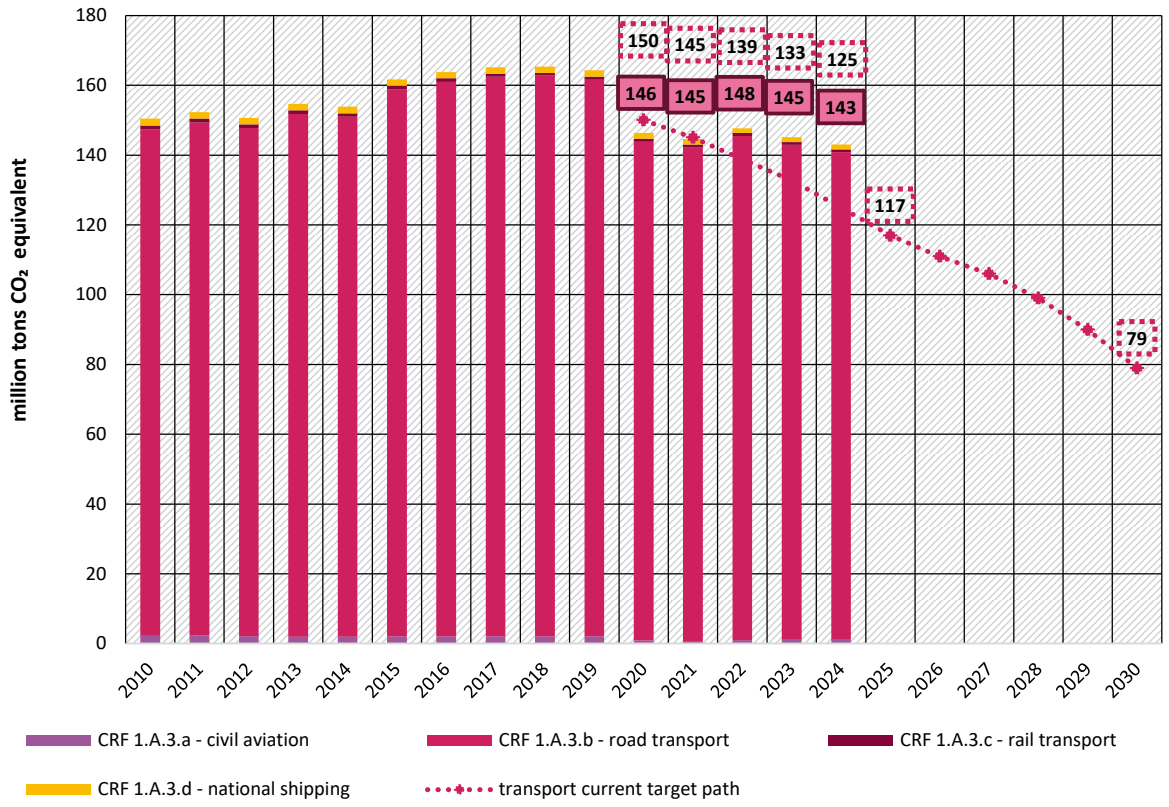
[1] The statistical classification of products by activity (CPA) is the European classification of products, goods and services and its product categories are related to the economic activities of the statistical classification of economic activities (NACE) (Eurostat 2025).

2.1.2 Greenhouse gas emissions

2.1.2.1 Direct greenhouse gas emissions in national transport

Greenhouse gas emissions from the transport sector in the National Greenhouse Gas Inventory were 148 million tons of CO_2e in 2021 (Figure 9) (UBA 2025). Between 2010 and 2019, greenhouse gas emissions rose from 153 to 164 million tons of CO_2e, while in 2020 and 2021 they fell as a result of the lockdowns due to the coronavirus pandemic and have not returned to the old level in the following years. The majority of greenhouse gas emissions (between 96% and 98%) come from road traffic. The data presented here includes direct greenhouse gas emissions from the use of means of transport in Germany (national transport). This definition does not include international traffic or all greenhouse gas emissions generated during the provision of fuel ("well-to-tank" emissions) or during the production, repair and disposal of vehicles and vehicle parts. Insofar as such emissions occur in Germany, they are also included in the National Inventory, but they are not attributed to transport but to other sectors (e.g. in the transformation sector, in industry).

Figure 9: Development of greenhouse gas emissions in Germany in the transport sector and target achievement according to Climate Protection Act



Source: (UBA 2025)

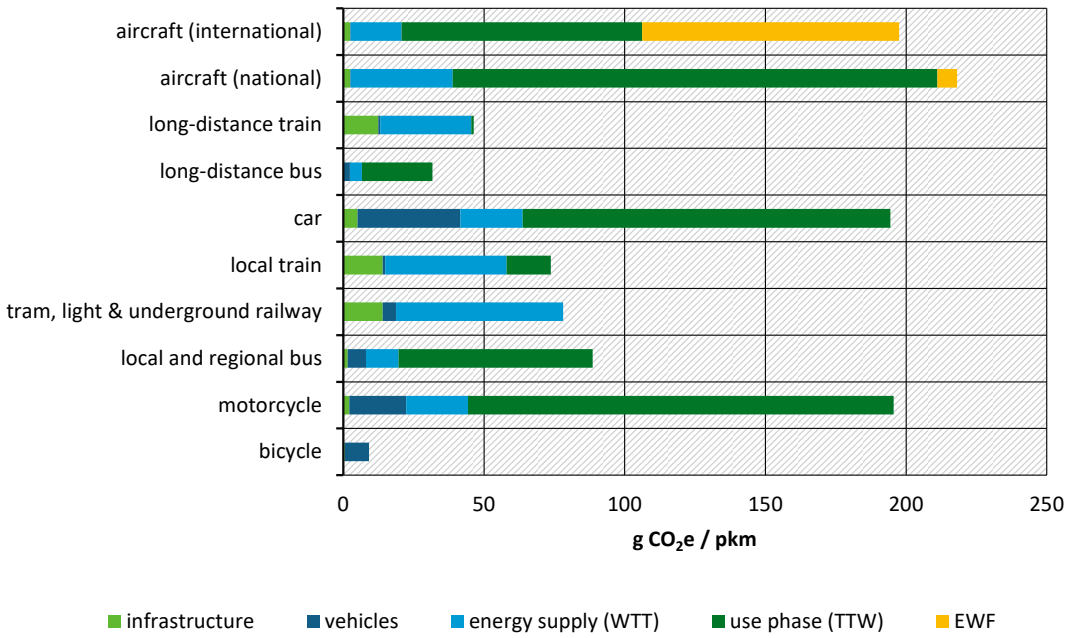
2.1.2.2 Specific greenhouse gas emissions including all life cycle phases

Specific greenhouse gas emissions of different means of passenger transport

The average specific greenhouse gas emissions per pkm for passenger cars in 2021 amounted to 162 g CO_2e, including direct tailpipe emissions as well as emissions from the provision and conversion of energy sources(UBA 2023a) with an average occupancy rate of 1.4 persons. If vehicle production and infrastructure are also taken into account, the specific greenhouse gas emissions per pkm in passenger cars rise to almost 200 g CO_2e, here: Data for 2017 based on a life cycle assessment comparison of different types of transport (Figure 10) (Allekotte et al. 2020). Car production has the second largest share after direct emissions (tank to wheel, TTW), ahead of energy provision (wheel to tank, WTT). The share of greenhouse gas emissions from infrastructure is comparatively low for passenger cars.

Compared to other modes of transport, the specific climate impact per pkm of passenger cars is therefore more than twice as high as for other modes of passenger transport (with the exception of air travel). In freight transport, too, the specific climate impact per tonne-km for HGVs is several times higher than for the alternatives rail and inland waterway (Allekotte et al. 2020).

Figure 10: Specific climate impact of passenger transport modes in Germany in 2017



Source: (Allekotte et al. 2020)

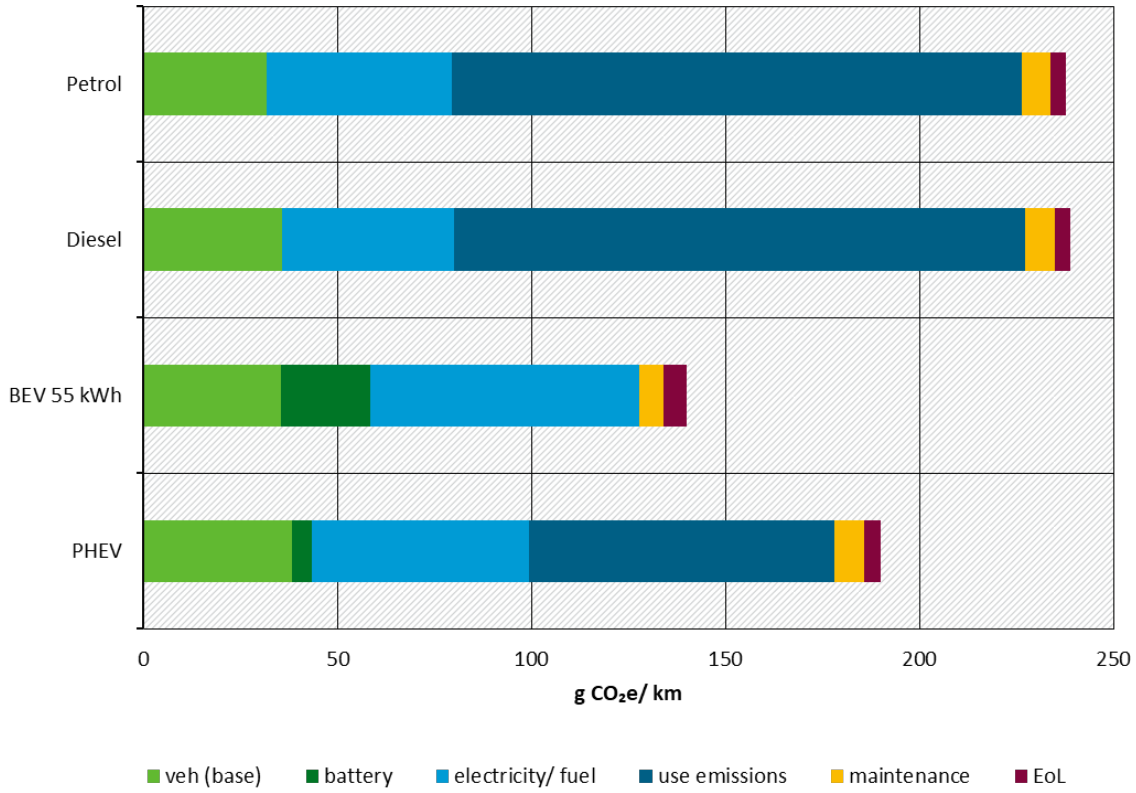
Specific greenhouse gas emissions from passenger cars with different powertrains

With increasing shares of electric cars in the German fleet, the GHG emissions will change significantly in the future. Direct emissions from operation (TTW) will fall as the proportion of combustion engine cars decreases. At the same time, emissions from energy provision will change due to the changes to the electricity mix in Germany. The vehicle production emissions, which are significantly higher for electric cars than for combustion engine cars, also influence the development of average specific GHG emissions in the passenger car fleet.

A current analysis from (Biemann et al. 2024) for the global warming potential per vehicle kilometer for passenger cars with different powertrains in Germany is shown in Figure 11. According to this, newly registered compact class petrol and diesel cars are roughly on a par, with electric cars performing significantly better, as the higher emissions from vehicle

production are more than compensated for by lower emissions in the use phase. For all powertrain variants, it can be assumed that the absolute global warming potential will fall in the later years of construction compared to today. However, these reductions are likely to be significantly higher for electric cars than for combustion engine cars, as the share of renewable electricity steadily increases, while combustion engines continue to rely heavily on fossil fuels.

Figure 11: Climate impact of compact class cars built in 2021 using an average electricity mix over the vehicle's lifetime



Source: (Biemann et al. 2024)

Note: The climate benefit of future BEVs will be even higher than todays, as the impact of increased battery sizes and improved battery manufacturing cancel each other out, while the electricity mix improves further over time (see also (Biemann et al. 2024)).

2.2 Direct influencing factors in the transport sector

2.2.1 Direct levers in transport and their impact on vehicle use and vehicle production

Measures in transportation can have a direct impact on the transportation system as well as on upstream processes such as the production of vehicles and infrastructure. The decisive influencing factors for the development of emissions and raw material consumption during the vehicle use phase are basically

- the transport demand, i.e. the mileage and transport performance of the respective means of transport,
- the vehicle fleet developments (number, size and drive systems of the vehicles)
- and the energy sources used (fossil, renewable).

In addition to these effects in the use phase, there are also other indirect effects, particularly on upstream vehicle production.

Depending on the issue (e.g. effects of political measures, technical potential), different future developments of the various influencing factors are depicted in scenario studies. This leads to different scenario-specific overall developments in GHG emissions as well as proportional contributions of the respective influencing factors to these developments.

Transport demand

Assumptions on transport demand relate to (1) the level of transport services (passenger and ton-km), (2) the shares of different modes of transport (modal split) and (3) the utilization of vehicle capacities and thus the resulting vehicle mileage (vehicle-km) to provide the transport service. Relevant GHG and raw material aspects are:

- **Level of transportation services**: A reduction in overall transport performance directly reduces the energy consumption in the use phase and thus the direct GHG emissions in vehicle operation as well as upstream GHG emissions from energy provision.
- A modal shift to means of transport with lower specific GHG emissions per transportation performance also reduces energy demand and GHG emissions in the use phase. When switching from fuel-powered motor vehicle transport to electric rail transport, the direct reduction in emissions in transport is partly offset by an increase in emissions from the provision of electricity in the conversion sector.
- Increased **vehicle utilization** also leads to reduced mileage and thus lower GHG emissions in the use phase for the same transport performance.
- In the case of longer-term development trends towards decreasing (vehicle) mileage, in addition to the direct effects in the use phase, indirect effects such as a change in demand for new vehicles (fewer cars and trucks, possibly more buses and rail vehicles) and the associated change in GHG emissions and raw material consumption in vehicle production must also be considered.

Alternative powertrains and energy efficiency of vehicles

In most scenarios, a central direct lever for GHG reduction in transportation is a switch to electric mobility for cars and trucks. In addition, further technical efficiency measures on the entire vehicle can reduce **energy consumption and GHG emissions in the use phase.**

- **Electromobility**: Switching to electric vehicles leads to a significant reduction in the mileage-specific final energy consumption due to the significantly higher efficiency of the electric powertrain compared to combustion engines. The overall GHG reduction achievable in the use phase depends on the energy source mix in the electricity supply. As electromobility increases, so do the requirements for the use of renewable energy sources in the conversion sector.
- **Efficiency improvements in the internal combustion engine powertrain**: Further efficiency improvements in the powertrain are also possible for vehicles with petrol and diesel engines, e.g. through increased hybridization. This reduces fuel consumption and the corresponding amount of GHG emissions.
- **Drive-independent efficiency improvements** can be achieved through a shift in new registrations towards smaller vehicle sizes (downsizing) as well as through a variety of technical measures (e.g. lightweighting, reduced air/rolling resistance, weight reduction through smaller batteries, lower equipment levels). They not only reduce the need for fossil fuels in vehicles with internal combustion engines and thus lower GHG emissions in transportation, but also the amount of renewable electricity required for electric vehicles.

Apart from their direct effects in the transport sector, drive changes and technical efficiency improvements also have relevant indirect **effects on GHG emissions and raw material consumption in vehicle production**. A shift towards smaller new vehicles leads to a reduction in GHG emissions and raw material consumption in vehicle production. In contrast, powertrain changes and hybridization lead to increased GHG emissions in vehicle production due to the significantly larger vehicle batteries (see chapter 2.1.2); at the same time, other (critical) raw materials are required in some cases. Depending on the alternative construction methods or materials used (e.g. aluminium), lightweighting also leads to a change in GHG emissions and a shift in raw material requirements in vehicle production. Accordingly, future technical developments in vehicle batteries and lightweighting are also relevant indirect levers for GHG developments and raw material consumption in the vehicle life cycle (see chapter 2.3).

Renewable fuels

A GHG reduction in the use phase is also achieved through renewable biofuels and electricity-based fuels. As with electromobility, direct emissions in the transport sector are eliminated, but this is partly offset by additional GHG emissions in other sectors (agriculture, conversion sector) in Germany and imports from other countries. The development of an infrastructure for electricity-based fuels (so-called e-fuels) also leads to significant additional raw material consumption, particularly for the required renewable electricity generation capacities.

In Europe, politicians and manufacturers have set the course for vehicles in the direction of electromobility, while synthetic fuels are to be used primarily in non-electrified inland waterway and air transport. Furthermore, no significant quantities of e-fuels are expected in the period up to 2035. Also due to the poor energy balance compared to battery electric vehicles (BEV), e-fuels for new vehicles, especially passenger cars, play no or almost no role in scientific scenarios. As the potential of sustainable biofuels is also very limited and biomass is primarily needed in other sectors, these renewable fuels will also only play a very small role in the further decarbonization of transport. For these reasons, renewable fuels are not considered in detail in the scenario analysis.

Interactions and proportional contributions of different measures to the overall GHG impact

The total GHG emission reduction achievable across all influencing variables is lower than the sum of the individual effects. The proportionate contributions of different measures to the total GHG savings can be defined and prioritized in different ways. This can be illustrated using an example.

- The modal shift reduces car mileage by a total of 10%. A subsequent change of drive therefore only affects 90% of the original car mileage and therefore also results in lower GHG savings compared to the initial situation with the same proportion of electric mileage.
- However, it is also possible to argue the other way round and prioritize the change of drive system first. In this case, the additional modal shift results in fewer GHG savings compared to the initial situation, as part of the modal shift in car mileage was already GHG-reduced due to electrification. At the same time, the additional shift has a dampening effect on the number of cars required and thus on the demand for raw materials.

Scenarios are usually designed systemically for the evaluation of mobility and drive-related measures. Many changes, including their interactions, are developed together, without prioritizing the measures among themselves. Accordingly, proportional contributions of individual levers to the combined overall potential should be broken down in proportion to the relationship between the individual single potentials.

2.2.2 Scenario analysis on the GHG savings potential of direct levers in transport

The influencing factors described in the previous chapter with direct impacts on the transport system and related GHG emissions have been examined in numerous scenarios in recent years. Depending on the issue, the scenarios have different focuses. In some scenarios, the emphasis is mainly on the turnaround in propulsion, while in other scenarios there is a stronger focus on the potential to avoid and shift transport. This means that GHG reduction potentials of individual levers are exploited to varying degrees depending on the scenario. With the comparative analysis of several scenarios with ambitious GHG reduction paths, bandwidths of GHG reduction potentials were estimated for the individual levers and these bandwidths in turn were classified between the levers with regard to their relevance for the combined overall potentials. In this way, important levers for reducing emissions were identified and prioritized. At the same time, the raw material consumption associated with the measures was evaluated.

- The **effects of existing political goals and measures** were analysed using the "with-measures scenario" MMS in the 2023 projection report (Harthan et al. 2023): The MMS maps the effects of the current politically adopted measures on various direct influencing variables in transport and the associated changes in GHG emissions.
- **Additional savings potentials** going beyond adopted measures wer analysed using the following scenarios:
  - In the "With further measures scenario" MWMS in the 2023 projection report, additional, already foreseeable measures were assessed. The additional GHG reductions are low.
  - The upper limits of additional potential for all direct levers in transport were derived from the GreenSupreme scenario (Germany - resource efficient and greenhouse gas neutral - Minimizing future GHG emissions and raw material consumption) of the RESCUE study(Dittrich et al. 2020a). Here, very high levels of ambition are assumed for all reduction paths in transport, including intensive behavioural changes in the population. GreenSupreme was developed in the 2018-2019 period using the scientific knowledge available at the time. Policy instruments to achieve these developments were not analysed in the RESCUE study. As part of the CARE project (UBA publication pending), GreenSupreme was adapted to real developments up to 2021 as well as current developments in general conditions throughout Germany (population, economic development) and backed up with selected policy instruments. GreenSupreme in the

RESCUE study assumes a sharp decline in private car ownership with increasing ride sharing. This is only replicated to a limited extent in CARE, as the policy instruments evaluated here only have a minor impact on car ownership. Therefore, in the scenario analysis, selected relative developments 2030-2045 from GreenSupreme in the RESCUE study were transferred to the results in CARE in a simplified form. In this way, a theoretical upper limit of this potential can be determined, even if the achievability through policy instruments has not yet been assessed.

- Various other scenarios were included in the analysis: The main RESCUE scenario GreenEe (Germany - resource efficient and greenhouse gas neutral - Energy efficiency) and the GreenLate scenario (Germany - resource efficient and greenhouse gas neutral - Late transition) with a delayed increase in the level of ambition for climate protection measures (Purr et al. 2019); "Climate Pathways 2.0" scenario studies (BDI/BCG 2021), Climate Neutral Germany 2045 (KND45; (Prognos AG et al. 2021)) and Climate Protection Instruments Scenario 2030 (KIS-2030; (Repenning et al. 2023)). The potential identified in all levers is largely within the range of MWMS and GreenSupreme. Only in the case of electric mobility for passenger cars does one study identify significantly higher potential than GreenSupreme; this was mapped in a supplementary sensitivity analysis.

2.2.2.1 Methodical approach

Definition of standardized framework data across scenarios

The future changes in influencing factors directly affecting traffic are derived in the scenarios as developments compared to a current baseline year or as changes in the target year compared to a trend development without additional measures. In particular, future traffic developments are strongly influenced by the scenario-specific assumptions on the development of the general framework conditions. The update of the GreenSupreme scenario in the CARE project and the scenarios in the 2023 projection report are based on the same population trends and comparable economic development up to 2035. Only after 2035 do the economic developments diverge, which, in addition to the additional effects of the measures, has a particular influence on the freight transport demand modelled in the scenarios.

Other emission-relevant developments outside of the direct levers in transport also had to be largely harmonized between the scenarios in order to differentiate the associated GHG impacts from the effects of the measures under consideration. In particular, a uniform national electricity mix (and thus a specific GHG factor for electromobility) and uniform assumptions on the percentage shares of renewable fuels were used to ensure comparability of the GHG impacts between the scenarios. In the scenario analysis, the electricity mix and renewable fuel shares from the MMS of the 2023 projection report are therefore used for all levers examined to calculate the GHG emissions of the use phase (well-to-wheel).[2]

Evaluation of GHG impacts in the use phase and in vehicle manufacturing

The core of the scenario analysis was the evaluation of the contributions of individual direct reduction paths to the GHG savings in the scenarios and the assessment of the associated material consumption. Table 1 shows the direct levers in transport that were examined.

[2] The effects of a transformation of energy systems at different speeds, and thus in particular the specific GHG emissions of electricity consumption, are addressed as indirect influencing factors (chapter 2.3.3).

Table 1: Direct influencing factors in transport

	Passenger traffic	Freight traffic
Transport demand	Mobility behaviour (number and length of trips per person)	Freight transport demand due to economic development
Shift to other means of transport	Shift to conventional ecomobility (cycling/walking & public transport), multimodality & car/ride sharing	Shifting truck transport services to rail, inland waterway, combined transport
Drive change	Electromobility	Electromobility, fuel cell
Increased efficiency	Drive-specific efficiency increases, across all drives (additional lightweighting)[3]	Efficiency increases for trucks of different size classes

Source: own table Oeko-Institut / ifeu

In addition to the GHG emissions in the use phase, the influencing variables that have a direct impact on transport and the measures that address them can also influence upstream and downstream GHG emissions in vehicle production and disposal as well as the raw material requirements in vehicle production. Therefore, changes in the number, size and composition of newly registered vehicles and decommissioned end-of-life vehicles associated with changes in the direct influencing variables were also determined from the scenarios. Based on this, emissions from vehicle production and disposal were calculated. A detailed explanation of the methodological approach in the scenario analysis is provided in Appendix A.1.

2.2.2.2 Results of the scenario analysis

This chapter shows summarised results of the scenario analysis for the additional GHG potentials beyond current policy measures in the use phase, in vehicle production and for the transport sector as a whole. In addition, Appendix A.1 contains detailed explanations of all the results, including an analysis of the impacts already foreseeable with current policy measures and the additional GHG impact potential in the individual levers.

GHG emissions in the use phase with current policy measures and additional GHG potentials

Direct GHG emissions from national transport in Germany will fall from 147 million tons of CO_2e in 2021 to 118 million tons of CO_2e by 2030 with currently adopted policy measures (MMS scenario) in the 2023 projection report. The main factors influencing this development are the increase in electromobility in car and truck transport (around 80% contribution to the GHG savings). Relevant contributions also come from modal shift to ecomobility modes (20%). After 2030, the direct GHG emissions from national transport modelled in the MMS of 2023 projection report decrease further to 87 million tons CO_2e (2035) and 34 million tons CO_2e (2045)[4].

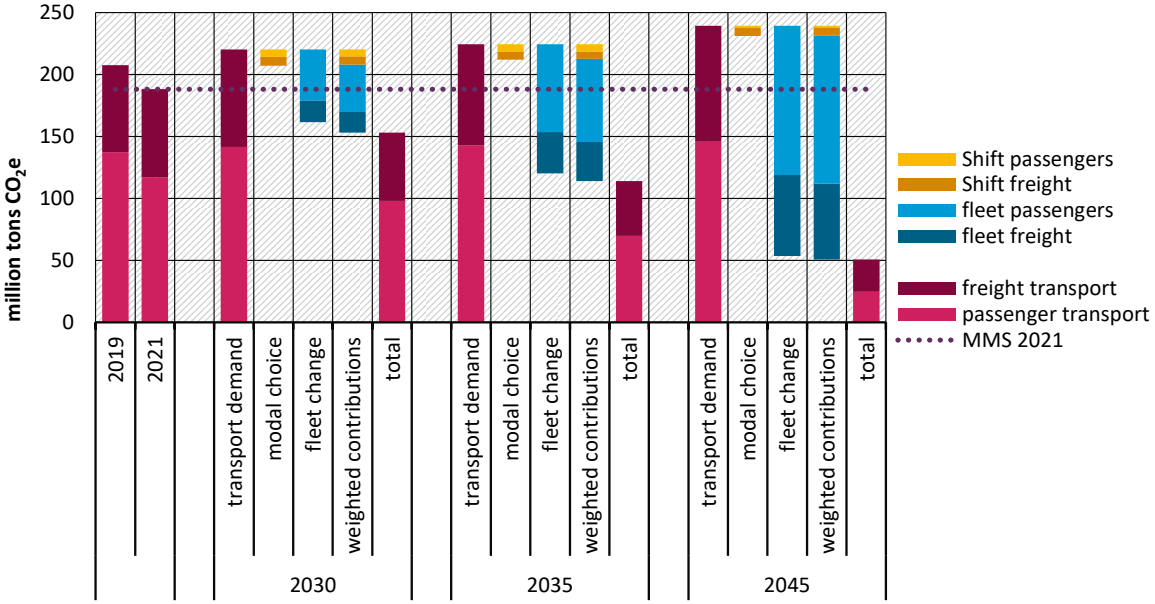
GHG emissions in the use phase are not only generated directly by the vehicles (tailpipe emissions, tank-to-wheel), but also in the provision of fuels and electricity (well-to-tank). As electromobility increases and the proportion of renewable fuels rises, emissions in the use phase shift from the transport sector to energy supply. Figure 12 shows the **total energy-related GHG emissions** of national transport in the use phase (well-to-wheel). In 2021, these were around 28% higher than direct GHG emissions. With policy measures in the 2023 MMS scenario, the

[3] Downsizing vehicles would also contribute to increasing efficiency across all drives, but is not being investigated in current scenarios.

[4] Note: The scenario analyses in AutoRess were carried out in 2023 using the then current 2023 projection report (Harthan et al. 2023). An update to the 2025 projection report (Förster et al. 2025) was available at the end of the AutoRess project. As a result of general development trends and additional measures, a significantly greater reduction in GHG emissions from national transport to 115 million tons CO_2e (2030), 66 million tons CO_2e (2035) or 15 million tons CO_2e (2045) is expected here as a trend.

well-to-wheel GHG emissions in 2035 are 32% higher than the direct GHG emissions from the vehicle. In 2045, the well-to-wheel emissions are 51% higher. Accordingly, future GHG emission reductions in transport in the use phase are somewhat weaker including energy supply (in the energy sector) than considering only direct GHG emissions in the transport sector. From 2021 to 2035, the GHG reduction well-to-wheel is 39% (instead of tank-to-wheel 41%). By 2045, well-to-wheel 73% (instead of tank-to-wheel 77%) of GHG emissions are reduced.

Figure 12: GHG emissions of national transport in the use phase (well-to-wheel) and GHG reduction contributions of different levers as a result of current policy measures

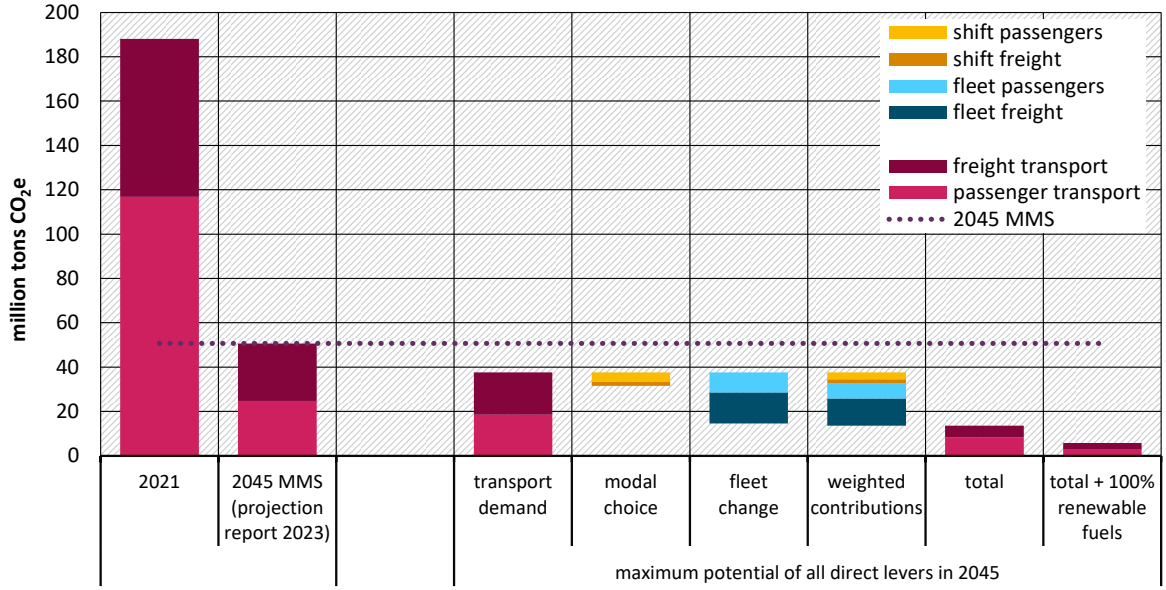


Source: own calculations Oeko-Institut / ifeu, based on (Allekotte et al. 2024; Harthan et al. 2023)

The basic picture of future GHG developments in transport with current policy measures and the contributions of various influencing factors do not change with the inclusion of energy supply (Figure 12). In 2030, modal shifts in passenger and freight transport will make a relevant contribution to GHG savings, but the majority of GHG reductions will come from the electrification of car and truck fleets, including the effects of an increasing share of renewable energies in electricity production. In the years after 2030, further GHG reduction contributions from modal shift in passenger transport will fall sharply, as a decline in transport services in the ecomobility modes is expected. At the same time, the GHG reduction contributions coming from electromobility will rise sharply due to the increasing electrification of vehicle fleets combined with the simultaneous expansion of renewable electricity generation.

Figure 13 shows the GHG emissions in 2045 for the use phase including energy supply with weighted maximum additional potentials of all direct influencing factors in transport considered. Additional GHG savings will mainly be achieved by electrifying the car and truck fleet while at the same time transforming electricity generation to renewable energies. Small additional reductions can be achieved by shifting from road to ecomobility modes, particularly in passenger transport. If all potentials are exploited, the total well-to-wheel GHG emissions of national transport fall by 93% by 2045 compared to 2021 to 14 million t CO_2e. According to the assumptions in the MMS, 75% of the remaining petrol and diesel vehicles in the fleet run on fossil fuels. If a complete switch to electricity-based fuels (PtL) is also assumed, the GHG emissions well-to-wheel in 2045 will only amount to 6 Mt CO_2e, a reduction of 97% compared to 2021. In a pure tank-to-wheel approach, as in the national GHG inventory, the transport sector will then be completely GHG neutral.

Figure 13: GHG emissions from national transport in the use phase (well-to-wheel) in 2045 with additional GHG reduction potentials



Source: own calculation Oeko-Institut / ifeu

GHG emissions from vehicle production

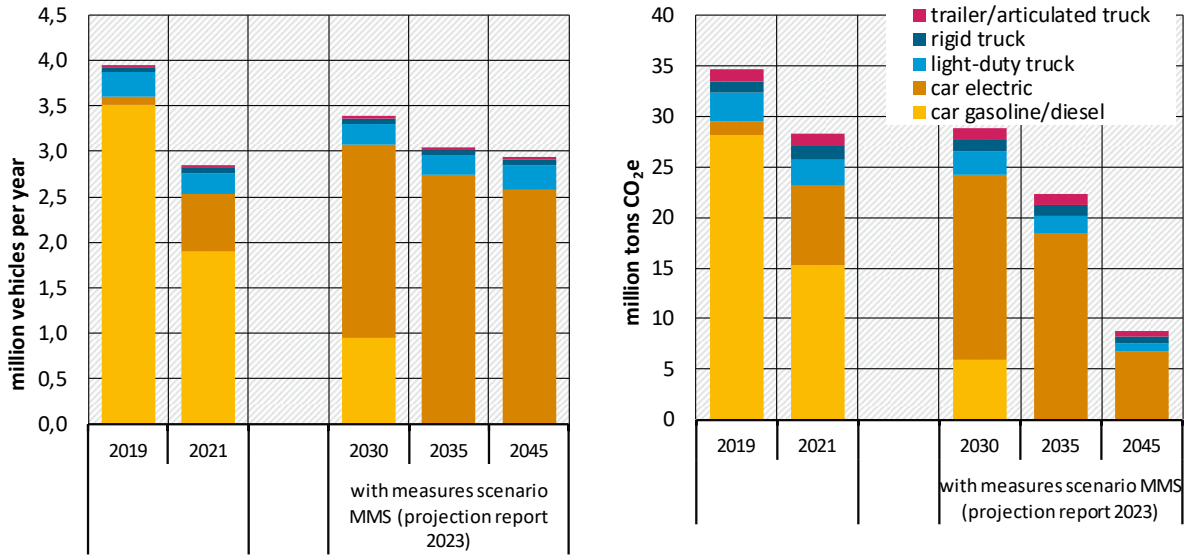
Figure 14 shows on the left the number of new vehicle registrations per year in the base year 2021 and in the years 2030, 2035 and 2045 with currently adopted policy measures (MMS) in the 2023 projection report (Harthan et al. 2023). For the coming years, the MMS models a renewed increase in annual new registrations to 3.4 million vehicles in 2030 (of which 3.1 million passenger cars). In 2035 and 2045, only around 3 million new vehicles (2.6-2.7 million passenger cars) will be registered despite a further increase in driving and traffic performance. At the same time, the share of alternative drive systems in new registrations will rise sharply. In 2030, electric cars will account for almost 70% of new registrations; from 2035, only electric cars will be newly registered. In truck traffic, the share of new registrations for alternative drive systems (electric, fuel cell) will rise to 33% by 2030, 54% by 2035 and 67% by 2045.[5]

Passenger cars dominate the GHG emissions from vehicle production, accounting for over 80% of total GHG emissions from car and truck production in 2021 (Figure 14, right). In 2030, the modelled GHG emissions from vehicle production are at a similar level as in 2021, despite a significantly higher number of new registrations and a simultaneous sharp increase in the share of electric vehicles with higher specific GHG emissions from vehicle production (see chapter 2.1.2). In the future, annual emissions from the production of newly registered vehicles will fall. The reason for this lies in the assumed decreasing GHG intensity of production systems in Germany and a complete long-term defossilisation of worldwide material supply until 2050, analogous to the scenario from (Biemann et al. 2024). If this very ambitious development is not

[5] Note: The scenario analyses in AutoRess were carried out in 2023 using the then current 2023 projection report (Harthan et al. 2023). An update to the 2025 projection report (Förster et al. 2025) was available at the end of the AutoRess project including also updated expectations on annual vehicle new registrations and the shares of different drive concepts. The specific figures used here in the scenario analysis are therefore now outdated for further analyses. However, this does not affect the fundamental findings of the scenario analysis on the GHG impact of changes in new registrations, drive concepts and other vehicle characteristics.

achieved, slower improvements of GHG intensity in production processes and material supply occur and manufacturing emissions might be higher in future years.

Figure 14: Number of new registrations in the with-measures scenario of the 2023 projection report and associated GHG emissions from vehicle manufacturing



Source: own calculation Oeko-Institut / ifeu

As already described in the previous chapter, the linking of new registration figures to traffic trends is very limited; other factors, in particular economic considerations of vehicle buyers (e.g. total costs of ownership), have a major influence. In addition, these various influencing factors are evaluated in different scenarios using different modelling approaches.

For this reason, the assessment of possible GHG effects of direct levers on vehicle production emissions was simplified. Different variants combining changes in the number of new registrations, shares of different drive concepts and lightweighting were compared to the reference situation. A reduction in new car registrations with an unchanged new registration structure leads to a reduction in GHG emissions from vehicle production to the same extent. An accelerated ramp-up of electromobility leads to higher emissions from vehicle production in 2030 compared to the reference situation. This GHG surcharge will disappear in subsequent years as soon as 100% alternative drive systems are achieved for new cars and trucks with existing measures. Additional lightweight aluminium construction for passenger cars leads to a significant increase in manufacturing emissions of up to 20%. In contrast, a reduced number of annual new registrations can partially or fully compensate for the additional emissions in vehicle production as a result of an accelerated change in drive systems and additional lightweighting.

Total GHG impacts for all life cycle stages in the scenarios and effects of direct levers

To assess the overall impacts, the GHG emissions from the use phase are combined with emissions from vehicle production. Emissions from vehicle maintenance and vehicle disposal[6] were also added; these were calculated in a simplified form due to their minor significance (see chapter 2.1.2.2). The emissions shown thus cover all life cycle phases for car and truck traffic.

[6] Note: Decommissioning is not synonymous with the end of the vehicle's life and thus its disposal. A significant proportion of decommissioned vehicles are exported to other (EU) countries and continue to be used there for several years. However, these vehicles are also disposed of with a time delay and can therefore be included in the scenario analysis.

However, the emissions were not distributed over a vehicle's lifetime as in a life cycle assessment. Instead, they were stated in the respective year of origin for the mileage of the existing vehicles (use phase, maintenance), new registrations (production) and decommissioning (disposal, end-of-life) in the corresponding year.

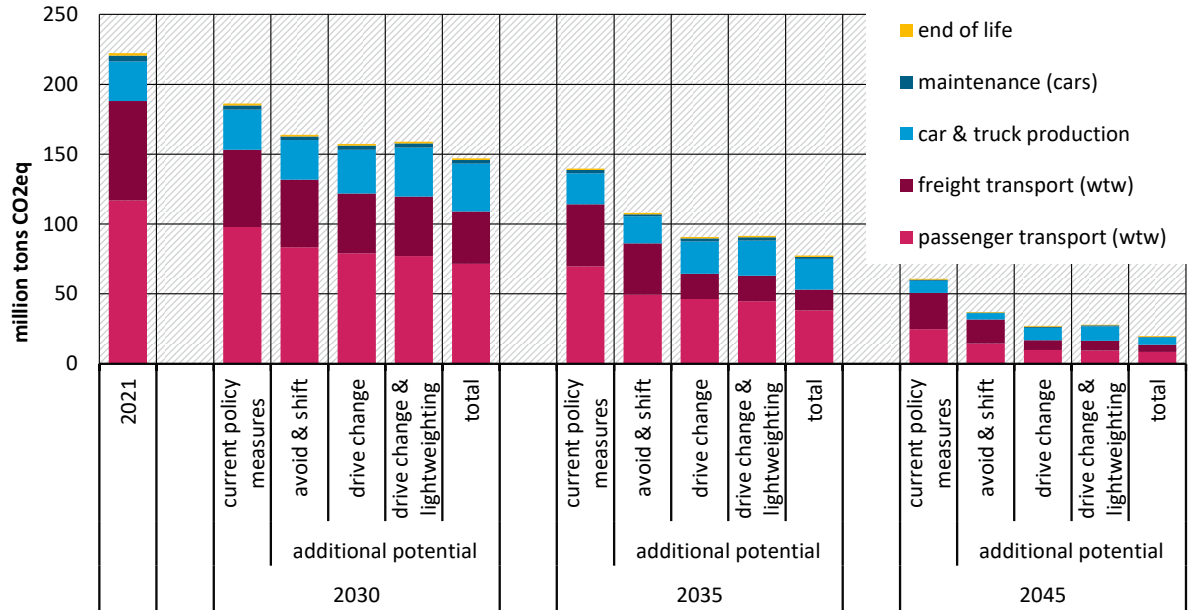
In 2021, 188 million tons of CO_2e, or 85% of the total GHG emissions from national transport considered here, were attributable to energy consumption in the use phase, including upstream energy supply. A further 28 million t CO_2e, or 13%, were attributable to the manufacturing of newly registered cars and trucks. The maintenance of existing cars and the disposal of decommissioned cars and trucks accounted for 6 million t CO_2e, or less than 3% of total emissions (Figure 15). In the coming years up to 2045, GHG emissions will fall at all stages of the life cycle. In the use phase, GHG emissions will decrease primarily as a result of increasing electric mobility, with smaller additional contributions from avoiding and shifting road transport and increasing efficiency. At the same time, the conversion of electricity generation to renewable energy sources is of central importance for low emissions from electromobility in the use phase.

Future emission reductions in the other life cycle phases, as calculated in the scenario analysis, particularly in vehicle manufacturing, are primarily the result of the assumed defossilisation of production processes in Germany and Europe and worldwide material supply. If defossilisation progresses more slowly, significantly lower GHG reductions will be achieved. However, even with strong defossilisation, the share of emissions from vehicle production in total emissions will increase in the future. Accordingly, the calculated total emissions from national transport decrease more slowly if all life cycle stages are taken into account than if only the use phase is considered.

The relative effectiveness of the various levers is similar, regardless of whether all life cycle stages are considered or only the use phase. Accelerated ramp-ups of electromobility offer clearly greater GHG savings potentials on the long-term than avoiding and shifting road transport, even when vehicle manufacturing is included.

No clear conclusions can be drawn from the scenario analysis for lightweighting. With the assumptions made in this scenario analysis on aluminium lightweighting, there is a slight overall increase in GHG emissions across all life cycle stages. The emission savings in the use phase due to more efficient vehicles are lower than the additional emissions from vehicle production. However, it should not be concluded from this that lightweighting generally leads to higher GHG emissions. Other approaches (in particular design methods that lead to an overall reduction in material quantities) can in principle also lead to GHG savings over the entire life cycle (see in-depth analysis of lightweighting in chapter 3.4).

Figure 15: GHG emissions with current policy measures and additional reduction potentials including all vehicle life cycle stages



Source: own calculation Oeko-Institut / ifeu

2.3 Indirect influencing factors

2.3.1 Raw material sources and mining

Description

Metals such as steel, aluminium, and copper constitute over 70% of vehicle weight, with nearly all metallic raw materials imported. (Dittrich et al. 2020a; Purr et al. 2019) RESCUE scenario assumptions for raw material sources and mining were based on 2010 data, projected unchanged, as mining was not a project focus. General assumptions include rising energy and material efficiency over time, driven by technological progress and regulatory requirements (Dittrich et al. 2023; Fundación Chile 2019).

Ore grades are empirically declining, increasing energy and material input per extracted metal unit (Mudd 2021). Mining companies pursue efficiency to reduce costs, and governments increasingly enforce environmental standards. Extraction and initial processing account for a significant share of greenhouse gas emissions and generate large amounts of waste and overburden (Delevingne et al. 2020; JRC 2023a). The environmental impact varies by deposit type and extraction method, as illustrated by lithium extraction from rock in Australia and brine in Chile, which differ greatly in emissions and waste profiles (Schmidt 2022).

Results

Mining activities contribute to greenhouse gas emissions, waste, and overburden, but the RESCUE assumptions did not reflect the increasing energy demand from declining ore grades or changes in countries of origin (Mudd 2021; Schmidt et al. 2020). The RESCUE scenarios are too general to derive specific measures for the automotive sector, and changes in supply chain due diligence or mining waste management were not addressed (Franks et al. 2021; Priester, Dolega 2015; Weiss et al. 2022).

Empirical studies show energy input and emissions rise as ore grades fall, especially for metals like copper and gold. The environmental effects of extraction methods, as seen in lithium production,

are substantial and vary by location and technique (Schmidt 2022). Data gaps exist for overburden and residual materials, and the effects of new legal requirements or improved waste management were not examined in detail (Destatis 2021a; Gilsbach 2020; grida.no o.J.; Priester et al. 2019)

In summary, it is assessed that the topic is relevant but not specific to transport and thus will not be explored in depth in the further course of the project.

2.3.2 Increasing the proportion of recycled materials in production: metals, glass

Description

Raising the share of secondary raw materials in vehicle production conserves resources and reduces greenhouse gas emissions, depending on the energy mix and recycling processes (Purr et al. 2019). RESCUE scenarios set ambitious targets: 67% scrap use in steel by 2040, 90% scrap and secondary content in copper, aluminium, and lead by 2050, a 25% increase in other non-ferrous metals, and 69% cullet in glass (Dittrich et al. 2020a). Linear increases from 2010 were assumed.

Battery raw materials are also subject to recycled content (BattV, Art. 8). Using recyclates reduces the demand for primary materials and can lower transport emissions if more scrap is processed domestically. The environmental benefit depends on energy required for recycling versus primary production, and the savings vary by material and context (Deutsches Kupferinstitut 2023; Gilsbach 2020; Vasters, Franken 2020; Wirtschaftsvereinigung Stahl 2020).

Results

Resource and emission savings from increased recyclate use are significant, provided recycling is less energy-intensive than primary production (German Steel Federation 2020; Vasters and Franken 2020). RESCUE did not compare available scrap quantities, and the required amounts are not globally available under the scenario assumptions. Achieving 90% secondary shares in copper production by 2050 is unrealistic (Dittrich et al. 2020a; Gilsbach 2020). The actual increase in recycled content depends on material flows and industry uptake. Examples from the automotive industry show growing use of recyclates, with some manufacturers targeting up to 40% recycled content in their fleets (Daimler 2021; Eberhardt 2021; Motorsport Total 2009; Volkswagen 2023). The assumptions in RESCUE relate to average metal production, and it remains uncertain to what extent the share of recycled materials in automotive production can be increased, given specific material sources and market constraints.

In summary, it is assessed that the topic is fundamentally relevant and will be explored in depth in the further course of the project.

2.3.3 Transformation of energy systems in Germany

Description

The transformation of Germany's energy system aims for greenhouse gas neutrality by 2050, affecting not only the direct energy use in the transport sector but also the upstream and downstream energy inputs for vehicle production, intermediate consumption, and disposal (Dittrich et al. 2020a; Purr et al. 2019). Companies are motivated to reduce energy inputs to lower costs and respond to policy pressures for decarbonization and improved energy efficiency, as seen in the 13.5% improvement in energy intensity in manufacturing between 2015 and 2020(Destatis 2025). The RESCUE scenarios assume a complete shift to renewable electricity, broad electrification of production processes, use of synthetic fuels where direct electrification is not feasible, and sector coupling to maximize efficiency. Specific targets include a 20% reduction in specific electricity demand in the steel industry and a 30% reduction in the

non-ferrous metals sector by 2050, along with annual efficiency gains in chemicals. Only minimal, process-related emissions are expected to remain, primarily from the construction of renewable energy infrastructure such as wind turbines and photovoltaics.

Results

A complete transformation of the energy system significantly reduces greenhouse gas emissions across the automotive value chain, achieving near-total greenhouse gas neutrality except for minor residual emissions from upstream processes like cement production for renewables infrastructure. The RESCUE project focused extensively on these aspects, but did not provide a detailed analysis of energy inputs specific to the German automotive industry and its upstream supply chain. The indirect effects of energy system transformation on vehicle manufacturing and intermediate products were acknowledged, but detailed sector-specific data and analysis remain limited. (Destatis 2025; Dittrich et al. 2020b; Purr et al. 2019)

In summary, it is assessed that the topic is fundamentally relevant but not specific to transport and too broad to be explored in depth in the further course of the project.

2.3.4 Transformation of energy systems in Europe and the rest of the world and effects on primary products and imported cars

Description

The German automotive industry relies on raw materials and intermediate products sourced globally, making the transformation of energy systems abroad highly relevant for reducing greenhouse gas emissions and primary raw material use in the sector. RESCUE assumes that for all imports from EU countries, production technologies will transform similarly to Germany, affecting all sectors and services. For non-EU imports, the speed of transformation varies by scenario, with the GreenSupreme scenario assuming that by 2050, production technologies abroad will match German standards. These changes influence the life cycle assessment of vehicles by reducing resource input and environmental impacts in the production of imported intermediate products(Dittrich et al. 2020a; Purr et al. 2019).

Results

Potential greenhouse gas savings in the upstream supply chain and in imported vehicles are substantial. In 2017, energy-related CO_2 emissions from imported inputs for vehicle manufacturing in Germany were 0.87 million tonnes, with an additional 1.58 million tonnes from imported vehicles, compared to 3.99 million tonnes from domestic production.(Destatis 2021b) Transforming energy systems abroad could avoid these emissions. Globally, vehicle production accounts for about 9% of all greenhouse gas emissions, including upstream and disposal processes (Stephan et al. 2019). The European automotive industry has already reduced its greenhouse gas emissions by 45.9% since 2006, mainly through increased use of renewable energy (acea 2022). Despite these advances, the RESCUE project did not quantify specific savings potentials for imported products, indicating a need for further research on sector-specific options to leverage these potentials.

In summary, it is assessed that the topic is fundamentally relevant but not specific to transport and too broad to be explored in depth in the further course of the project.

2.3.5 Improving material efficiency in upstream production and service sectors

Description

Material efficiency in the automotive sector is monitored using indicators such as total raw material productivity, which increased by 8–12% in Germany between 2010 and 2019 (Destatis 2025; Lutter et al. 2022). Drivers for improved efficiency include cost reduction, regulatory pressure, and the shift to electromobility, which tends to move environmental burdens from the use phase to production. The RESCUE scenarios assume annual material efficiency improvements of 1.2% in sectors without specific targets, resulting in substantial raw material savings over time: 12.6% in 10 years and 34.7% in 25 years (Dittrich et al. 2020a; Purr et al. 2019). These assumptions impact not only manufacturing but also repairs, waste management, transport, and insurance services.

Results

The specific contribution of material efficiency improvements in supplier industries and services to greenhouse gas and raw material savings was not quantified in RESCUE. Analysis for the EU automotive supply chain in 2007 showed that the steel industry accounted for 38% of GHG emissions, followed by energy (10%), with other significant contributors including mechanical engineering, aluminium, chemicals, rubber, and glass (Deloitte Sustainability 2016). The potential for GHG reduction in upstream services remains lower than in material-intensive industries. The RESCUE project did not specify additional measures for supplier industries, suggesting further research could identify technologies and strategies to enhance efficiency in vehicle construction and intermediate goods (Dittrich et al. 2020a; Lutter et al. 2022; Purr et al. 2019).

In summary, it is assessed that the topic is not specific to transport and too broad to be explored in depth in the further course of the project.

2.3.6 Lightweighting

Description

Lightweighting in automotive engineering aims to reduce vehicle weight through material substitution and constructive design changes. The RESCUE project, building on Renewbility III (Zimmer et al. 2016), defined scenarios with varying levels of lightweighting: 10% (high-strength steels, 10% weight reduction), 20% (additional aluminium substitution, 20% weight reduction), and 30% (further substitution with carbon fiber reinforced polymer (CFRP), 30% weight reduction). The ambition level is determined by the speed of market adoption in new vehicle registrations. Material composition shifts from steel and cast iron to aluminium and carbon fibre as lightweighting increases, with implications for both production and end-of-life recycling.

Results

Lightweighting reduces the use of steel and cast iron but increases demand for aluminium or other lightweight materials. In GreenSupreme, per mid-range vehicle, 10% lightweighting saves about 120 kg of steel/cast iron; 20% saves 458 kg of steel/cast iron and requires 239 kg more aluminium; 30% saves 564 kg of steel/cast iron, with 155 kg more aluminium and 86 kg carbon fibre required (Zimmer et al. 2016). Detailed GHG calculations from Renewbility III found that only the 10% variant reduced emissions, while higher levels increased GHG emissions in vehicle production, mainly due to the energy intensity of aluminium and CFRP. Accordingly, efficiency gains in the use phase can be offset by additional GHG emissions from lightweighting in car production, especially for BEVs with a cleaner electricity mix. Some studies suggest lightweight

aluminium construction may still result in net lifecycle GHG increases (FVV 2021), while others find overall emission savings depending on material and energy mix (Dünnes 2015; e-mobil BW GmbH 2012). The impact of lightweighting depends on the extent of energy system transformation and should be reassessed as upstream energy inputs evolve. In conclusion, it was assessed that the topic is relevant specifically to transport and will be explored in depth in the further course of the project.

2.3.7 Repair

Description

RESCUE assumed in its green scenarios that products, including consumer goods, would increasingly be designed for repairability, with consumers opting for higher-quality, repairable items, leading to a 33% average increase in product lifespan. For cars, assumptions focused on new registrations and lifetimes based on mileage, with increased usage intensity but not extended service life in GreenSupreme. Repairs extend the useful life of vehicles and components, reducing the need for new purchases and thus saving primary raw materials and production-related emissions. However, longer vehicle lifespans can slow the market penetration of new, more efficient technologies, while shorter lifespans may accelerate recycling, especially for batteries, which is relevant given the criticality of some battery materials (Allianz 2022a; b; Bräuninger et al. 2013).

Results

Repairs can significantly reduce greenhouse gas emissions, especially when replacing new, CO_2-intensive parts like glass. For example, increasing repair rates by 2% could save 30,000 tons of CO_2 across Europe (Allianz 2022b; Bräuninger et al. 2013). Repairing headlight glazing or windscreens can save up to 98–99% of CO_2 emissions compared to replacement (Allianz 2022a). Video inspections instead of on-site visits also reduce emissions. Nevertheless, the benefits of repair must be weighed against the potential delay in fleet renewal and the adoption of new technologies. The RESCUE project did not analyse repairs in detail for cars and their components, suggesting this could be explored further in AutoRess. In the RESCUE project, it was assumed in the GreenMe, GreenLife and GreenSupreme scenarios that items are increasingly being produced in such a way that they are (easily) repairable. Consumers are also more likely to opt for high-quality and repairable goods. The lifespan of goods increases by 33% on average. This assumption was formulated for a large selection of consumer goods, but not for cars. For cars, assumptions were made about new registrations and lifetimes, depending on mileage. It was assumed in GreenSupreme that the intensity of use, but not the service life of cars, would increase.

In summary, it is assessed that the topic is fundamentally relevant to transport and will thus be explored in depth in the further course of the project.

2.3.8 Remanufacturing

Description

Remanufacturing involves industrially reprocessing and reusing parts after use, distinct from workshop-based repair. RESCUE did not make assumptions regarding remanufacturing of car parts(Dittrich et al. 2020a; Purr et al. 2019). Remanufacturing reduces waste and saves primary raw materials and energy compared to producing new components. Not all parts are suitable due to wear, changing requirements, or safety concerns. The VDI Center for Resource Efficiency has developed criteria to assess suitability, with starters, alternators, and combustion engines

found to be suitable. For electric vehicles, remanufacturing of components (especially batteries) can reduce costs and enhance attractiveness (Herrmann, Vetter 2021; Kreisköther et al. 2016).

Results

Studies show substantial resource and greenhouse gas savings from remanufacturing. For example, remanufactured engines in the EU are associated with only 22–33% of the environmental impact compared to new engines, due to lower energy and upstream material requirements (Bobba et al. 2020c). In 2012, 8% of end-of-life vehicles in the EU were reused, mostly engines, starters, and alternators. Case studies indicate energy savings of 40–56%, coal savings of 73–78%, and CO_2 reductions of 53–76% for remanufactured components (Lange 2017). However, some processes, such as cylinder head remanufacturing, may increase oil consumption. The timing of remanufacturing should be balanced against the benefits of introducing more efficient new technologies. Remanufacturing, especially for batteries and powertrains, offers significant potential for resource and emission savings and warrants further investigation (Bobba et al. 2020c; Herrmann, Vetter 2021; Kreisköther et al. 2016; Lange 2017).

In conclusion, it is assessed that the topic is fundamentally relevant to transport and will thus be explored in depth in the further course of the project.

2.3.9 Changes in demand for goods and services

This indirect influencing factor is not about the change in modal shift, but about changes in demand for various goods and services with an impact on transportation. For the sake of completeness, this indirect influencing factor should also be listed.

Description

The RESCUE project incorporated various assumptions regarding the shift in demand for goods and services relevant to transport impacts. These include reduced food waste, altered dietary patterns, and increased preference for regional, seasonal products, all leading to lower freight demand. A shift toward durable consumer goods and a decrease in the purchase of short-lived items further reduces transport volumes. Reduced shopping and increased leisure travel were assumed to influence passenger transport behaviour. Capital goods such as housing were projected to decrease in volume and increase in modular construction, limiting freight needs. While freight transport effects were modelled in the RESCUE scenarios, passenger transport changes were not quantified. These behavioural and consumption pattern shifts primarily affect the usage phase of vehicles and freight intensity, with indirect influence on car ownership (Dittrich et al. 2020a; Purr et al. 2019).

Results

Despite the relevance of altered consumption patterns, RESCUE did not quantify specific GHG or resource savings due to these changes. The effect on passenger transport remains analytically underdeveloped, with only freight-related impacts considered in modelling. The assumption that shopping trips decrease while leisure trips increase lacks numerical substantiation. Moreover, the complexity and inertia of behavioural change, especially on a societal scale, pose methodological challenges. As such, the project recognized the theoretical potential of demand-side changes but deemed in-depth exploration impractical within the scope of AutoRess (Dittrich et al. 2020a; Purr et al. 2019).

In summary, it is assessed that the topic is too broad to be explored in depth in the further course of the project.

2.3.10 End-of-life vehicle disposal

Description

No targeted assumptions were made within RESCUE regarding end-of-life vehicle (ELV) disposal, due to the specific legal and technical treatment requirements.(Dittrich et al. 2020a; Purr et al. 2019) However, the process begins at the last stage of a vehicle's life cycle and involves dismantling, shredding, and recycling. Proper disposal supports emission reductions by avoiding the release of hazardous substances such as refrigerants and enhances material recovery through the reuse of spare parts and recycling of materials. While high mass recycling rates (94% in 2020) are achieved in approved facilities, concerns remain about downcycling and material quality loss. The raw material composition of ELVs is evolving, with a growing share of plastics, light metals, and batteries due to increasing electromobility (UBA 2023a; Zimmermann et al. 2022).

Results

Although Germany meets the formal recycling targets for ELVs, the quality and sustainability of recycling processes are unclear. For example, glass backfill and the downcycling of vehicle steel limit value retention. Illegal exports and dismantling in non-approved facilities led to an estimated 167,000 tons of CO_2e emissions in 2018. As vehicle compositions change—particularly with battery-heavy electric vehicles—the environmental management of ELVs becomes more complex. RESCUE did not assess these dynamics in detail, highlighting a gap in the life cycle-oriented analysis of the sector's end-of-life impacts (UBA 2023a; Zimmermann et al. 2022).

In summary, it is assessed that the topic is fundamentally relevant to transport and will be explored in depth in the further course of the project.

2.3.11 Bio-based plastics and composites

Description

RESCUE made no specific assumptions concerning the use of renewable raw materials ("NaWaRo") or bio-based plastics in automotive components(Dittrich et al. 2020a; Purr et al. 2019). These materials are introduced during the raw material phase and potentially reduce fossil carbon input. Depending on the application, NaWaRo may lower production emissions and costs. In some cases, lighter composites can contribute to reduced fuel consumption during the use phase. However, environmental impacts vary widely depending on the feedstock and land use, including biodiversity effects and competition with food production. The overall weight share of NaWaRo-based components in vehicles is low, and the use-phase impacts have received limited attention in life cycle assessments to date (Zimmermann et al. 2022).

Results

Despite theoretical environmental benefits, quantification of GHG or raw material savings from NaWaRo use remains insufficiently supported by data. Most life cycle assessments focus on the production phase rather than use-phase or end-of-life implications. The minor material share in vehicles suggests limited potential for broad systemic impact. RESCUE's lack of inclusion of this topic indicates both a research gap and limited perceived relevance for near-term emissions or material savings in the automotive sector (Zimmermann et al. 2022).

In summary, it is assessed that the topic is too broad a topic to be explored in depth in the further course of the project. However, in this project bio-based plastics are used as one of the levers in the GHG neutrality scenario for the plastic sector.

2.3.12 Plastic recycling

Description

All RESCUE green scenarios assume a progressive increase in the recycling of plastics, notably mechanical recycling reaching 75% by 2050. This starts in the raw material phase and impacts both upstream and final production. Recycling reduces primary material demand and, depending on the energy source, may significantly lower GHG emissions. For example, emissions from recycled plastic are around 0.4 tons of CO_2 per ton, compared to 2.4 tons for virgin plastic (Material Economics 2018). Solvent-based technologies like the CreaSolv process show markedly lower emissions and fossil resource consumption than thermal recycling methods (Potrykus et al. 2023). While RESCUE did not isolate car-specific effects, the principles apply to automotive plastics in terms of both mass and impact (Dittrich et al. 2020a; Purr et al. 2019).

Results

Although vehicle-specific figures are unavailable, broader studies confirm substantial savings potentials through expanded plastic recycling. Automotive manufacturers are increasingly engaging with these processes, as illustrated by BMW's goal to increase recycled thermoplastics from 20% to 40% (Plasticker-News 2022). Different recycling methods—mechanical, solvent-based, chemical—each present distinct trade-offs in terms of emissions, energy use, and scalability. RESCUE's general support for high-recycling scenarios aligns with current industrial trends but does not address the interdependencies among recycling technologies or policy mechanisms for material recovery (Dittrich et al. 2020a; Potrykus et al. 2023).

In summary, it is assessed that the topic is fundamentally relevant to transport and will be explored in depth in the further course of the project.

2.4 Prioritization of direct and indirect influencing factors

Based on the analyses of direct and indirect influencing factors, a basic prioritization of influencing factors with regard to their relevance to GHG and raw materials was carried out. This prioritization was the basis for the in-depth analysis of selected technical and social options in the further course of the project (see chapter 0). Table 2 shows an overview of all direct and indirect influencing factors investigated and their identified relevance for in-depth analyses.

Table 2: Relevance of direct and indirect influencing factors

Influencing factor	Relevance	Comments
Direct influencing factors		
Transport demand	low	Primarily determined by general population (passenger transport) and economic development (freight transport). Very limited influence of transport-related measures (hardly addressed in RESCUE scenarios).
Modal shift	low	Limited GHG savings potential until 2030. Significantly decreasing potential after 2030 with increasingly electrified vehicle fleets (already on trend).
Drive change	**high**	The switch to electromobility is the central lever for GHG reduction in the use phase. The speed of the fleet ramp-up and the vehicle configurations (in particular battery sizes and types) are highly relevant for the GHG emissions and material requirements of vehicle production. The focus is on passenger cars, which dominate overall GHG emissions and material requirements of vehicle production.

Influencing factor	Relevance	Comments
Increasing efficiency a) Downsizing b) Lightweighting	**medium-high**	With increasingly electrified vehicle fleets, additional increases in vehicle efficiency have only a small additional GHG savings potential in the use phase. At the same time, they can have a greater impact on the demand for raw materials. a) Downsizing reduces the overall demand for raw materials. b) The effects of lightweighting depend on the type of lightweighting and the materials used (aluminium, composite materials, etc.).
Indirect influencing factors		
Raw material sources and mining	medium	GHG relevance low. Significant relevance with extended ecological assessment, but high analysis effort and not a specific issue for the vehicle sector.
Increasing the proportion of recycled content a) of battery materials b) of non-batter metals	**high**	Relevance and technical options vary for individual commodities. Focus on metals. We recommend assessing the use of recycled battery materials (lithium, cobalt, nickel) and the use of recycled content of glider and powertrain (non-battery) metals, separately.
Transformation of energy systems in Germany	low	Rapid progress in the transformation of energy systems in Germany is already foreseeable with currently adopted political measures.
Transformation of the energy system in Europe and the RoW: effects on primary products and imported cars	low-medium	Relevant for the GHG emissions of imported inputs (e.g. battery production) in vehicle production and their share of total GHG emissions in the vehicle life cycle.
Improving material efficiency in upstream production and service sectors	low-medium	Increasing material efficiency in upstream industries serves companies' own interests by reducing material and energy costs. However, the potential for significant GHG emission reductions in the upstream production and service sectors related to vehicle manufacturing is likely to be low.
Lightweighting	**medium-high**	Linked to direct influencing factor "increased efficiency". Additional lightweighting has low GHG relevance overall. Depending on the technical implementation, additional emissions in vehicle production can more than compensate for the savings in the use phase. Depending on the lightweighting variant, different relevance for the use of raw materials is possible.
Repair	**high**	Improved reparability improves the longevity of vehicles. On the one hand, this reduces GHG emissions from vehicle production. On the other hand, fleet renewal and thus possibly the rapid ramp-up of new, GHG-saving vehicles is slowed down.
Remanufacturing	**high**	Remanufacturing involves the industrial and standardized processing and reuse of car parts after vehicle decommissioning. With regard to the GHG potential of remanufacturing, it is necessary to analyse which reuses are advantageous in terms of raw materials and greenhouse gas emissions, and at what point remanufacturing becomes disadvantageous overall due to the delayed implementation of new, more economical technologies. The remanufacturing of batteries (replacement of individual cells) or even the reuse of the vehicle body with a completely renewed powertrain could also be an object of investigation.

Influencing factor	Relevance	Comments
Changes in demand	low	Changes in demand for goods and services indirectly cause changes in passenger and freight transport demand. Significant changes in demand require changes in behaviour across a very broad spectrum, which can only be brought about with a great deal of effort.
End-of-life vehicle disposal	**high**	With regard to the disposal of end-of-life vehicles, the prescribed overall recycling rates, material-specific recycling rates and the fate of vehicles that are not sent for regular disposal are particularly relevant for possible savings in greenhouse gases and raw material requirements. The impact of the forthcoming revision of the ELV Regulation at EU level and whether further measures are required must also be discussed here.
Renewable & bio-based raw materials	low-medium	Relevance depends heavily on the specific biomass upstream chains.
Plastic recycling	**medium-high**	The current recovery rates of plastics from vehicles are relatively low; new recycling processes (technical options) could realize relevant savings potential.

Source: own table Oeko-Institut / ifeu

3 In-depth analysis of the technical and social options in the priority subject areas

3.1 Scope and model development for the in-depth analysis

10 technical and social options were selected as a result of the systemic analysis of direct and indirect factors influencing GHG emissions and raw material consumption in chapter 2. These were then analysed in depth. The current status quo, development trends with current drivers and fields of action for additional drivers to reduce GHG emissions and material requirements were researched and discussed in expert workshops. A model of car transport in Germany was set up for AutoRess, including all stages of the vehicle life cycle. This model was used to derive comparable GHG and materials savings potentials up to 2045 for all 10 options.

Table 3 provides a compact overview of the 10 options and the issues investigated. Individual subject areas also offer very diverse technical starting points. In addition, the intensity with which levers are implemented is highly relevant to impacts. For this reason, up to 5 variants were modelled for each option and bandwidth of GHG and material effects was estimated.

Table 3: Overview of analysed technical and social options

Option	Analysed approaches
1. Alternative powertrains	Different battery technologies and cell materials (LFP, solid-state NMC, Na-Ion); Variation in battery capacities
2. Vehicle downsizing	Shift in new car registrations towards smaller vehicles
3. Lightweighting	Use of lightweight materials, in particular aluminium, in various vehicle components; lightweight construction of battery housings
4. Design for circularity	Car designs that increase longevity or the amount of components that can be reused / repurposed
5. Reuse/Repurpose batteries	Higher shares of re-used and re-manufactured spare parts
6. Reuse/Remanufacturing body	Higher shares of „high repairability and reuse potential“
7. Recycled content battery	Changes in return rates of battery materials from battery recycling; Effect of graphite recycling
8. Recycled content body	Different rates for recycled metal content in the vehicle body (battery excluded)
9. Plastics recycling/renewable	Plastic recycling; use of non-fossil plastic sources
10. End of Life	Higher shares of dismantled materials prior shredding, higher share of material recovery of glass and higher share of high-quality recycling of steel, aluminium, copper

Source: own table Oeko-Institut / ifeu

3.1.1 Selection of materials

In AutoRess, measures are to be identified with which both greenhouse gases can be saved and the overall resource consumption and associated ecological and social consequences of car production can be reduced. However, a vehicle consists of a variety of materials that cannot be analysed individually. There are indicators such as Cumulative raw material expenses (KRA) and raw material consumption (RMC) (see chapter 2.1.1.2), which extrapolate the consumption of

individual materials to a raw material consumption. However, the quantity of the KRA or RMC per se does not contain any information on the ecological assessment of raw material use. For this reason, a selection of materials was made in AutoRess and analysed individually. Table 4 describes the selection of relevant materials. On the one hand, materials with a high mass share in passenger cars (see chapter 2.1.1.1) and at the same time a high share of automotive production in cross-sectoral material requirements were considered. On the other hand, selected critical battery materials with high relevance for the drive transition in transportation.

Table 4: Selection of vehicle materials

Material	Reason
Powertrain independent vehicle materials	
Steel	▶ High mass share in the vehicle and in the environmental impact of vehicle production. ▶ High proportion of global steel demand accounted for by vehicle production, which is not set to decrease - and thus in terms of current and future environmental impact. ▶ Availability of secondary material dependent on recycling quality (downcycling) ▶ Use of steel for the automotive sector in Germany is 26% in 2020 (second largest sector after construction with 35%)(Wirtschaftsvereinigung Stahl 2020). In the EU27, the share is around 16% (RMIS 2023a). ▶ Medium aggregated environmental hazard potential (Iron) (Dehoust et al. 2020) According to (Sander et al. 2020) high GWP of the metals iron, aluminium and copper when considering the quantities used per vehicle.
Aluminium	▶ Bauxite/aluminium is included in the EC's current list of critical raw materials (CRM 2023); import dependency (extraction) is 55%; the EU's main sourcing countries are Guinea (62%) and Brazil (12%); the EoL-RIR is 32% [EC, 2023] ▶ Share of aluminium use in the EU27 at approx. 38% for means of transport and automotive industry (CRM, 2023), for Germany at 45%(WVMetalle 2021) ▶ Medium to high aggregated environmental hazard potential
Plastics	▶ As a total or selected groups of plastics. Many different plastics are used in vehicles; in terms of mass, they play a lesser role than metals, but they are relevant when it comes to lightweighting issues and post-shredder technologies. ▶ According to (Sander et al. 2020) - with the exception of iron, copper and aluminium - the GHG relevance of the plastics PP, PU, PA, PE and ABS used is significantly higher than the GWP of other metals when considered per vehicle (specific GWP/material * mass fraction per vehicle) see also Figure 1 below ▶ If selected, focus on components or types of plastic that are difficult to recycle (with substitution considerations for the latter) ▶ Problematic: thermosets
Glass	Weight proportion approx. 40 kg/vehicle Proportion of primary mineral material unavoidable
Vehicle materials in both glider and powertrain/batteries	
Copper	▶ High material requirements in the vehicle and thus in the environmental impact of vehicle production. Demand will increase with e-mobility, but also general networking in the vehicle. ▶ Relevant, future increasing share of vehicle production in global copper demand (see (FVV 2021) : Other sectors dominate today, but share of transport will rise sharply with defossilization, for BEV by vehicles, for e-fuels infrastructure). According to DERA, a total of 5.5 million tons of copper will be required globally in 2040 for high-growth future technologies alone (including electric drives, wind turbines, expansion of the power grid, etc.), which corresponds to around 27% of global primary production in 2018 and

Material	Reason
	represents an increase of 137% (sustainability path SSP1 of the IPCC) compared to 2018.(Marscheider-Weidemann et al. 2021) ▶ Copper is included in the EC's current list of critical raw materials (Grohol, Veeh 2023); the import dependency of extraction is 45%; the EU's main sourcing countries are Chile (14%) and Peru (10%); the EoL-RIR is 30% (Grohol, Veeh 2023) ▶ 9% of German copper use in 2020 is attributable to the automotive sector(WVMetalle 2021) ; this share also applies at EU27 level (JRC 2023b) ▶ High aggregated environmental hazard potential (Dehoust et al. 2020)
Nickel	▶ 57% of Germany's current nickel use in 2020 is in the stainless steel industry (e.g. for automotive engineering, share n.a.); 13% is used for nickel alloys, (so far) only 3% for batteries(WVMetalle 2021) ▶ Important battery metal, demand will rise sharply (in the case of current battery types). DERA forecasts a global demand of 1.28 million tons for nickel in 2040; an increase by a factor of 6.8 compared to 2018. This is due to the use of nickel in solid-state battery cells in electromobility applications(Marscheider-Weidemann et al. 2021) ▶ Nickel is included on the EC's current list of critical raw materials (Grohol, Veeh 2023); the import dependency of processing is 75%; the EU's main sourcing countries are Russia (29%), Canada (6%) and Australia (6%); the EoL-RIR is 16% (Grohol, Veeh 2023) ▶ High aggregated environmental hazard potential (Dehoust et al. 2020) ▶ Con: Recycling already established = hardly any need for action (but see EoL-RIR only 16%)
Battery materials	
Lithium	The key technology metal for batteries. Demand will increase massively in the future. According to DERA, demand will grow by approx. 590% compared to current lithium production (2018), primarily due to the demand for electric vehicles with lithium-ion batteries. (Marscheider-Weidemann et al. 2021) Other sectors hardly relevant compared to vehicle production. At the same time, no established recycling cycles yet. Lithium is included on the EC's current list of critical raw materials (Grohol, Veeh 2023); the import dependency of processing is 100%; the EU's main sourcing countries are Chile (79%) and Argentina (6%); the EoL-RIR is 0% (Grohol, Veeh 2023) Medium aggregated environmental hazard potential (Dehoust et al. 2020)
Cobalt*	Key technology metal for batteries. Demand will increase massively in the future, including the risk of (temporary) supply bottlenecks. Other sectors hardly relevant compared to vehicle production. Environmental risks Deep-sea mining (= reduce demand, avoid risks) Around half of the current use of cobalt goes into battery production. According to DERA, demand will increase by around 400% by 2040 compared to 2018, mainly due to use in lithium-ion storage systems, superalloys and solid-state batteries. (Marscheider-Weidemann et al. 2021) Cobalt is included in the EC's current list of critical raw materials (Grohol, Veeh 2023) the import dependency of extraction is 81%; the main global producers are D.R. Congo (63%), Russia (7%) and Canada (4%); the EoL-RIR is 22% (Grohol, Veeh 2023) High aggregated environmental hazard potential (Dehoust et al. 2020)
Graphite	▶ Around 60% of graphite is used for industrially used refractory materials in steel, iron, glass and ceramic production. Around 14% is used for lithium-ion batteries. Depending on the scenario, the current production volume that flows into battery systems can increase to 88%(Marscheider-Weidemann et al. 2021) ▶ Natural graphite is included in the EC's current list of critical raw materials (Grohol, Veeh 2023); the import dependency of extraction is 99%; however, the supply risk has decreased compared to the previous CRM assessment due to a greater diversification of supply (from 2.3 to 1.8), the economic importance has remained constant (Grohol, Veeh 2023)

Material	Reason
	▶ Low aggregated environmental hazard potential (Dehoust et al. 2020) ▶ Poor data situation

* Manganese is another critical battery material. However, its relevance and potential savings are generally comparable to those of cobalt. It was therefore not modeled separately in AutoRess.
Source: own table Oeko-Institut / ifeu

3.1.2 Development of a model for GHG and material impacts

In AutoRess, we analysed GHG emissions and primary material savings potentials in Germany's car transport sector for different mainly technical options, taking into account all life cycle phases of the vehicles. As a starting point for the assessment of future GHG and material savings potential in the vehicle life cycle, it is first necessary to evaluate how the various influencing factors and the resulting GHG emissions and material requirements will develop without additional interventions ("current drivers"). The 10 options analysed in-depth are used to assess additional potential ("additional drivers"). Depending on the option, these intervene at different points in the GHG emissions and material requirements in the vehicle life cycle. Accordingly, a direct comparison of the effects between the topic areas is not readily possible.

For this reason, we developed a detailed model in which the GHG and material effects of various options can be analysed in comparison to the baseline development. We do not consider all motorized transport in Germany, but concentrate on car transport, which is particularly relevant in terms of GHG emissions and resources (see chapter 2.2.2). In the calculation model, the car transport system in Germany in the period 2020/21 to 2045 is mapped in 5-year steps across all life cycle phases, taking into account and linking all relevant influencing factors. Status quo and trend developments of all influencing factors relevant to GHG emissions and material requirements are adopted from existing analyses or derived in addition. The effects of the analysed options on the various influencing factors can be recorded and the resulting changes compared to the trend development are determined directly in the model. Once the model results of several thematic fields are available, a comparison of the additional GHG and material savings potential between the thematic fields can be made and combinations can also be evaluated.

The AutoRess model methodology, key assumptions of relevant influencing factors and the model results for the baseline development of GHG emissions and material requirements are explained below. The GHG saving potentials and material effects of the individual technical options compared to the baseline are explained in the corresponding chapters.

3.1.2.1 Methodology and assumptions for baseline development

Table 5 provides an overview of important factors influencing GHG emissions and material requirements.

Figure 16 also illustrates how various factors interact over the vehicle's lifetime in terms of material requirements. The temporal interaction of new registrations, vehicle operation and disposal of End-of-life vehicles (ELVs) must also be taken into account in the analyses. Vehicles newly registered in a given year are only successively decommissioned in later years. Used parts and recycled materials available from vehicle recovery therefore correspond to different vehicle generations and thus material compositions than the vehicles newly produced in the same year. The chart also illustrates selected interactions with other areas. Only a limited proportion of the vehicles decommissioned are recycled in the same year. Many decommissioned cars are exported to other countries and continue to be used there, where they are disposed of at a later date. The use of secondary materials in the production of new vehicles should also not be considered in

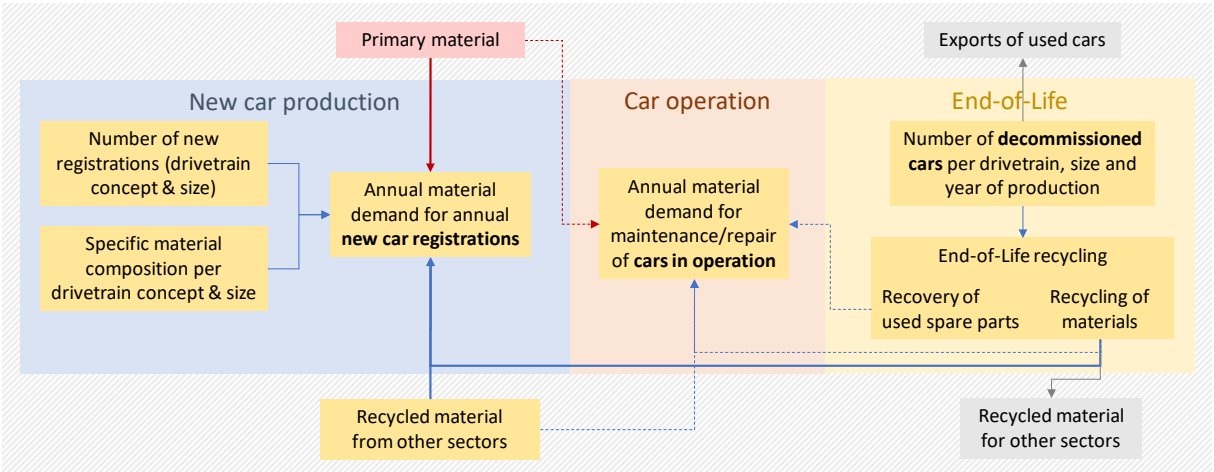
isolation for the transport sector, but rather in the interplay between the cross-sectoral recovery of materials and the material requirements of other sectors.

Table 5: Factors influencing GHG emissions and material effects in the vehicle life cycle

Car production	Car operating phase	End of life
• **Number** of new vehicles registered annually • **Size/weight** of new vehicles and installed components • **Material composition** of newly registered vehicles and their components • **Origin** of materials (primary, recycled content)	• Energy consumption by energy source in **operation** • Material requirements and energy consumption for **maintenance/repair**	• **Number** of decommissioned vehicles • **Recycling rate**: what proportion of decommissioned vehicles are recycled • **Recovery rates** of materials (of different **qualities**)

Source: own table Oeko-Institut / ifeu

Figure 16: Influence of various factors on the material requirements of cars in different life cycle phases



Source: own figure, ifeu

The main assumptions for the baseline development with current drivers are described below along the individual life cycle stages of new car production, car operating phase and car disposal.

New car production

The development of GHG emissions and material requirements in passenger car production depends not only on the number of cars produced annually with different drive concepts, but also on developments in the technical characteristics of new vehicles, in particular vehicle (and component) sizes and material composition. Furthermore, the year-specific production conditions (use of renewable energies) and the origin of the materials (recycled content) also determine the level of annual GHG emissions from vehicle production.

For passenger car traffic in Germany, the relevant number of cars produced annually is the **number of new car registrations**. We adopt these assumptions, differentiated by drive concept, from the With-Measures scenario of the Projection Report 2024 (Harthan et al. 2024) that was published during the course of the project. In the years 2025 and 2030, 3.1 to 3.2 million new passenger cars will be registered in each year, with the proportion of battery electric vehicles increasing continuously. After 2030, annual new registrations will fall to 2.8

million cars (2035) and 2.6 million cars (from 2040). From 2035, only BEVs will be newly registered (Figure 17, right).

Vehicle dimensions and weights as well as engine power have risen continuously over the past decades (see chapter 3.3). It can be assumed that this growth in size will continue in the coming years. For the initial situation, the AutoRess model is based on average vehicle weights per drive concept corresponding to the unladen weights of new passenger car registrations in 2021; these also take into account different sales shares of different market segments (e.g. diesel cars are on average significantly larger than petrol cars). Based on previous developments, the model assumes a further increase in weight of 1.2% per year up to 2030. A proportional increase is assumed for drive power. After 2030, the weights in the baseline remain constant.

Average percentage **material compositions** of the vehicle glider and powertrain are taken from LCA data sets in (Biemann et al. 2024) and remain constant in all years. Across all drive systems and size classes, a car consists primarily of steel and cast iron, followed by plastics and rubber, various other metals such as aluminium and copper and glass. Particularly relevant here are also raw materials that are required in batteries and are considered critical. According to the EU's definition, critical raw materials are those that are processed in economically relevant sectors on the one hand and whose supply is associated with risks on the other. The EU maintains a list of critical raw materials, which is updated every three years. Examples of critical raw materials used in electric cars include lithium, cobalt and graphite (Grohol, Veeh 2023).

Battery capacities of electric cars are taken from a recent LCA study (Biemann et al. 2024) for the base year and assumed to be 61 kWh (gross capacity) on average. Due to the current trend towards longer vehicle ranges, the average battery capacity will increase disproportionately to the increase in weight to 88 kWh (gross capacity) by 2030. At the same time, foreseeable changes in **battery configurations** (energy density, cell chemistry) are taken into account in the baseline. More details on battery development trends are given in chapter 3.2.

Specific GHG emissions of car production per vehicle component for today are also adopted from the recent LCA study (Biemann et al. 2024). These factors take into account both the energy mix in material provision and production processes as well as the current proportion of recycled content based on current LCA databases. In the future, the energy mix in Europe will increasingly switch to renewable energies, particularly for the provision of electricity in vehicle production processes. Accordingly, related GHG emission contributions in the baseline will fall in the coming years.

In an increasingly defossilised world, the provision of materials will also become increasingly low-GHG in the long term. Specific GHG emissions from car production in a fully defossilised world were examined in (Biemann et al. 2024). In terms of GHG emissions, the importance of resource-saving car production decreases in this case, as also shown in the scenario analysis in chapter 2.2.2. However, it is not possible to predict the emission reductions that can actually be achieved in the next 20 years due to the global supply of materials for car production. In the modelling of GHG savings potentials in AutoRess, the specific GHG emissions from material provision are therefore left constant in all years. This tends to lead to an overestimation of future emission contributions from the provision of materials. At the same time, it emphasizes the effects of material savings in the fields of action analysed in the event of only slowly progressing global defossilisation.

The use of recycled materials not only has an impact on GHG emissions in car production. The higher the **recycled content**, the fewer raw materials have to be extracted from nature. Today's recycled contents come mainly from the LCA database ecoinvent 3.8 (Wernet et al. 2016) for further details see Table 88 in the appendix). In the baseline developments, we assume no

significant change of recycled contents. Cell materials for batteries are an exception. Almost no recycled materials are used today. However, the new European battery regulation (European Parliament, Council of the European Union 2023) sets out requirements for the recycling of old batteries and for the recycled contents to be achieved in new batteries in the future. The baseline development is therefore also based on these legal requirements. Table 6 and Table 7 provide an overview of the recycled contents assumed in the baseline for the material groups investigated in AutoRess.

Table 6: Recycled content in selected materials the car glider and powertrain in the AutoRess baseline development (all years)

Steel & iron	Aluminium	Copper	Plastics	Glass
Flat steel: 10% Long steel: 26% Cast iron: 35%	Wrought aluminium: 30% Cast aluminium: 74%	19%	2.5%	0%

Source: based on several ecoinvent processes (Wernet et al. 2016), further details in appendix Table 88

Table 7: Recycled content in the battery cells in the AutoRess baseline development

	Lithium	Nickel	Cobalt
2021	0%	0%	0%
2030	6%	6%	16%
2035+	12%	15%	26%

Source: (European Parliament, Council of the European Union 2023)

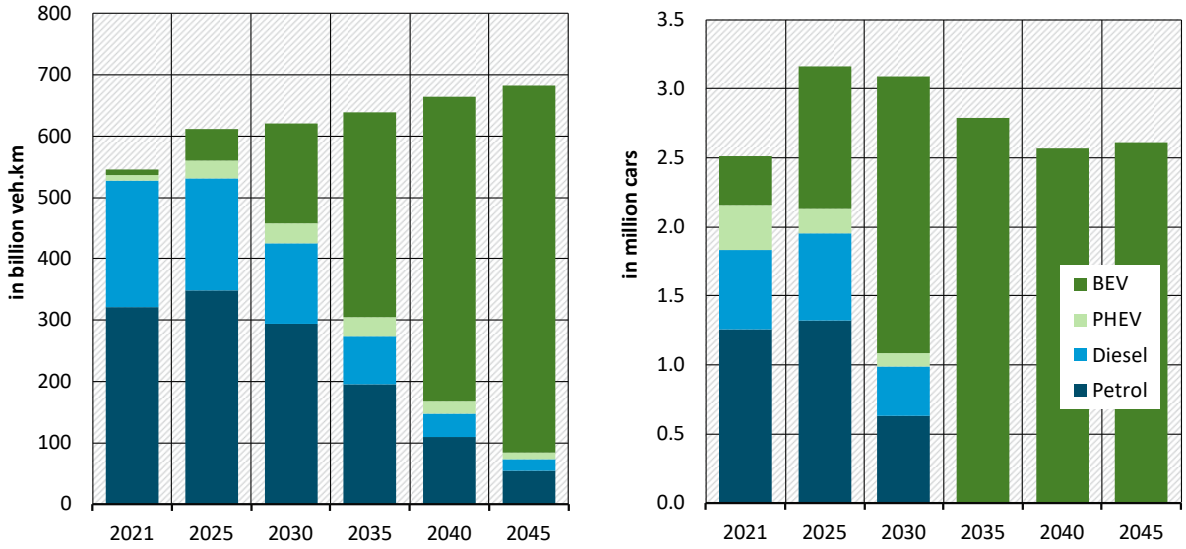
Car operation, maintenance and repair

The use phase covers energy consumption and the resulting GHG emissions during car operation on the one hand, and emissions and material requirements during car maintenance and repair on the other.

Model input data for car operation are the total mileage of passenger car traffic, the mileage shares of individual drive concepts (fleet composition), average specific energy consumption in the fleet and GHG factors of the energy sources used (fuels, electricity). In the baseline development in AutoRess, all consumption-relevant model input data and the direct emission factors of the fuels (tank-to-wheel), taking into account the shares of renewable energy sources, are taken from the with-measures scenario of the 2024 projection report (Harthan et al. 2024). Supplementary factors for the upstream emissions of fuels (well-to-tank) are taken from the TREMOD model (Allekotte et al. 2024).

Figure 17 (left) shows the baseline development of car mileage in Germany by drive concepts. From 2021 to 2030, car mileage increases by 14%, the mileage share of battery electric cars increases to 26%. Even after 2030, car mileage continues to rise steadily and is 10% higher in 2045 than in 2030. Battery electric cars have a mileage share of 88% in 2045.

Figure 17: Annual mileage (left) and new registrations (right) of cars in Germany by drive concept



Source: based on the "with existing measures scenario" (MMS) of the 2024 Projection Report (Harthan et al. 2024)

Emissions and material requirements for the maintenance and repair of cars are also part of the modelling in the car operation. Overall, the available findings show that the relevance is very low compared to other life cycle stages, which is also reflected in the very limited data availability.

Current mileage-dependent GHG factors are taken from ecoinvent (Wernet et al. 2016). Analogous to car production, the baseline development assumes decreasing emission contributions from the increasingly decarbonized energy supply. The specific emission contributions of material supply for spare parts remain unchanged or increase slightly due to increasing vehicle sizes.

Mileage-specific material demand for car repair is only available for steel and copper. No reliable information could be found for other materials. However, with the available information, car repair contributes only 2% to annual steel consumption and 1-2% to annual copper consumption in Germany's car transport sector (see Figure 20 and Figure 22 in the baseline development results). Overall, it can therefore be assumed that the repair phase is of very little relevance to the overall material requirements.

End-of-Life: reuse and recycling

Input parameters required for modelling the GHG emissions from vehicle disposal and the recovery of recycled materials for the production of new passenger cars include:

- The number of decommissioned cars and their material composition, which are processed in the recycling plants.
- The recovery of functioning used parts that reduce the need for new spare parts. In addition to reuse within the vehicle sector, the reuse of batteries in other sectors (mainly as stationary storage units) must also be taken into account. This reuse or repurpose of vehicle parts simultaneously reduces the amount of recoverable materials for the production of new cars.
- The recovery of materials in the subsequent recycling processes, as well as what proportion of them is of suitable quality (e.g. low impurities) for the production of new vehicles.

The number of cars decommissioned in Germany is not suitable as an input variable for the number of recycled cars whose recovered materials can be used in the production of new cars. A significant proportion of these will continue to be used as second-hand cars in other countries. In addition, in a European recycling market, materials recovered in other EU countries can also be used to produce new cars for the German market. The AutoRess model contains basic data from 2019 onwards. For all new passenger cars registered from 2019 onwards, the annual decommissioning is derived using the survival functions stored in the model. These correspond to the assumptions in the impact assessment of the European ELV directive (European Commission 2023a). On this basis, a material composition of the passenger cars decommissioned in a year is also derived automatically in the model. In addition, the model assumes a total number of annually decommissioned cars available for recycling, which is derived from the ratio of new car registrations to decommissioned cars in the EU. It amounts to 2.5-2.8 million cars per year. For the difference between the total number of decommissioning and the decommissioning of cars from model year 2019, the model assumes a simplified mix of petrol and diesel cars in line with the current composition of the vehicle stock. In 2019, only cars built before 2019 are decommissioned. Their share falls to around 40% by 2035, and in 2040 only 1% of the total number of decommissioned cars are built before 2019.

The majority of decommissioned cars in the EU end up in a regular recycling plant. At the same time, used cars are also exported from the EU, and there is also a significant proportion of decommissioned cars with unknown whereabouts. Based on the impact assessment of the ELV Directive, the model assumes that in all years 65% of the decommissioned petrol and diesel cars, but 90% of the decommissioned electric cars in a given year are recycled in the recycling plants. The other model input parameters relevant for vehicle recycling are also adopted from the ELV Impact Assessment (European Commission 2023a). In the baseline development, they remain unchanged in all years. Table 8 provides an overview of material-specific reuse rates, recovered recyclate shares and the shares of materials contained therein that can be directly reused in new car production.

We have derived our own assumptions for batteries. At present, almost no electric cars are recycled. The model assumes that 10% of the installed battery capacity of all disposed electric cars will be reused in 2030 and 30% from 2035. Around two thirds in stationary applications and one third in the repair or refurbishment of used cars. Recycling has not yet been established for battery materials. The EU Battery Regulation (European Parliament, Council of the European Union 2023) sets target values for the recovery of cell materials, which we also assume in the AutoRess baseline development. We also assume that, as a result of the targeted development of recycling processes, the recovered cell materials will be fully usable in the new production of vehicle batteries. Table 9 provides an overview of model baseline assumptions for battery recycling.

Table 8: Model baseline assumptions for recycling of glider and powertrain materials

	Steel & iron	Aluminium	Copper	Plastics	Glass
ReUse rate	7%	7%	1%	4%	5%
Recycling efficiency	87%	80%	65%	17%	99%
Share of closed-loop suitable recycling material	2%	1%	5%	20%	0%

Source: (European Commission 2023a).

Table 9: Model baseline assumptions for recycling of battery cell materials

	Lithium	Nickel	Cobalt
ReUse rate		2030: 10% 2035+: 30%	
Recycling efficiency	2025: 50% 2030+: 80%	2025: 90% 2030+: 95%	2025: 90% 2030+: 95%
Share of closed-loop suitable recycling material		100%	

Source: (European Parliament, Council of the European Union 2023), own assumptions

Vehicle disposal accounts for less than 1% of total GHG emissions across all stages of a car's life cycle. Specific GHG emission factors for vehicle disposal are taken from (Biemann et al. 2024).

3.1.2.2 Baseline developments of GHG emissions and material requirements of car transport in Germany

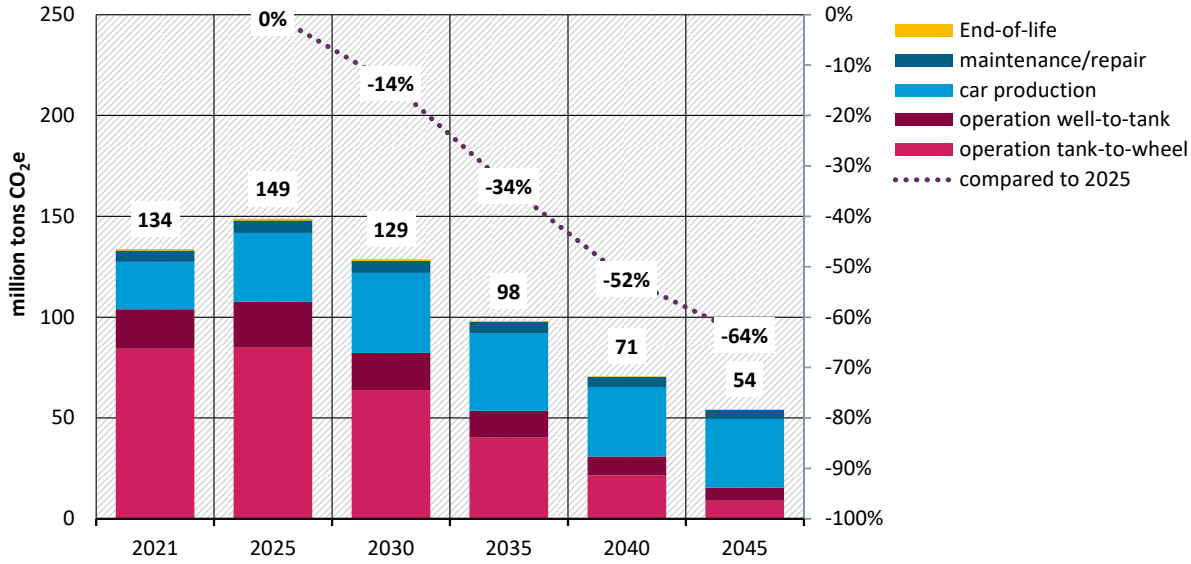
GHG emissions

In the baseline development without additional drivers, GHG emissions from car transport in Germany will only fall by 4% from 134 million tons to 129 million tons by 2030, but by almost 60% to 45 million tons by 2045 (Figure 18). The decisive factor here is the emission savings in the vehicle operation. Direct GHG emissions (tank-to-wheel) will fall from 84 million tons of CO_2e in 2021 to 9 million tons, and upstream emissions from fuels and electricity (well-to-tank) will also fall from 20 million tons to 6 million tons. The main factors influencing this development are the increase in electromobility and the decarbonization of the electricity supply.

By contrast, emissions from car production will initially rise from 24 million tons of CO_2e to 40 million tons of CO_2e between 2021 and 2030, before falling again to 34 million tons of CO_2e by 2045. Various factors are responsible for this development. The increase in emissions up to 2030 results equally from the higher annual number of new registrations and the increasing proportion of new registrations of electric cars with higher specific GHG emissions during production. From 2030 to 2035, the number of new electric car registrations per year will initially continue to rise up to 100% new registration share. After 2035, the number of new car registrations will fall. At the same time, the specific emissions from car production will fall after 2030 as renewable energies are increasingly used in the production processes. As described in chapter 3.1.2.1, in an increasingly defossilised world, the provision of materials will also become increasingly low in greenhouse gases in the long term. However, it is not possible to predict the emission reductions that can actually be achieved in the next 20 years due to the global supply of materials for car production. In AutoRess, the specific GHG emissions from material provision are therefore left constant in all years leading to an overestimation of future emission contributions from the provision of materials. As a result of these model assumptions, the share of vehicle production in total annual emissions from passenger car traffic will increase from 18% in 2021 to 31% by 2030 and to 63% by 2045.

The annual GHG emissions from vehicle repair and disposal also fall by 2045, with the share of vehicle repair in total emissions from passenger car traffic rising from 4% to 8%. As with vehicle production, the model also depicts the conversion of energy consumption to renewable energy sources, but not the possible long-term defossilisation of material supply processes. Assuming complete defossilisation of the global supply of materials, manufacturing emissions would also be more than 90% lower than today (see (Biemann et al. 2024)).

Figure 18: GHG emissions of car transport in Germany including all phases of the life cycle



Source: own calculations, ifeu

Material demand for new cars and recycled content

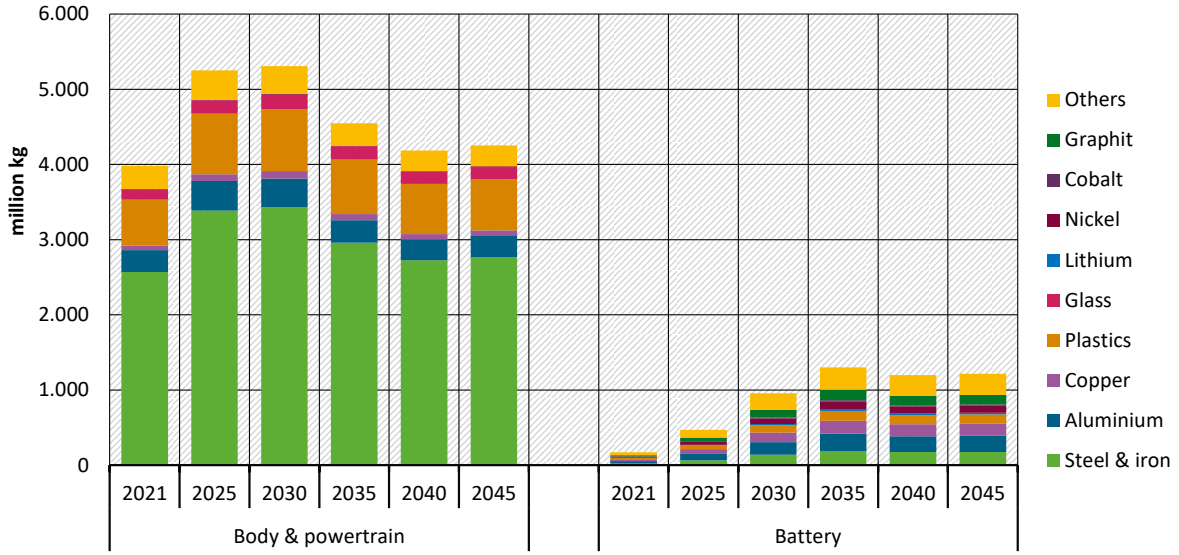
For the material groups selected in the AutoRess project, we use the model to evaluate the total annual material requirements in passenger car transport and the quantities of primary materials required and recycled contents achieved in vehicle production.

Figure 19 shows the total annual material requirements in car production by material group and differentiated between glider & powertrain and batteries. The overall development of material requirements for glider & powertrain is mainly driven by the total number of new car registrations. In addition, the assumptions of further increases in vehicle weights contribute to the rising material requirements up to 2030. The shift in new registrations towards electric cars (100% share of new registrations from 2035) is mainly reflected in the sharp increase in material requirements for batteries. The share of batteries in the total annual material requirements of new cars will rise from 4% in 2021 to 22% from 2035.

Material requirements for gliders and powertrains are dominated by steel and iron as well as aluminium and plastics. Together, these account for approx. 88% by weight. Other weight-relevant material groups are copper and glass. Steel, aluminium and plastics together also account for 42% of material requirements in batteries (mainly in the battery housing). Copper, nickel and graphite also have significant shares of 8-14% each. In contrast, the cell materials lithium and cobalt[7] are barely visible in the overall material balance, each accounting for 1-3% by weight.

[7] The battery cell material manganese is not considered individually in AutoRess; its material requirements in car production are proportional to cobalt.

Figure 19: Annual material demand for new passenger cars in Germany



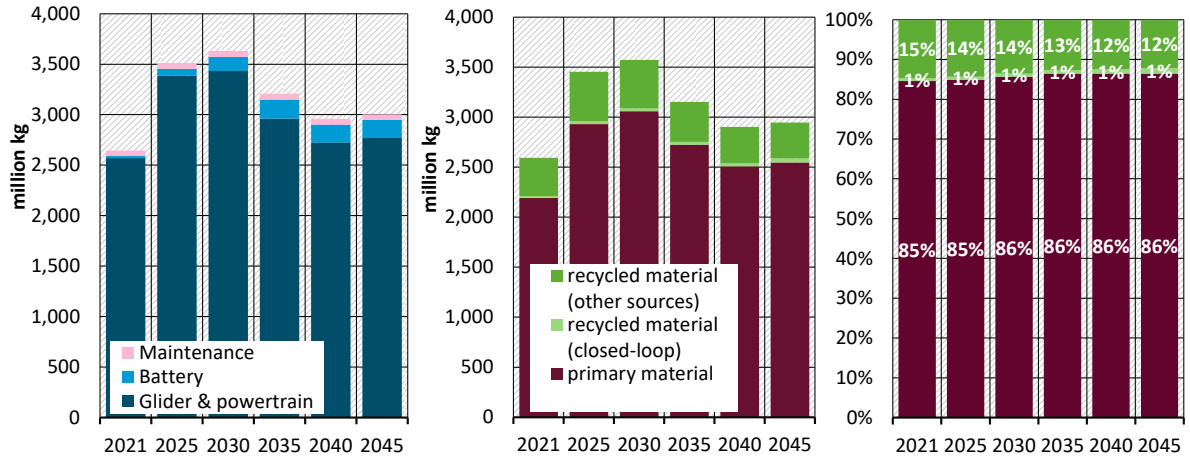
Source: own calculations, ifeu

Figure 20 to Figure 28 show the development of annual material requirements for selected individual material groups by vehicle component (left) and by material origin (center) and the proportion of recycled materials (right) achieved in the baseline development.

There are major differences between the material groups in terms of the proportionate material requirements for the body and powertrain or battery. The recycled contents and what proportion of these can come from closed-loop recycling, i.e. from the annual recovery of materials from decommissioned cars in the European Union derived in the model, also differ greatly in the material groups. In the case of the bulk metals under consideration, larger proportions of recycled contents are already being achieved today. These come almost exclusively from recycling processes from other sectors or regions and hardly change in the baseline development with current drivers. In the case of plastics and glass, almost no recycled materials are used today or will be used in the future without additional regulation.

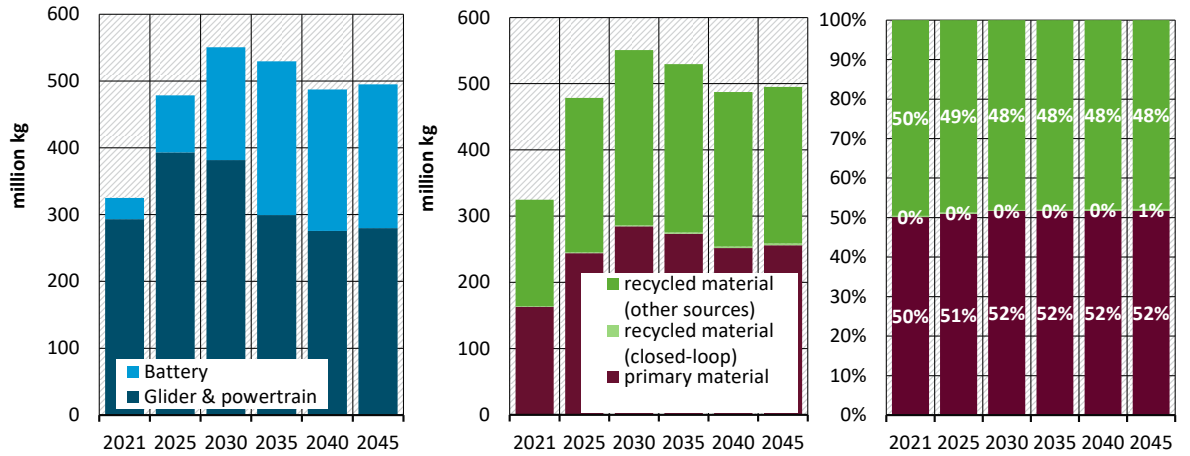
No recycled material is currently available for battery cell materials like lithium, cobalt or nickel. In the future, the availability of recycled material for cathode materials will increase in basic development. The reasons for this are, on the one hand, the increasing number of decommissioned electric cars and, on the other, the legal requirements of the EU battery regulation (European Parliament, Council of the European Union 2023) on battery recycling and the use of recycled content in new vehicle batteries. In the baseline development with current drivers, the requirements for recycled content in new batteries can only be met from 2040 onwards from the closed-loop recycling of electric cars recovered in the European Union. After 2045, the availability of recycled materials from end-of-life electric cars will continue to increase, as from 2035 onwards, only electric vehicles will be newly registered, which will be recycled after a time delay following their useful life. In the case of graphite, hardly any recycled content will be used in the baseline development until 2045 as there are no explicit legal requirements for graphite recycling.

Figure 20: Material demand for new passenger cars and recycled content – steel & iron



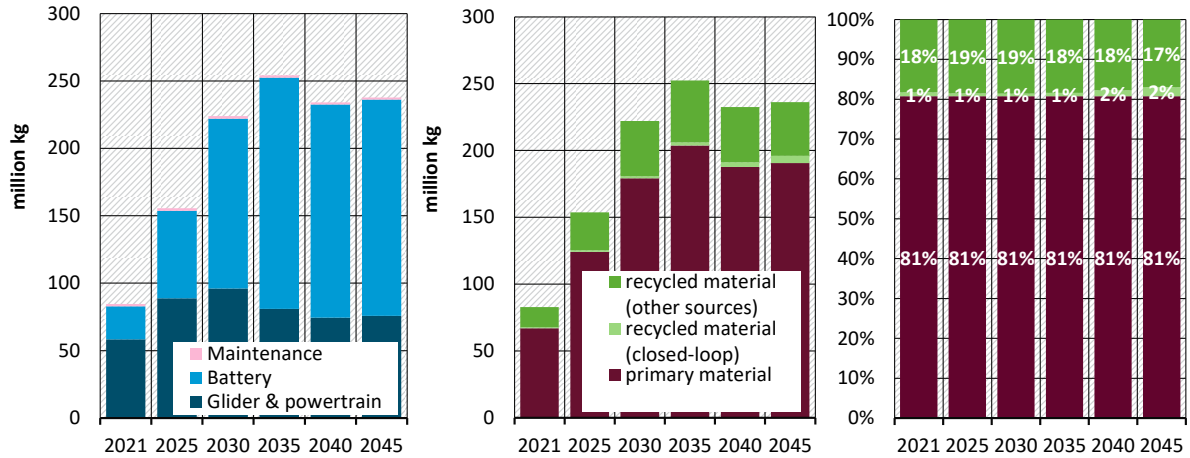
Source: own calculations, ifeu

Figure 21: Material demand for new passenger cars and recycled content – aluminium



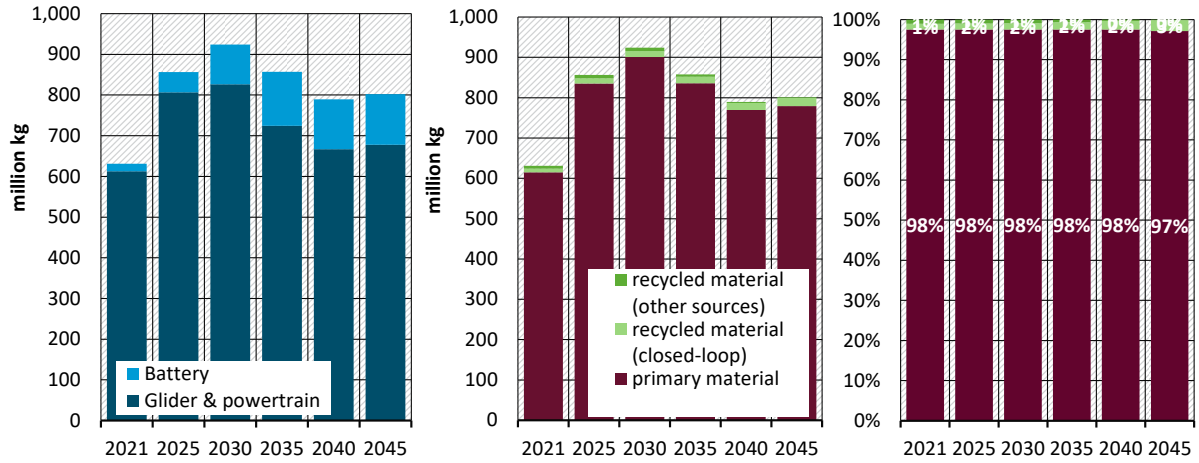
Source: own calculations, ifeu

Figure 22: Material demand for new passenger cars and recycled content – copper



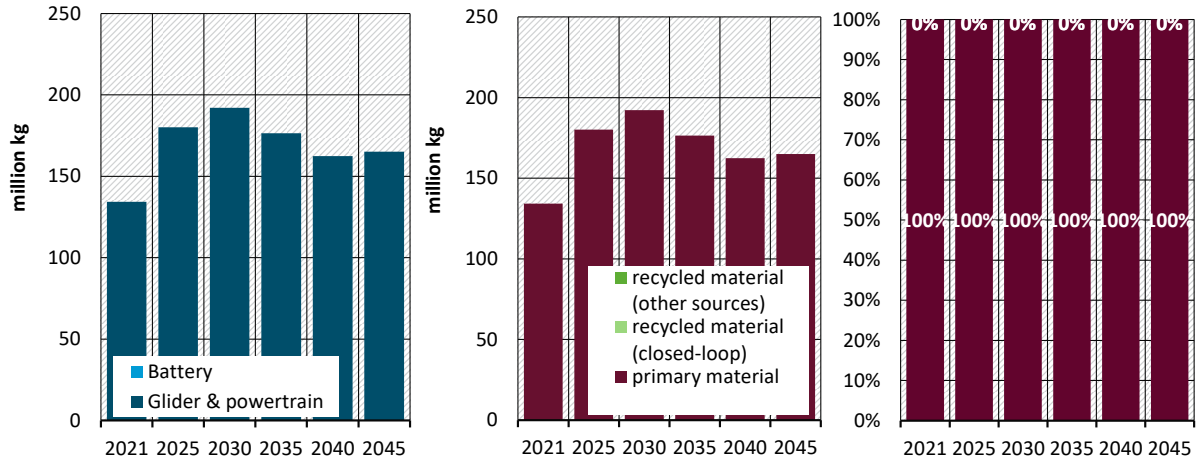
Source: own calculations, ifeu

Figure 23: Material demand for new passenger cars and recycled content – plastics



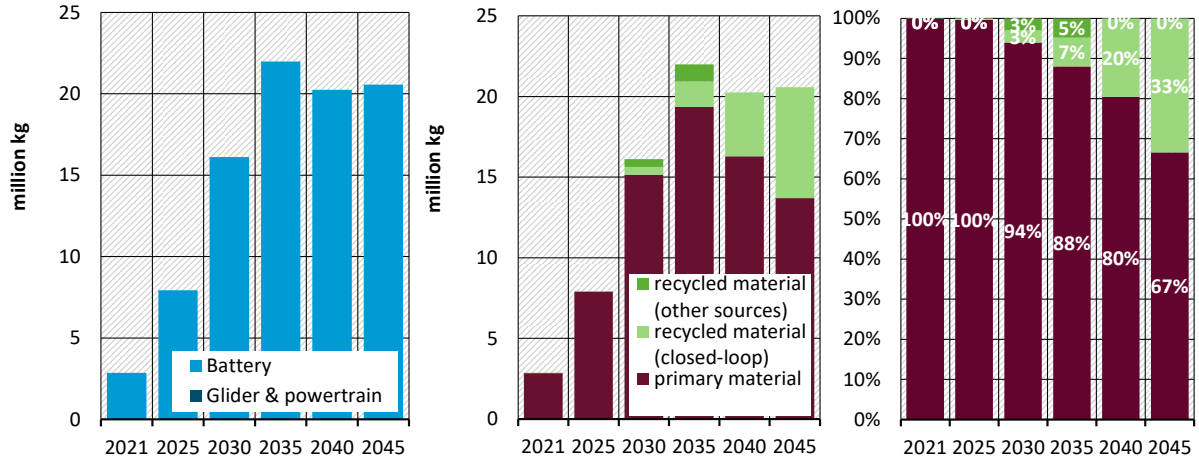
Source: own calculations, ifeu

Figure 24: Material demand for new passenger cars and recycled content – glass



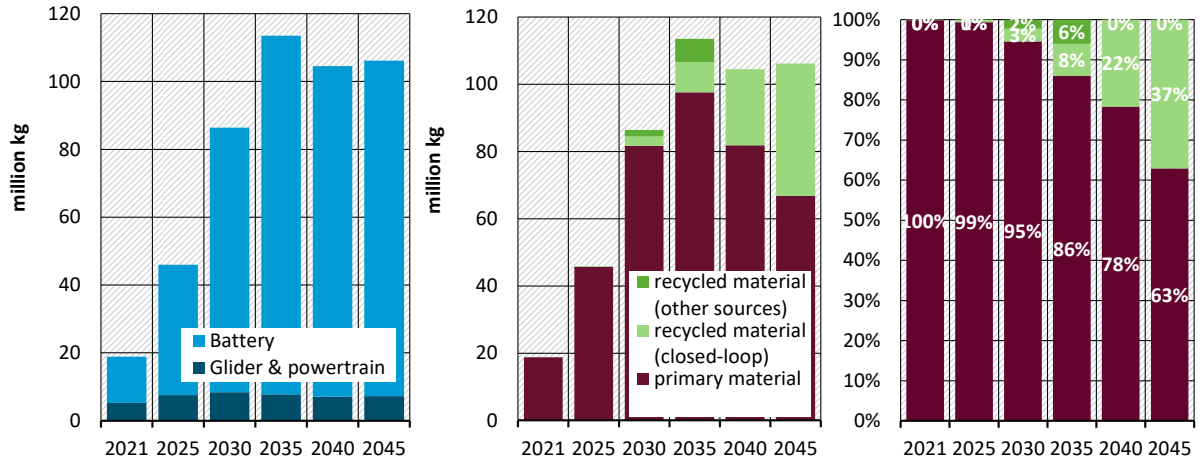
Source: own calculations, ifeu

Figure 25: Material demand for new passenger cars and recycled content – lithium



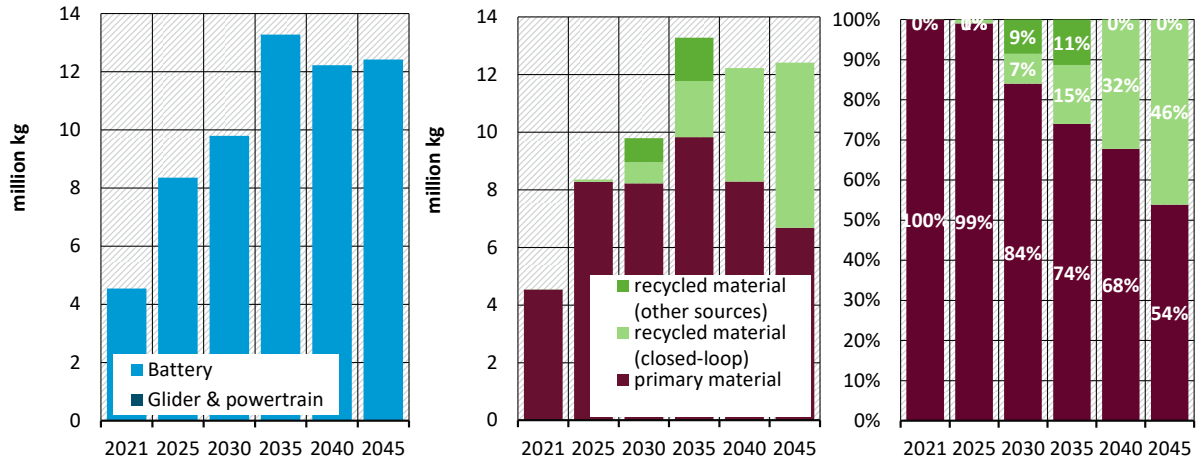
Source: own calculations, ifeu

Figure 26: Material demand for new passenger cars and recycled content – nickel



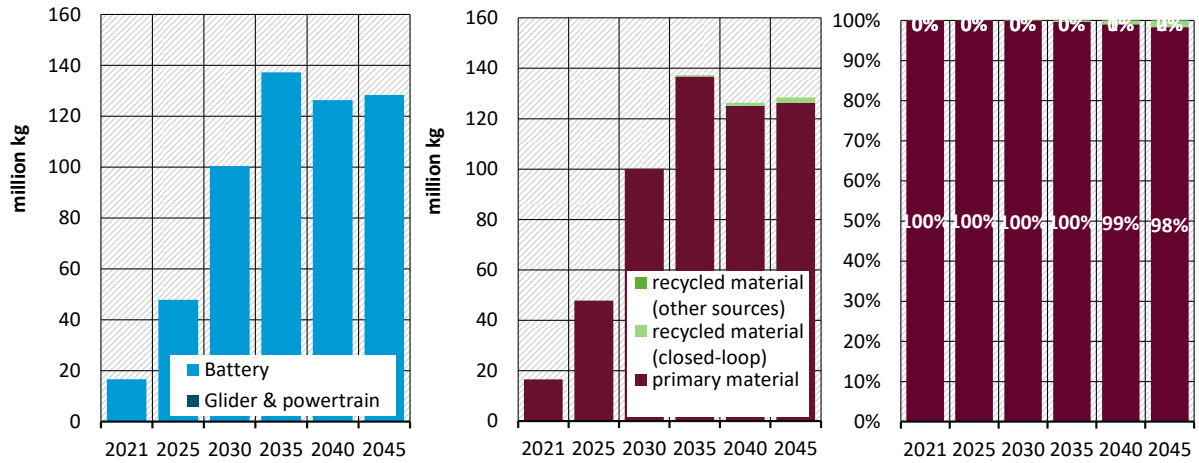
Source: own calculations, ifeu

Figure 27: Material demand for new passenger cars and recycled content – cobalt



Source: own calculations, ifeu

Figure 28: Material demand for new passenger cars and recycled content – graphite



Source: own calculations, ifeu

3.2 Alternative powertrains

3.2.1 Background

The switch to electromobility for passenger cars is a key lever for GHG reduction in transport. The direct use of electricity in electric vehicles has clear efficiency advantages over the use of electricity-based fuels in conventional combustion engines. Thus, in the with-measures scenario of the "Projektionsbericht 2024" (Harthan et al. 2024), only battery-electric passenger cars (BEV) are newly registered in Germany from 2035 onwards. However, energy savings and advantages in terms of GHG emissions in the use phase of electric cars are partly offset by additional emissions from vehicle production (e. g. due to the traction batteries), which also affect the raw material demand. Thus, this option focuses on the impact of different key parameters such as the range of the electric cars or the type of battery used and their impacts on GHG emissions and raw material demand.

The data for car production is largely based on the data collected in the UBA project "Analysis of the environmental impacts of vehicles with alternative powertrains or fuels on the way to greenhouse gas-neutral transport" (Biemann et al. 2024) with some adjustments. In addition to the GHG emissions from the production of conventional internal combustion engine (ICE) and electric cars, the (critical) raw materials used in the cars (or their components) are assessed.

The initial focus is on determining the differences in raw material demand as a result of the change from combustion engine cars to electric cars and the resulting changes in GHG emissions during vehicle use and production. Vehicle recycling (including battery recycling) and the use of recycled materials in production, as well as light-weighting or downsizing are analysed in other subject areas. Similarly, vehicle repair and maintenance are not explicitly considered here.

3.2.2 Status quo

Main characteristics of cars today

Characteristics of average newly registered cars were extracted from the KBA data on new vehicle registrations in 2021 and are shown in Table 10.

Table 10: Main characteristics of the average newly registered car in Germany 2021

	Empty weight (t)	Motor size (kW)	Usable battery size (kWh)	Real range (km)
Petrol	1.409	121	-	n. a.
Diesel	1.936	120	-	n. a.
PHEV Petrol	1.920	128	-	n. a.
BEV	1.831	82	55	330 km

Source: own calculations based on KBA FZ 14 (KBA 2024))

Range of electric cars

Own calculations based on data from the with-measures scenario from the German projection report 2024 (Harthan et al. 2024) lead to an energy consumption for the average electric car (including charging losses) of 0.70 MJ/km in 2021 - this corresponds to 19.4 kWh per 100 km. This consumption increases to 0.81 MJ/km (or 22.5 kWh/ 100 km) by 2030. Thereafter, energy consumption remains almost constant over the years and stabilizes at 0.80 MJ/km by 2045. Possible drivers for increasing vehicle consumption could be increasing vehicle weights (caused, among other things, by the growing vehicle size and larger traction batteries) as well as changes

in user behaviour (e.g. increased use of electric cars on longer motorway journeys or for towing a trailer, etc.) if they replace the previous combustion engine cars in widespread use.

The described energy consumption data fits relatively well the data from the Handbook for Emission Factors (HBEFA 4.2) (Notter et al. 2022), where an average consumption of 19.5 kWh (plus 14% charging losses) is given, although in reality today's electric cars are often driven more economically. A study for the Federal Environment Agency (Helms et al. 2023) arrives at an average consumption of 18 kWh/100 km for electric cars, which corresponds to the average WLTP consumption plus 15%. The slightly lower energy consumption compared to HBEFA 4.2 is due to slightly different traffic situations and lower loads of electric cars. However, the study (Helms et al. 2023) also shows that the range of values is very wide, as high additional energy consumption can occur, particularly due to auxiliaries such as heating or cooling, depending on the ambient conditions.

One driver in the consumption of an electric car is the weight of the traction batteries, which, in addition to the battery type and its characteristics, depends largely on the vehicle range (and thus the installed battery capacity).

Table 11 shows an analysis of battery capacities in electric car models on the German market. It gives the average battery size of a compact class car newly registered in Germany, which increases significantly over the years. Some car models have different battery sizes; however, the KBA new registrations data only shows the vehicle model (but not explicitly the battery size). Therefore, two values are given here: a minimum and a maximum value.

Table 11: Development of battery sizes in electric cars (compact class) in Germany since 2020

	Battery capacity ø (min)	Battery capacity ø (max)	WLTP range ø	Real range ø
NZL 2020	38.1 kWh	52.1 kWh	k. A.	-
NZL 2021	42.9 kWh	68.5 kWh	k. A.	-
NZL 2022	52.8 kWh	70.6 kWh	400 to 500 km	300 to 400 km
NZL 2023*	58 kWh	77 kWh	450 to 600 km	400 to 500 km

* Complete data for the new registrations in the compact class segment by model name and environmental feature for 2023 are not yet available from the KBA; thus the battery sizes of the VW ID.3 as the most popular model is listed here
Source: own calculations based on KBA FZ 14 (KBA 2024) and (EV database 2024)

However, most newly registered electric cars in Germany are not compact cars, but SUVs. According to the KBA, 42.5% of newly registered electric cars in 2022 were SUVs. The top 10 newly registered models in 2023 had a battery capacity between 56 and 68 kWh, while the top 5 models in the SUV segment in 2023 had a battery capacity of 60 to 69 kWh.

These values differ only slightly from those of the compact class passenger cars, which is also due to the fact that the "SUV" segment is very diverse and there are many cars that resemble SUV-like compact class passenger cars.

In (Biemann et al. 2024) an average (usable) battery capacity of 55 kWh is assumed for the compact class car in 2020/2021, which corresponds to a real driving range of around 330 km. In addition, (Biemann et al. 2024) assumes that the usable battery size of electric cars will increase to 80 kWh[8] by 2030 (corresponding to a real driving range of around 420 km). These

[8] The installed battery size is 10% higher than the usable battery size to improve the battery liftime and performance.

assumptions are still plausible and are therefore kept. However, AutoRess assumes a linear increase in battery capacity between 2021 and 2030.

Since individual electric cars on the market already have significantly larger battery capacities of more than 100 kWh, it is conceivable that battery sizes and ranges will continue to increase after 2030. However, from a raw material and GHG perspective, it is desirable to limit the increase in battery sizes.

An analysis of the data in (EV database 2024) shows that there are significant differences between the battery capacity installed in BEV cars and the usable battery capacity. The range is relatively large at +4% to +14%, which is why +10% for the gross capacity compared to the net capacity of the traction batteries is assumed here (see also (Biemann et al. 2024)). For the smaller batteries of the Plug-in Hybrid or Hybrid cars (PHEV or HEV), however, higher differences of +30% (PHEV) or +50% (HEV) are expected. These differences between usable and installed capacity serve to extend the battery service life. It can therefore be assumed that the battery in a modern car will not need to be replaced during the car's life.

Battery types for electric cars today

Today, vehicles use almost exclusively lithium-ion batteries as the energy storage. Here, several different cell chemistries are on the market, the most relevant one today being the nickel-manganese-cobalt cell chemistry (NMC). Therefore, we will use this for our status quo assessment.

3.2.3 Foreseeable development trends

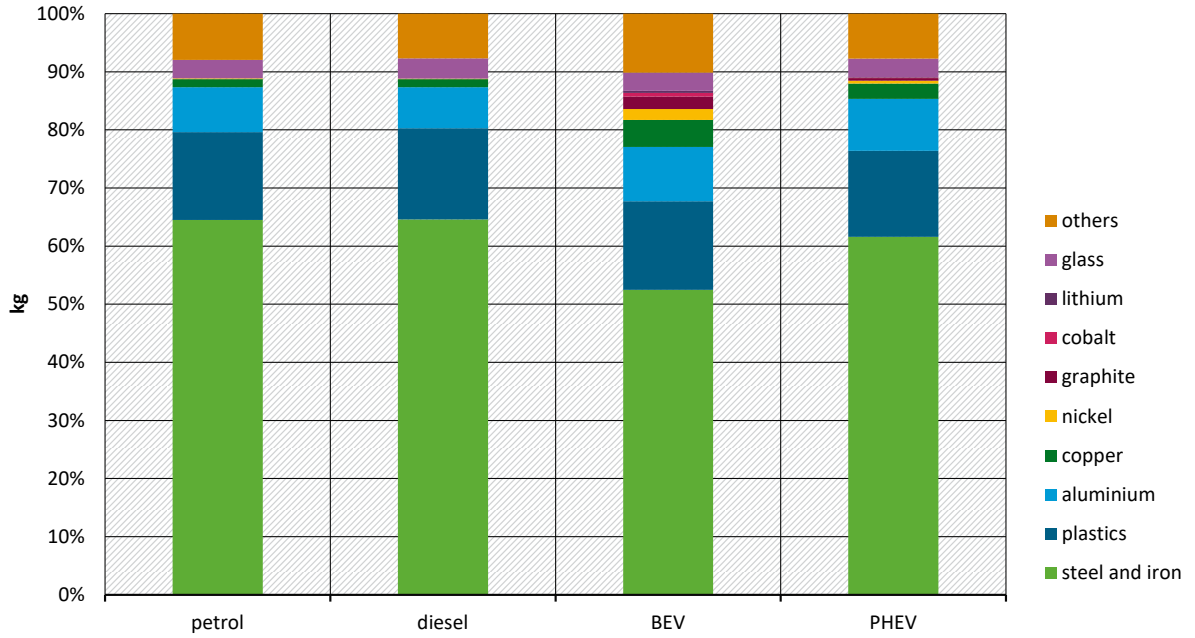
Developments for production of average cars in Germany and their impact on raw material demand and GHG emissions

In addition to the switch to electromobility, we assume an increase of the usable battery capacity to 80 kWh until 2030 (chapter 3.2.2). Afterwards, the battery size stays the same.

Here, impacts on GHG emissions and raw material demand from the production phase of the average cars due to a change in powertrain and car range are assessed.

Figure 29 provides an overview of the most important material groups in the average cars today.

Figure 29: Material groups in the average car (newly registered in 2021)

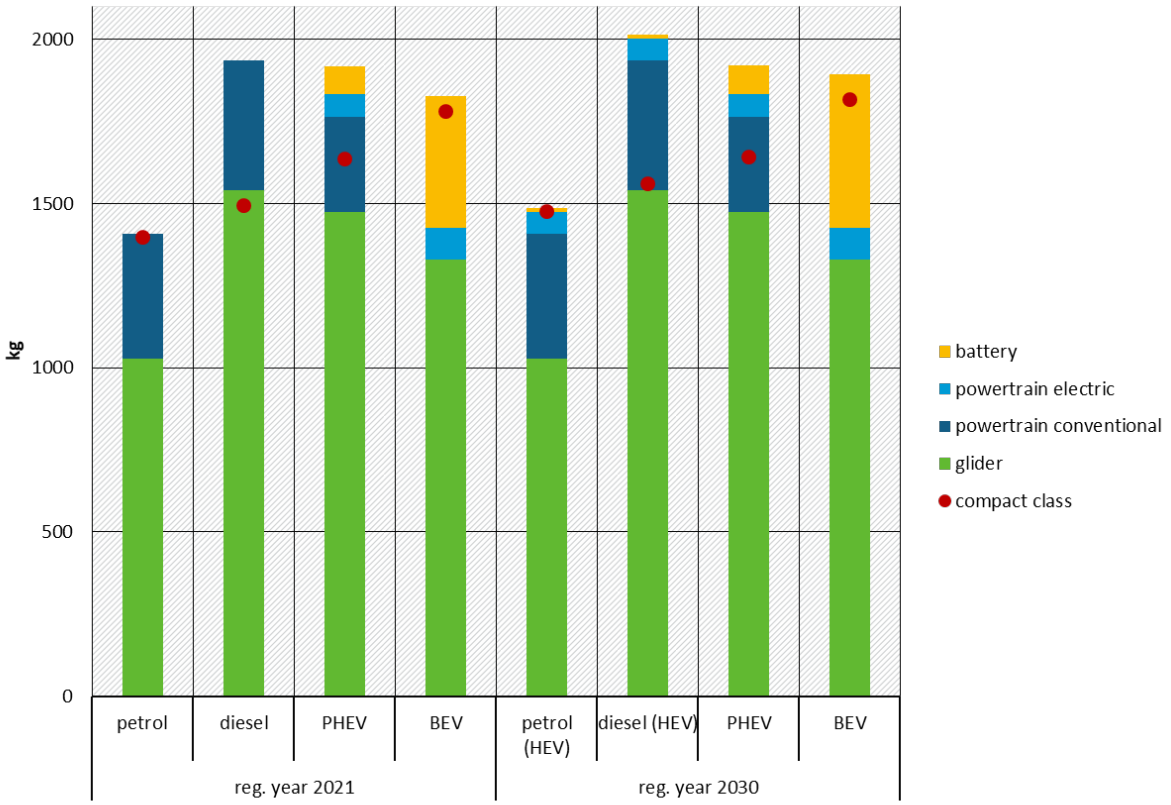


Source: own figure, Oeko Institute/ ifeu

The analysis shows that steel and iron dominate in terms of mass, followed by plastics. Aluminium and copper also have a relevant share of the raw materials in today's cars. Nickel is also contained in all vehicles, but in smaller quantities in combustion engine cars than in electric vehicles. BEV and PHEV cars also contain raw materials that are only found in traction batteries (graphite, cobalt and lithium). The "others" group contains a large number of raw materials (including platinum group metals and neodymium), which are used in smaller quantities in vehicles but not assessed in depth here.

The breakdown of car weights by component in Figure 30 shows that the overall weight of the vehicle is dominated by the glider. It can also be seen that the powertrain of the battery-electric car (BEV) is significantly lighter than that of the combustion engine car. Even in the compact class car segment diesel cars are on average heavier than petrol cars, that is even more true for the average car shown here. The plug-in hybrid electric car is also significantly heavier than the petrol car, which is only partly due to the additional powertrain. From 2030 onwards, we assume that all conventional combustion engine cars are full hybrids to reduce their fuel demand- this leads to an increase in vehicle weight due to the additional components.

Figure 30: Component weight of the average passenger car (newly registered in 2021 or 2030)



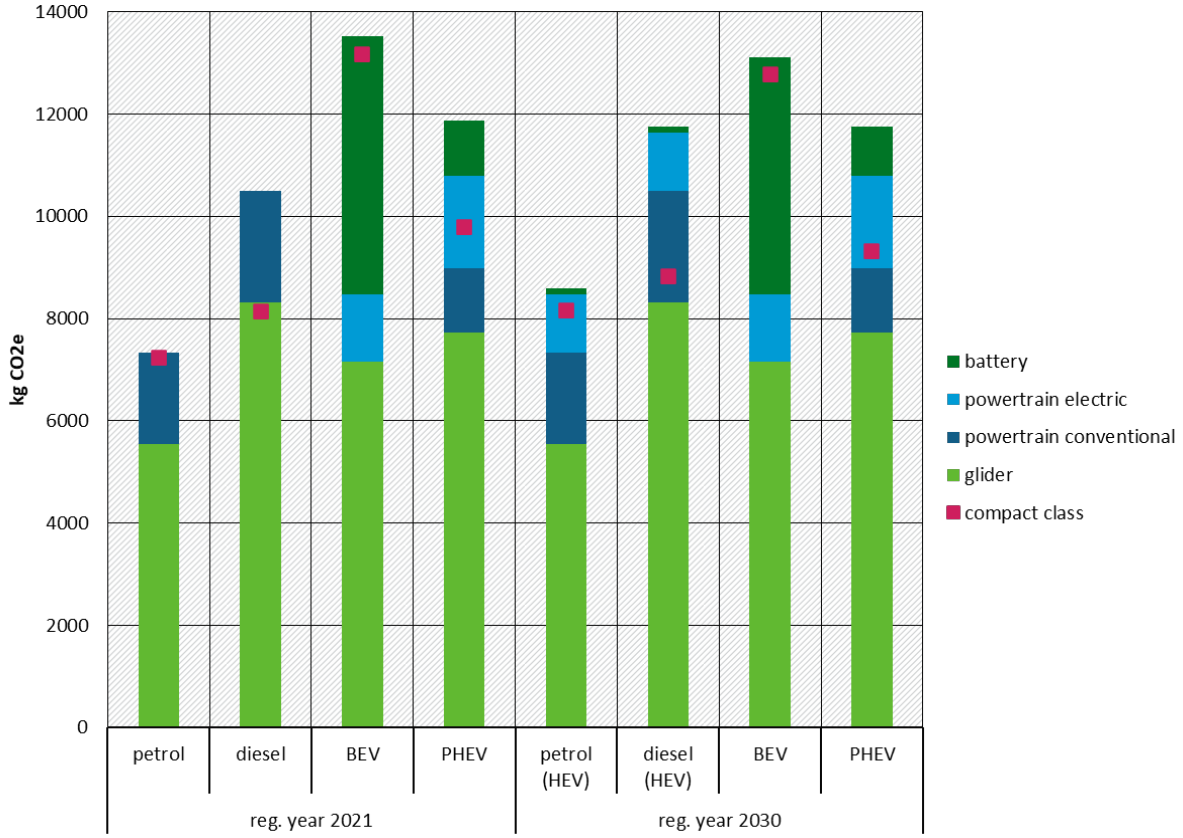
Source: own figure, Oeko Institute/ ifeu

Note: Across all new registrations, the average new diesel car in 2021 had a higher kerb weight than a new BEV car. Within the compact class car segment, BEVs are heavier than diesel cars. However, the heavier purchase segments account for a disproportionate share of new diesel cars compared to battery electric cars.

Figure 30 also shows the average weight of a compact class car in Germany in 2021. It can be observed that the average petrol and battery-electric cars are relatively close to the compact class cars, while PHEV and diesel cars are significantly heavier.

The GHG emissions of manufacturing of cars in Figure 31 behave similarly to weights - with the exception of the BEV car, where the battery results in significantly higher emissions. It is also striking that the powertrain of the BEV car has only a slightly lower global warming potential than the internal combustion engine powertrain, despite its lower weight.

Figure 31: GHG emissions (GWP 100a) of the production of the average car (newly registered in 2021/ 2030)



Source: own figure Oeko Institute/ ifeu based on (Biemann et al. 2024)

Note: The GHG emissions of the compact class car shown here differ slightly from those in the study (Biemann et al. 2024) as AutoRess uses a global instead of purely European aluminium supply.

Regardless of the powertrain, the vehicle glider accounts for the highest proportion of GHG emissions from manufacturing of today's passenger cars, followed by the powertrain (including exhaust gas treatment in the case of combustion engine cars). For electric cars, the GHG emissions from the production of the traction battery are also very relevant for the overall emissions. They depend on the battery size and the GHG emissions per kWh of battery capacity.

The influence of the vehicle size on GHG emissions from vehicle production is also clearly evident, with the emissions of average diesel and PHEV cars being significantly higher than those of average compact class cars with the same powertrain. This shows the relevance of downsizing in chapter 3.3.

The following developments are decisive for the development of GHG emissions from passenger car production up to 2030: Due to the hybridisation of conventional passenger cars, they will require an additional electric powertrain and a small battery in future, making production more complex and increasing the weight of the car (with the same vehicle configuration/equipment). In the case of electric cars, the larger battery (80 kWh instead of 55 kWh usable battery capacity) and the improved battery production and higher energy density roughly balance each other out. The battery, as a particularly GHG and raw material-relevant component, is analysed in more detail next.

Developments in the production of traction batteries and their impact on raw material demand and GHG emissions

A central component of every electric vehicle is the traction battery, which, as shown in the previous chapter, has a major influence on the GHG emissions of vehicle production and the raw material requirements. Various battery technologies and their raw materials/GHG emissions are therefore analysed in more detail here.

Each vehicle battery consists of the battery cell (including anode, cathode and electrolyte), cooling, battery management system and packaging. The battery cell is a major driver of the greenhouse gas emissions from batteries, as it needs high amounts of energy (electricity as well as heat). China, Korea, Japan and the US are currently the biggest cell producing countries. Another influencing factor is the energy density, since it directly corresponds to the amount of materials needed for the battery.

Concerning battery types, several battery technologies are currently being discussed as possible alternatives to the commonly used NMC lithium-ion batteries today, while the proportions of the different cell materials can vary. Some years ago, the NMC111 with a balanced ratio between nickel, manganese and cobalt used to be very common. Today, the composition is shifting towards higher nickel proportions and lower cobalt (and manganese) proportions. In this study, analogous to (Biemann et al. 2024) we assume NMC622 batteries with an energy density of 150 Wh/kg at system level for 2021. From 2030 on, NMC811 batteries with an energy density of 200 Wh/kg and improved cell production compared to 2021 are assumed (see also (Biemann et al. 2024)). These assumptions, which are conservative, are also retained in the baseline scenario for the years after 2030. The effects of further drivers in the area of battery development are analysed in the next step.

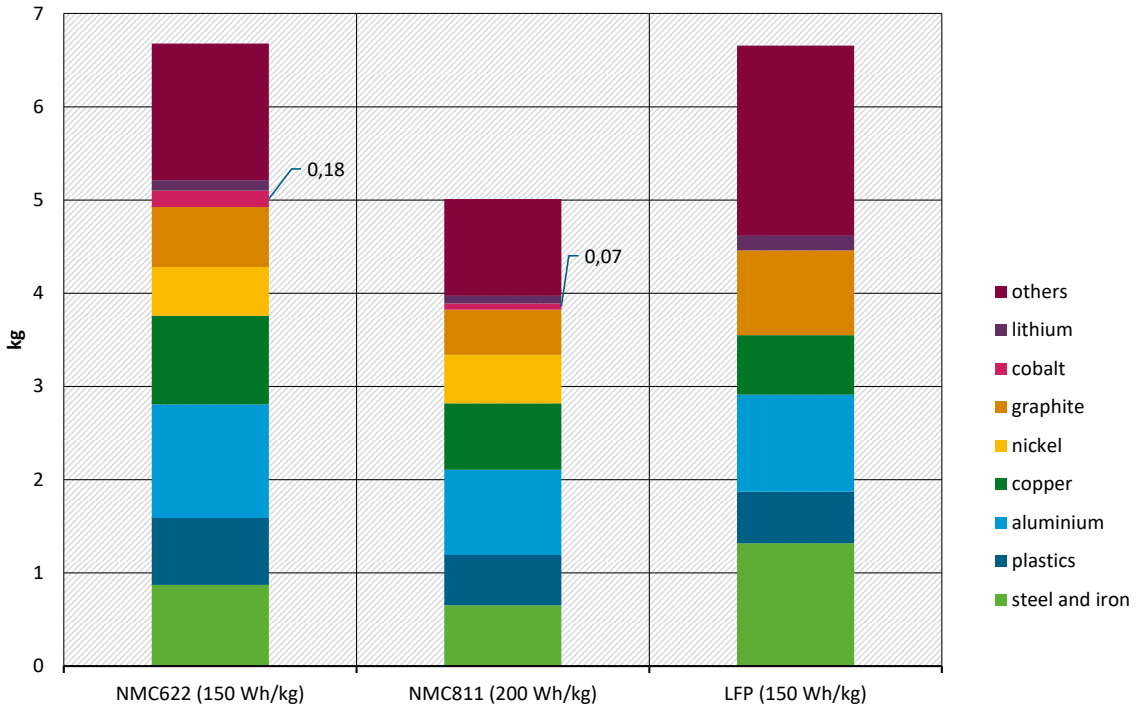
One emerging cell chemistry is the lithium iron phosphate (LFP) battery. The main advantage of the LFP battery is that it does not require nickel, cobalt or manganese. It can be cheaper, safer and more durable than the NMC battery (ENBW 2023), depending on the other components and the cell production. The current energy density of LFP batteries is lower than for NMC batteries with just 150 Wh/kg at system level. This increases the GHG emissions per kWh of installed battery capacity and the higher battery weight makes the vehicle heavier. However, efforts are being made to further increase the energy density of LFP batteries and thus decrease their weight.

Typically, LFP batteries are most often used in cheaper cars for the smaller car sizes where cost is most relevant. Thus, for AutoRess we assume that 18% of all electric cars receive a LFP battery from 2030 on- the rest use an NMC811 battery.

In the model (see also chapter 3.1), the battery weight is calculated from the usable battery capacity, the energy density of the battery at system level and the ratio of installed to usable capacity. For the battery in an electric car in 2021, with a usable capacity of 55 kWh and an energy density of 150 Wh/kg, the weight is around 400 kg. As the energy density of batteries has increased in recent years due to new battery technologies, this has limited the increase in weight due to the larger batteries. Thus, on average, the 80 kWh battery with either NMC811 or LFP only weighs 467 kg in 2030.

In Figure 32 we compare the raw material demand of the NMC622 battery with an energy density of 150 Wh/kg to the NMC811 with 200 Wh/kg and the LFP battery with an energy density of 150 Wh/kg.

Figure 32: Raw material demand of batteries per kWh (NMC622, NMC811 and LFP)

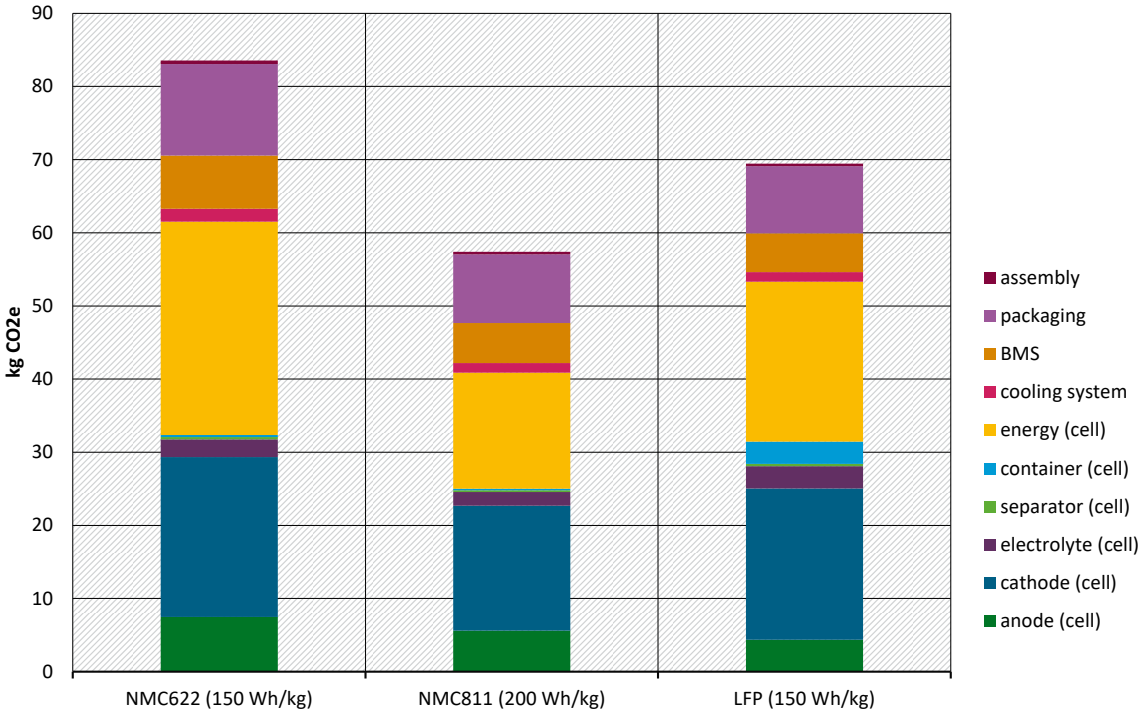


Source: own figure, Oeko Institute/ ifeu

There are two effects visible here: Due to the 25% higher energy density of the NMC811 battery, the battery weight is reduced and fewer raw materials, including critical ones such as lithium or graphite, are required. At the same time, the changes in cell chemistry lead to a significant reduction in the amount of cobalt from 0.18 kg per kWh battery for NMC622 to just 0.07 kg per kWh battery for NMC811, while the amount of nickel stagnates, as the higher energy density and the higher nickel content per kg battery balance each other out. The LFP battery contains neither cobalt nor nickel, but its lower energy density compared to the NMC811 leads to a higher demand of raw materials overall and a slightly increased lithium demand.

The improvements in energy density and the change in cell chemistry are also reflected in the GHG emissions from battery production shown in Figure 33. The change in cell chemistry leads to significantly lower contributions from the cathode for the NMC811 battery compared to the NMC622 battery and an overall decrease of the GHG emissions from 83.6 kg CO_2e per kWh for the NMC622 in 2021 to 57.4 kg CO_2e per kWh for the NMC811 in 2030. The LFP battery has higher emissions of 69.5 kg CO_2e per kWh due to its lower energy density.

Figure 33: GHG emissions of batteries in 2021 (status quo, NMC622) and 2030 (foreseeable developments, NMC811/ LFP) per kWh



Source: own Figure, Oeko Institute/ ifeu based on (Biemann et al. 2024) (with adaptions)
Note: GHG emissions for the NMC811 battery in 2030 differ from (Biemann et al. 2024) due to different assumptions regarding where cell manufacturing takes place (world mix in AutoRess vs. Europe-only)

However, another reason for the decrease of emissions in 2030 is the assumption that the energy required for cell manufacturing can be decreased and that cell manufacturing is at least partly shifted to Europe[9]; thus, the contributions of the energy requirements of cell production ("cell energy") are significantly lower. By using additional renewable energy to manufacture the battery cells in the future, this can be further improved in the future.

However, information from the expert meeting on batteries showed that Europe is currently struggling to achieve its plans for an increased cell manufacturing capacity. Therefore, we did not assume a complete shift of cell manufacturing to Europe for AutoRess.

3.2.4 Fields of action and issues

Possible range developments of electric cars

In the baseline, the usable battery size increases to 80 kWh by 2030 and remains constant afterwards. In addition, a further (linear) increase in battery size after 2030 to 100 kWh (V1: battery size max) or a decrease back to the 2021 battery size (V2: battery size min) is analysed. The maximum battery size is based on the assumption that ranges of electric cars will be roughly equal to those of combustion engine cars and continue to increase. The minimum scenario is based on the assumption that more cars with shorter ranges will enter the market, as fast-charging capacities are expanded to such an extent that a shorter range is marketable. The exact battery sizes for the two cases do not reflect a realistic development, but are merely intended to

[9] Cell manufacturing takes place in: China (20% in 2030 and 23% in 2030), US (42% in 2021 and 34% in 2030), South Korea (7% in 2021 and 5% in 2030), Japan (13% in 2021 and 10% in 2030) and EU27 (6% in 2021 and 25% in 2030) and Rest of World (3%).

illustrate the effects of a further increase in battery size following the current trend as well as a possible decrease of battery sizes as the more sustainable pathway. The battery size also influences the energy demand during the cars use phase (see also chapter 3.4.2 where an additional energy demand of +0.47 to +1.17 kWh/ 100 km and 100 kg extra weight is given). Here, we use an average increase in energy demand for the BEV of +0.6 kWh/ 100 km and 100 kg. As a side note: In this field only the battery itself is changed, but the basic car design stays the same (see chapter 3.3 for the effect of downsizing).

Emerging battery technologies

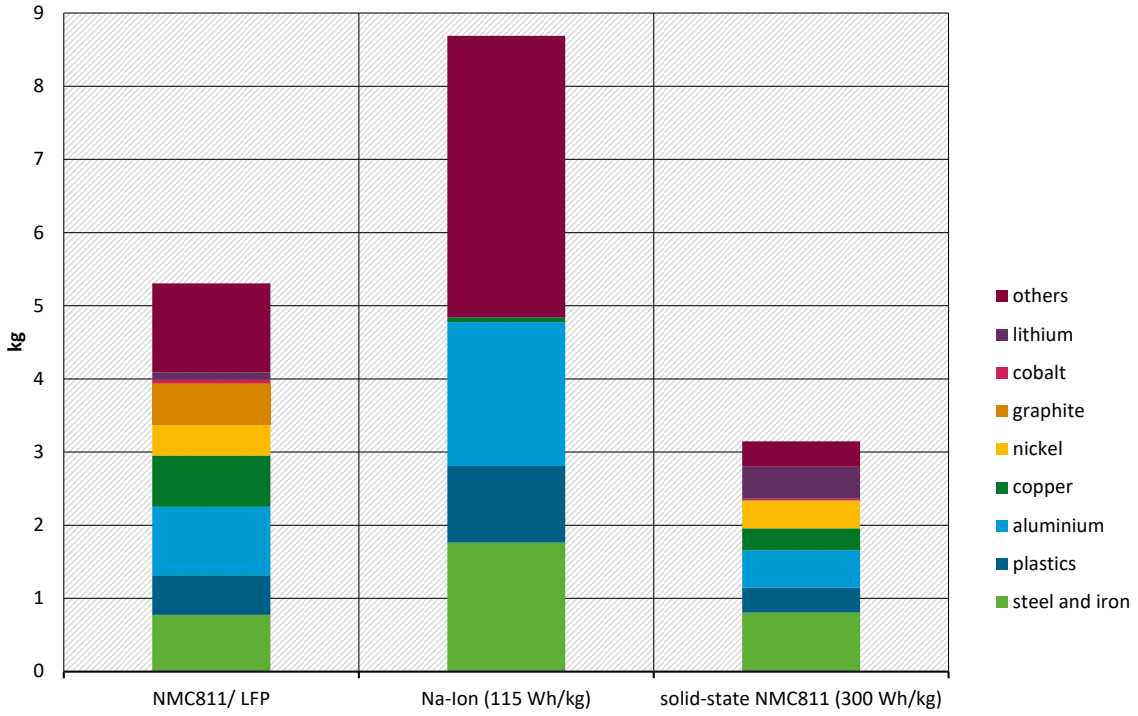
Solid-state NMC batteries are similar to current classical NMC batteries, but use a solid instead of a liquid electrolyte (in our case lithium phosphorus oxynitrite, LIPON). They have a lithium anode with a copper current collector and a NMC cathode with a nickel current collector (Lastoskie, Dai 2015; Schmaltz et al. 2022). Solid-state NMC811 batteries reduce the amount of cobalt/ nickel and most other materials due to their higher energy density, but at the cost of an increased amount of lithium being needed. The other battery components remain the same. The assessment for AutoRess is based on the life cycle inventory data derived by ifeu for the FVV study (FVV 2021). Common energy densities of solid-state NMC811 batteries are at 300 Wh/kg and thus higher than for the conventional NMC811 batteries. Using solid-state NMC811 batteries may reduce GHG emissions from battery manufacturing from 56.6 kg CO_2e/ kWh battery (mix of NMC811 and LFP) to 50.3 kg CO_2e/ kWh battery in 2030.

So far, sodium-ion (Na-Ion) batteries have mainly been used in stationary applications, but the first Chinese electric car with a Na-ion battery is already being produced (electrive 2024). Compared to other battery technologies, Na-ion batteries have the advantage that they do not contain lithium, but the more readily available raw material sodium. However, they still have significant disadvantages in terms of energy density compared to NMC batteries. According to (Wickerts et al. 2024) Na-ion batteries have an energy density of 160 Wh/kg at cell level - this corresponds to an energy density of 115 Wh/kg at system level, assuming that the mass of the cell in the battery system is 70%. (Wickerts et al. 2024) calculates GHG emissions of 86 kg CO_2e per kWh battery cell for the Na-ion battery under today's production conditions, which corresponds to GHG emissions of 107 kg CO_2e per kWh for the entire battery (using a similar periphery as for the NMC battery).

When switching to Na-ion batteries, GHG emissions from battery manufacturing may even increase to 86 kg CO_2e/ kWh battery in 2030 if no further improvements in battery design and manufacturing for Na-ion batteries are made. This leaves LFP batteries with 66 kg CO_2e/kWh as the less GHG emission intensive low-cost battery concept compared to Na-ion.

Looking at the raw material demand in Figure 34 shows why Na-ion batteries may still be interesting from a resource perspective. Currently used Na-ion batteries need neither cobalt, nickel or graphite nor lithium to function, but rather rely on very widely available materials. Only the amount of aluminium in the Na-ion battery is increased compared to the NMC811/ LFP mix.

Figure 34: Raw material demand of Na-Ion and solid-state NMC811 batteries in 2030 compared to a mix of NMC811/ LFP per kWh



Source: own figure, Oeko Institute/ ifeu

In addition to these emerging battery technologies which are already (partly) available on the market, other cell chemistries are also being researched and further developed. (Biemann et al. 2024) highlighted the **lithium-air** battery, as it has the theoretical potential to achieve extremely high energy densities of up to 1500 Wh/kg. By comparison, energy densities of maximum 500 Wh/kg are foreseen for conventional lithium metal batteries under ideal conditions. However, in the foreseeable future, achievable energy densities for Li-air batteries are at around 200 Wh/kg (i.e. in a similar range to the energy density of the NMC811 battery) (see also (Biemann et al. 2024)). However, information from the expert meeting on batteries showed that despite ongoing research efforts for Li-Air batteries, they still face considerable challenges concerning longevity and usability. Whether these challenges will be overcome and when (or if at all) they will enter the market is thus still unclear. As the focus today is on other, more established technologies, we have decided not to include Li-Air batteries in AutoRess.

3.2.5 Modelling

Modelling for alternative powertrains focuses on the cars use phase and car manufacturing. Energy demand of the electric cars is changed when considerable weight increases or decreases are observed. GHG emissions and raw material demand from battery manufacturing is also changed based on the findings from the previous subchapters. All other variables are kept the same, to better be able to compare the different options directly, thus no changes in the glider or powertrain are analysed.

We have assessed the impacts of 5 different variations which are as follows:

- Variation V1: minimum battery capacity (lower car ranges after 2030)

- Variation V2: maximum battery capacity (higher car ranges from 2030 onwards)
- Variation V3: LFP batteries (complete switch to LFP batteries from 2030 onwards)
- Variation V4: Na-Ion batteries (complete switch to Na-Ion batteries from 2030 onwards)
- Variation V5: solid-state batteries (complete switch to solid-state NMC 811 batteries from 2030 onwards)

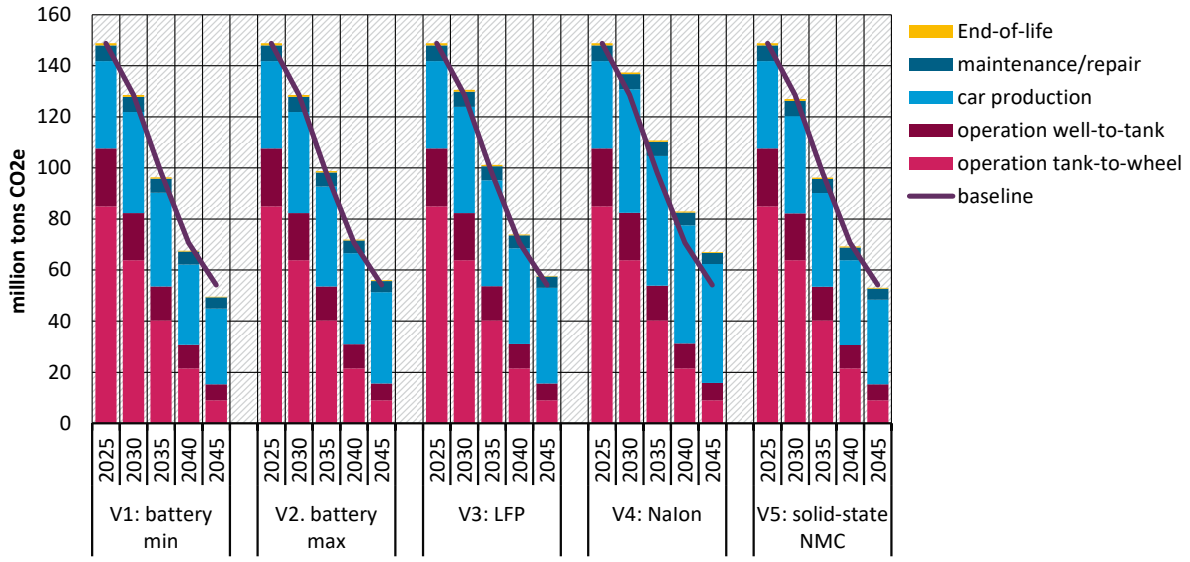
Further descriptions on these variations were already given in chapter 3.2.4.

3.2.6 Results

Comparison of GHG emissions

Looking at the GHG emissions for cars from all lifecycle phases shows only small differences between the variations and the baseline (see Figure 35). In this topic area, only battery production (as part of the car production) and operation were addressed. The predominance of conventional cars for the first scenarios years shows the limited impact of changes since the tank-to-wheel emissions still dominate the picture. From 2035 onwards only electric cars are newly registered and their impact on the car production but also their growing relevance for the well-to-wheel emissions become evident.

Figure 35: GHG emissions for cars for the different variations (alternative powertrains)

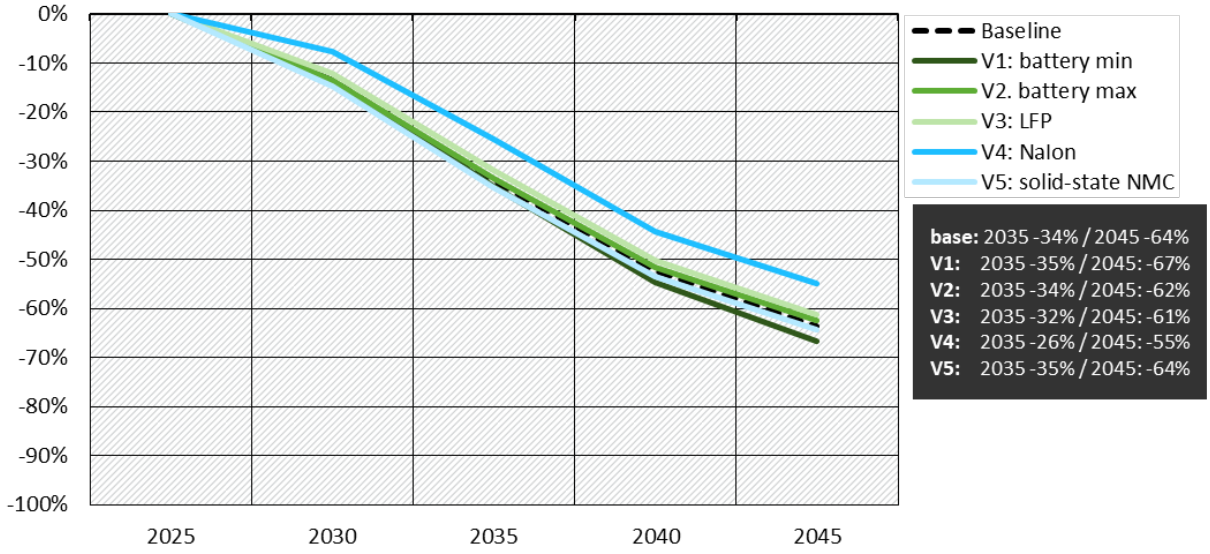


Source: own figure, Oeko Institute/ ifeu

A closer look at the differences between the variations and the baseline (see Figure 36) shows clearly the disadvantage of using only Na-ion (V4) batteries- due to their higher weight and higher GHG emissions per kWh battery capacity, car production as well as well-to-tank emissions are increased. Compared to the baseline, using only Na-ion batteries increases the GHG emissions in 2045 by +9%. However, it needs to be noted that this may not be an entirely fair comparison, since Na-ion batteries are a new concept and may be further improved in the future. LFP batteries (V3) also have slightly higher GHG emissions and weights compared to the baseline, but there are various efforts to improve them further. Solid-state NMC batteries (V5) have a lower weight and lower GHG emissions, leading to improvements in car production as well as well-to-tank GHG emissions compared to the baseline.

The impact of the battery size (V1: min and V2: max) is mainly relevant for the year 2045. The smaller battery (V1) has -3% GHG emissions compared to the baseline, while the large battery (V2) has +1% compared to the baseline. Limiting the battery size is thus more beneficial than switching to a different battery technology with a higher energy density and lower GHG emissions like solid-state NMC (V5) which only achieves a -1% difference to the baseline.

Figure 36: Change in GHG emissions for cars for the different variations compared to 2025 (alternative powertrains)



Source: own figure, Oeko Institute/ ifeu

A combination of V1 (minimum battery capacity) and V5 (solid-state NMC) can lead to even higher GHG emission reductions (not shown in the figure) compared to the baseline development.

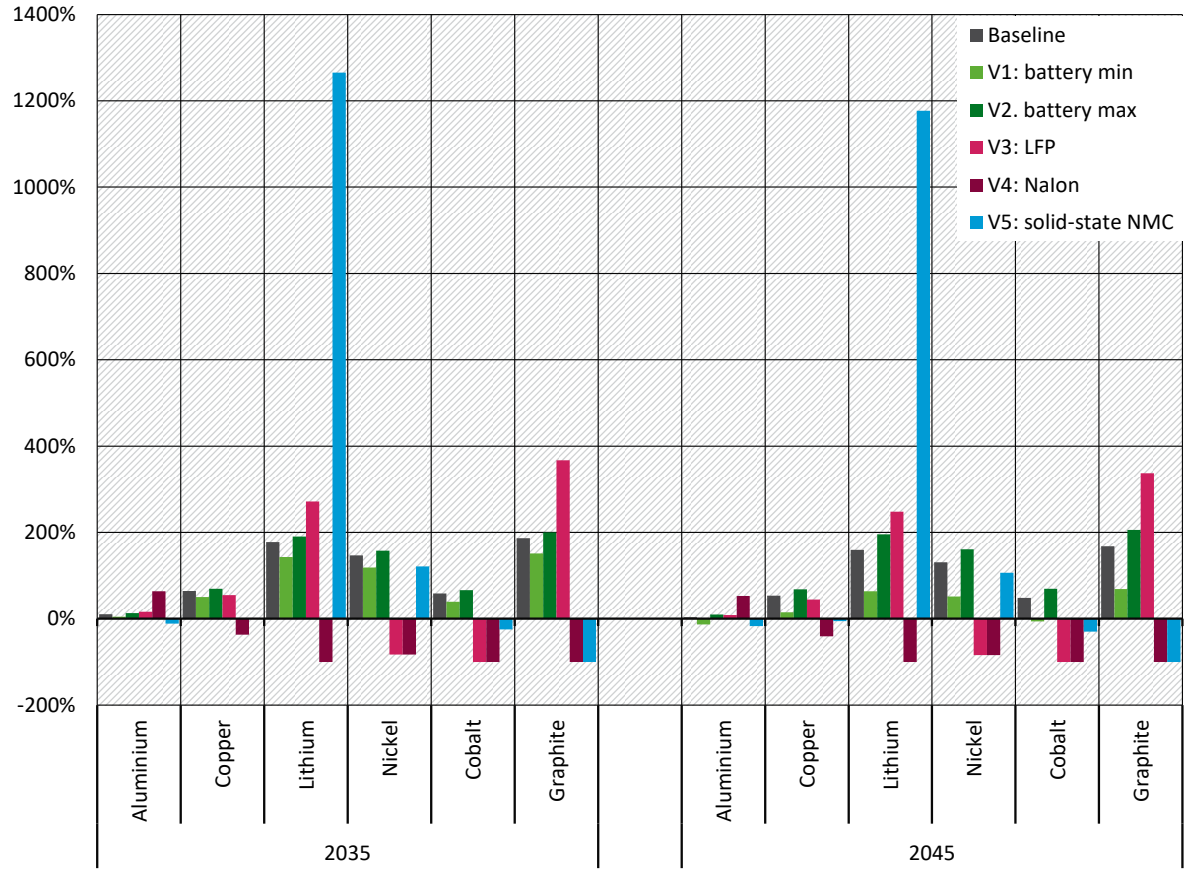
Comparison of material demand

Due to the focus on the car battery, major changes in the material demand are observed for the different battery materials (lithium, nickel, cobalt and graphite as well as copper and aluminium) (see Figure 37). Compared to 2025, material demand for all variations as well as the baseline is increased (with only some exceptions for certain battery types). Materials which are mainly (or even exclusively) used in the glider and powertrain (steel, plastics, glass) are not significantly changed between the variations and thus not shown here.

The differences in battery size (V1 and V2) directly correspond to changes in the total material demand of the two variations compared to the baseline.

The highest differences in the material demand between the variations occur for lithium, where using only solid-state NMC batteries (V5) leads to a huge increase in the lithium demand due to the usage of a lithium anode, while considerably decreasing the demand for all other raw materials compared to the baseline. Na-ion batteries (V4) show a huge decrease for lithium, nickel, cobalt and graphite as well as copper compared to the baseline while increasing the demand for aluminium. LPF batteries (V3) are nickel and cobalt-free, decreasing the demand for these critical raw materials compared to the baseline. However, due to the assumed lower energy density, raw material demand for lithium and graphite is higher than in the baseline.

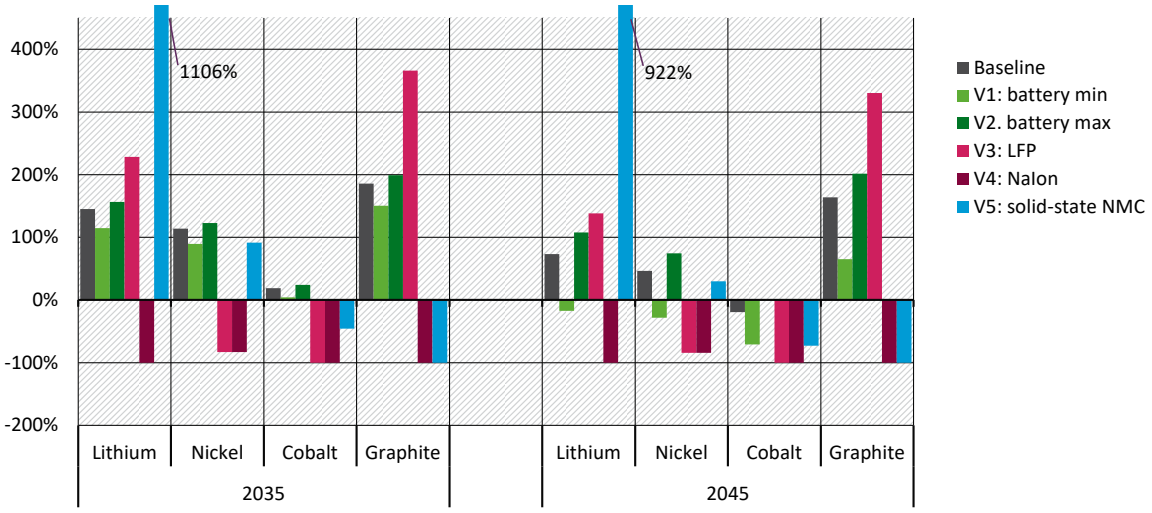
Figure 37: Changes in material demand (total) for cars for the different variations compared to 2025 (alternative powertrains)



Source: own Figure, ifeu/ Oeko Institut

Generally, differences due to the battery type are more pronounced for 2035 than for 2045, due to higher new vehicle registrations in earlier years. This is especially relevant when looking at the demand for primary raw materials (see Figure 38): due to lower amounts of batteries being available for recycling, lower amounts of secondary material are available and supply problems for primary raw materials are more likely to occur.

Figure 38: Changes in material demand (primary) for cars for the different variations compared to 2025 (alternative powertrains)



Source: own Figure, ifeu/ Oeko Institut

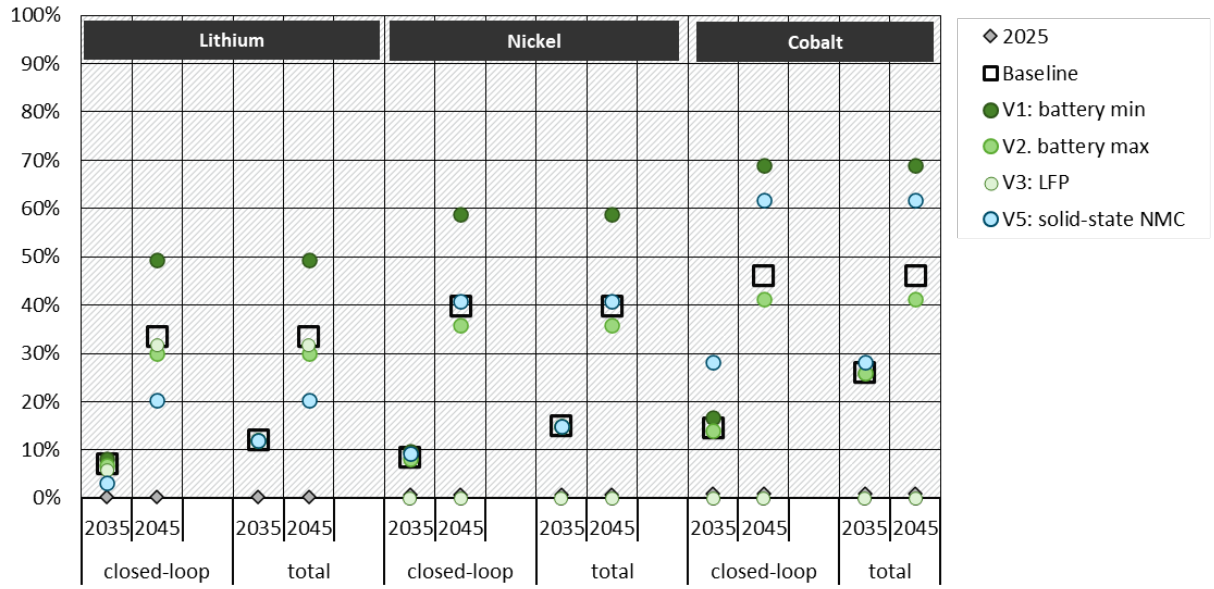
Note: Only the most relevant battery materials are shown here.

Comparison of recycled content

The recycled content shown in Figure 39 of the main battery materials is rising for the baseline and all variations compared to the 2025 values. Further, recycled content in 2035/45 is always higher than in 2025. Having smaller batteries (V1) is always beneficial and leads to a higher recycled content than using bigger (V2) batteries.

LFP batteries (V3) contain no nickel or cobalt, thus, using entirely this battery technology does not supply any closed-loop recycled materials. For solid-state NMC (V5) batteries, recycled content is higher for cobalt, but lower for lithium than in the baseline.

Figure 39: Recycled content for car batteries for the different variations (alternative powertrains)



Source: own Figure, ifeu/ Oeko Institute

Note: Nalon batteries (V4) contain no lithium, nickel or cobalt and are thus not shown here.

3.3 Vehicle downsizing

3.3.1 Background

There has been a clear trend towards growth in passenger cars in recent years. This is reflected both in the increase in larger vehicle segments and in a shift towards higher empty weights within the existing segments. Electromobility is providing an additional boost to the increase in weight, as electric vehicles tend to weigh even more due to their heavy batteries. This trend not only affects the German market, but is also reflected in the global vehicle markets. This increase in vehicle size (over)compensates for efficiency improvements in the powertrain, which is why potential energy consumption and GHG savings are not realized during car operation. At the same time, as vehicle masses increase, the material requirements of new cars also increase. In the case of BEVs, high vehicle weights lead to higher energy consumption. This means larger batteries are required to achieve the same range, which increases the demand for specific battery materials and places greater demands on the electricity sector to provide renewable energy. If the trend towards ever larger cars can be stopped and reversed, this will reduce both GHG emissions during operation and GHG emissions and resource requirements in vehicle production.

Evaluations of the causes of growth show that the increasing sizes and weights within the segments are partly determined by technical and legal requirements (safety, exhaust emissions legislation). However, the majority of growth isn´t driven by technical reason, but is requested by the customer. Examples for this are the demand for additional equipment, larger vehicles, better visibility. Downsizing is therefore less a technical issue, but primarily a question of private purchasing behavior as well as commercial car procurement.

Possible starting points for car downsizing are:

- Stopping or reversing the shift towards larger purchasing segments: Experience from other industrialized countries with similar motorization to Germany (e.g. Japan) shows that significantly higher market shares of small passenger car segments can be achieved with appropriate legal framework conditions.
- Stopping the growth in size in the segments by reducing the number or size of components installed.

An overarching assessment of possible reductions through downsizing of individual components is only possible to a very limited extent for the entire vehicle market due to the large number of standard components and additional equipment with a wide range of design variants. At the same time, the weight differences that can be achieved by eliminating or downsizing individual components are significantly lower than the weight differences between individual vehicle segments. The analysis of downsizing potentials in AutoRess therefore focuses on the question of what GHG and material savings can be achieved through a general shift towards smaller vehicle sizes.

3.3.2 Status quo

Development of vehicle sizes of new car registrations in the past

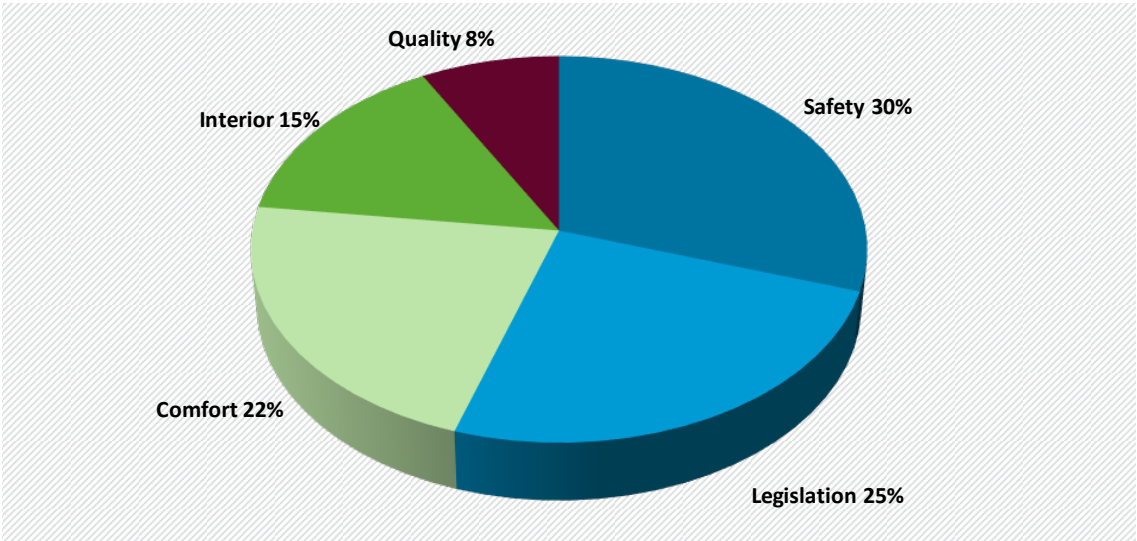
In the past, there has been a continuous increase in the weight of new passenger cars and a shift between vehicle segments (KBA 2024). Main reasons for this are increasing empty weights within all segments - from small cars to the luxury class as well as a shift in the number of new registrations from smaller vehicle classes (small cars, compact cars) to larger segments (SUVs,

all-terrain vehicles). After 2018, the statistics also reflect the increasing proportion of new registrations of electric cars with higher specific weights due to their batteries. These developments can be observed not only in Germany, but also in other countries. A study by the Global Fuel Economy Initiative (GFEI) also shows similar trends (GFEI 2023) for other car markets worldwide. Interestingly, the trend towards "SUVcation" does not necessarily lead to larger cars in terms of car footprint, but primarily to an increase in vehicle weight, as many models are growing in height. A detailed overview of the development of new vehicle weights is given in chapter 2.1.1.1.

Causes of growth in car size and weight

The increase in vehicle weight in recent years can be partly explained by electrification. But most of the increase in weight can be attributed to increased legal requirements as well as changes in customer demand. According to estimates in (Reiland et al. 2019) the mass of the base vehicle has hardly changed since 1980, weight increases are primarily due to additional components (incl. exhaust gas aftertreatment). According to (Weitbrecht 2021) safety optimisations and legal requirements on exhaust gas aftertreatment contributed about half of the weight increase, followed by comfort improvements, interior fittings and quality improvements (Figure 40). Other sources also confirm these developments: (Crosetti 2021; Scott 2022) describe that cars have gotten bigger because they are equipped with improved safety features, offer more amenities for comfort and convenience, and provide higher engine performance.

Figure 40: Causes of increasing vehicle weights



Source: own illustration based on (Weitbrecht 2021)

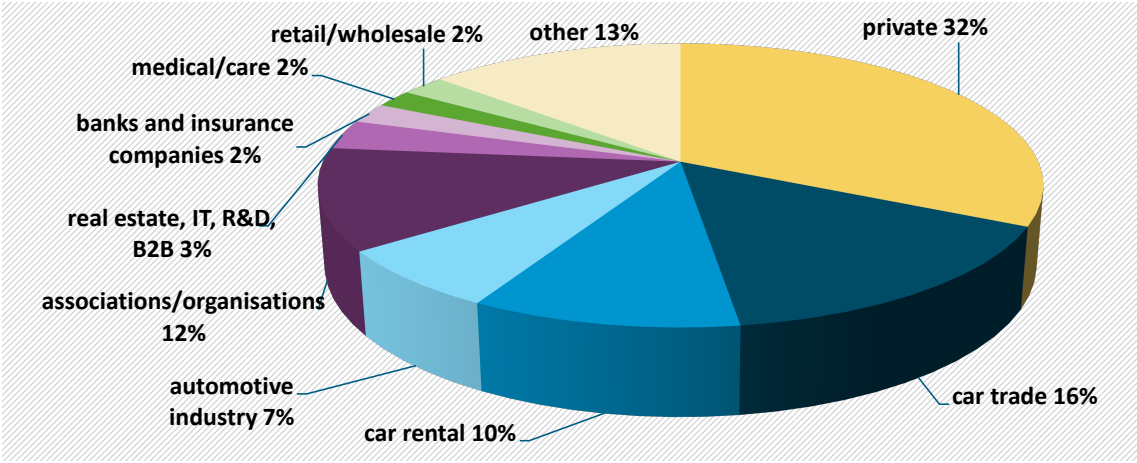
Relevance of purchasing behaviour for the average empty weight of new cars

The share of new registrations in different segments, but also the average weight of new cars within the segments, differs considerably between different buyer groups. With a view to possible measures to change purchasing behaviour, a differentiated view of annual new registrations is therefore helpful.

In 2023, private buyers accounted for just under a third of all new car registrations in Germany, but two thirds were new commercial registrations (Figure 41) – thereof about the half in car trade (one-day registrations), automotive industry and the car rental sector. In these commercial sectors, vehicles are resold after a short holding period and are therefore also highly relevant for the private car stock.

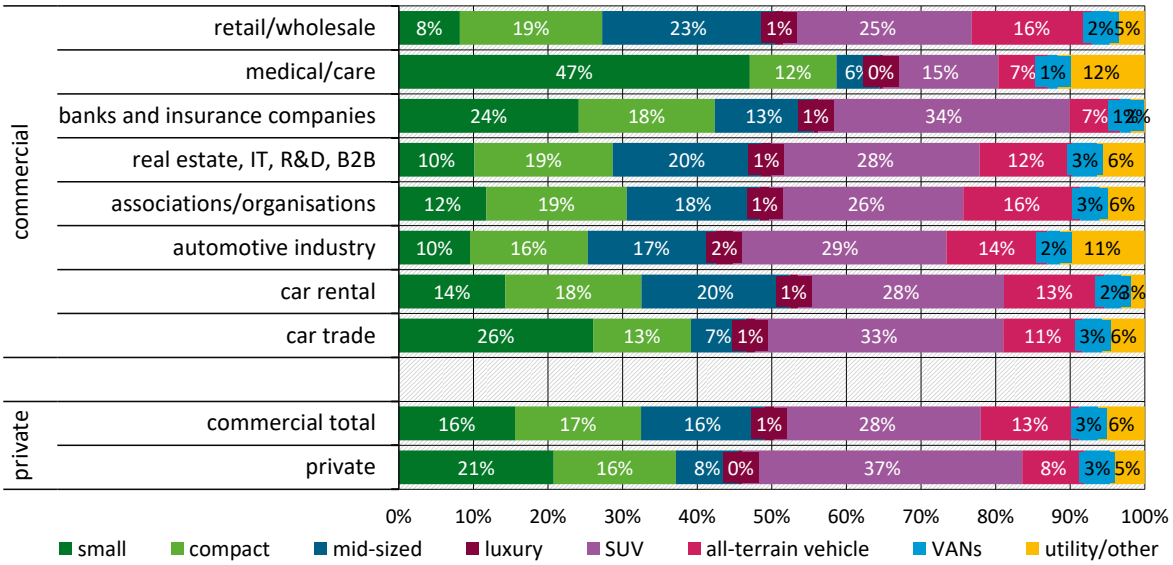
Figure 42 compares the shares of different segments in new registrations. In 2023, 37% of new private registrations were for small and compact cars, the same proportion as for SUVs (excluding all-terrain vehicles). Midsize cars and SUVs each accounted for 8% of new registrations. In terms of new commercial registrations overall, mid-sized cars (16%) and all-terrain vehicles (13%) had significantly higher shares in new registrations than in private purchases, while small cars and SUVs had lower shares. This picture is partly made up of different shares of new registrations in the individual sectors, e.g. the medical/care sector with very high new registration shares of smaller cars.

Figure 41: New car registrations in Germany in 2023 by economic sector



Source: own analyses, based on (KBA 2024)

Figure 42: Shares of purchasing segments in new car registrations in 2023 by economic sector



The KBA segments mid-sized and upper mid-sized are summarised under mid-sized.
Source: own analyses, based on (KBA 2024)

Only limited conclusions can be drawn about the average vehicle weights for individual buyer groups from the shares of the purchase segments alone. Despite considerable differences in the structure of new registrations the average empty weight of new passenger cars was only 29 kg or 2% higher on average for new commercial registrations than for new private registrations.

Accordingly, differences between the sectors in terms of the share of new registrations of individual segments are widely set off by weight differences within the segments.

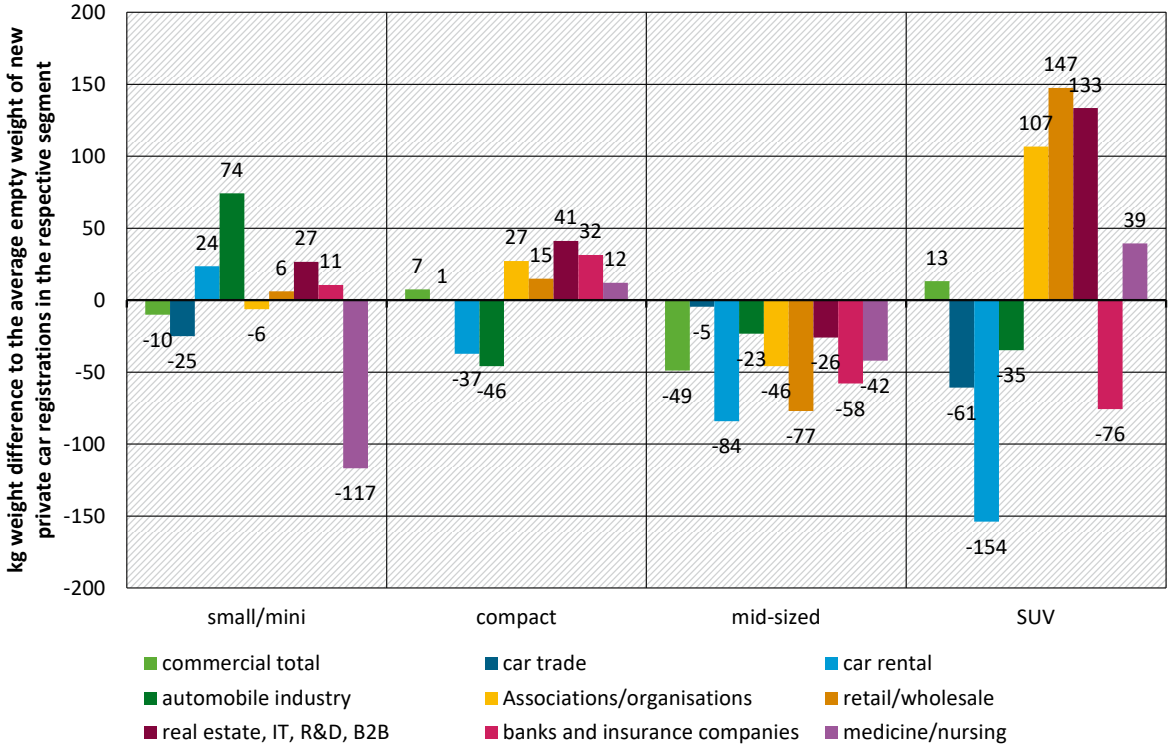
The analyses in Figure 43 confirm that there are also considerable differences in the average empty weights between different buyer groups within the segments.

- For small and compact cars, there are only slight differences in the weight of new registrations between individual economic sectors and compared to new private registrations. Main exceptions are for small cars the automotive industry (+74 kg) and the medical/care sector (-117 kg) compared to private new registrations.
- New commercially registered mid-size cars in 2023 were 1-5% lighter than privately purchased mid-size cars overall and in all sectors analysed.
- New SUVs in the car rental sector were approx. 150 kg lighter than privately purchased SUVs. In contrast, new SUVs in the retail/wholesale trade were 150 kg heavier. A reason could be that SUV models range from mini and compact SUVs to large vehicles.
- With the exception of the car rental sector, new commercially registered all-terrain vehicles were heavier than new privately registered all-terrain vehicles, with an average additional weight of between 10 and 100 kg.

Differences in the average vehicle weights within the individual segments are likely to be on the one hand due to the categorisation of individual models with sometimes major differences in the vehicle dimensions to the segments (particularly in the case of SUVs). On the other hand, different model variants (powertrain concept, engine power, equipment) can also play a role here.

Basically, the analyses show that very different preferences play a role in purchasing decisions. With regard to the future development of the car population, in addition to private buyers ("clients"), the car trade, car rental and automotive sector are particularly interesting for target group-oriented measures. At the same time, cross-sector similarities (e.g. company cars for sales representatives, field service) can also offer starting points for purchasing behaviour.

Figure 43: Weight differences of new passenger car registrations between selected owner groups in 2023 in selected market segments



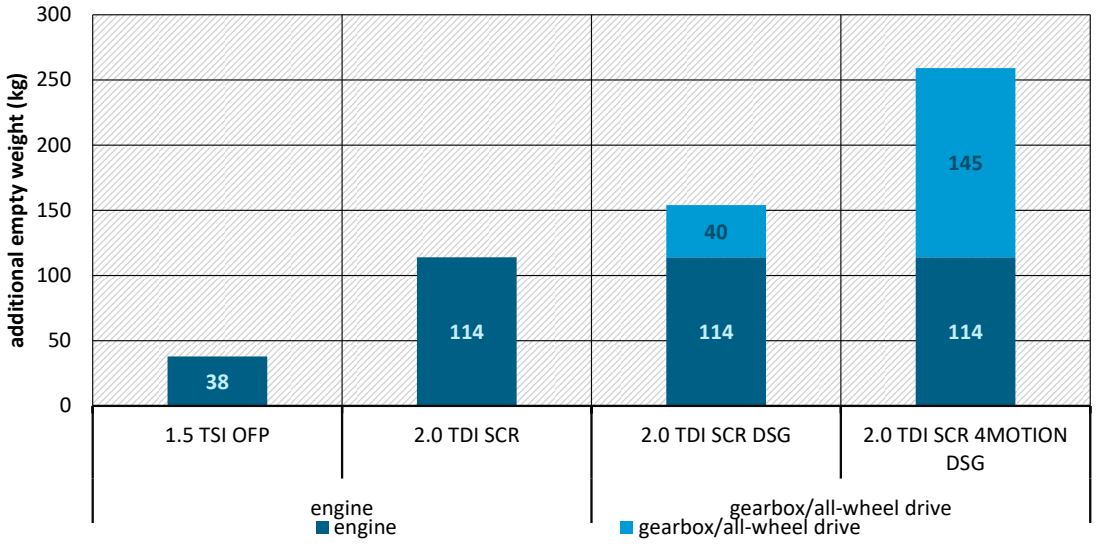
The KBA segments segments mid-sized and upper mid-sized are summarised under mid-sized.
Source: own analyses based in (KBA 2024)

Impact of different model configurations on the vehicle weight

The impact on the vehicle weight is not only characterized by the model variants, but also by the (additional) equipment. While different model variants are taken into account in the official empty weights, special equipment is not included and therefore cannot be analysed in detail.

In addition to the analyses of the average empty weights within the purchase segments, we exemplarily analysed the relevance of various model variants and additional equipment for the vehicle weight Figure 44 shows an example of the weight differences between various engine and transmission combinations for the compact SUV "Volkswagen T-Roc" as well as the special case of a convertible. Compared to the basic version with a small petrol engine (1,301 kg), the next largest petrol engine (1.5 litre capacity instead of 1.0 litre) results in an additional weight of just under 40 kg. Choosing a 2.0 litre diesel engine with SCR exhaust gas aftertreatment means more than 100 kg extra weight. Changing from a manual gearbox to an automatic gearbox results in a further 40 kg extra weight, with automatic gearbox and all-wheel drive even +145 kg. In total, a VW T-Roc with a diesel engine and all-wheel drive weighs over 250 kg more compared to the base engine. With the achievement of a share of BEVs in new registrations of 100% as of 2035, weight differences in the ICEV powertrain will no longer be relevant for vehicle weights in the future. In contrast, different range configurations of electric cars can lead to greater weight differences. Effects of different battery capacities are topic of the technical option “Alternative powertrains” (see chapter 3.2).

Figure 44: Additional weights of various model variants of the VW T-Roc



DSG: automatic transmission; 4Motion: all-wheel drive.
Source: own illustration, based on German Car Database (https://www.teoalida.com/cardatabase/germany/)

Individual components and additional equipment can contribute to the vehicle weight to varying degrees. The number and variety (and therefore also weight differences) of equipment components are very high. They are also installed in new cars to varying degrees depending on the purchase segment and customer requirements. Accordingly, it is not possible to make a general statement about weight increases due to individual vehicle equipment. Table 12 shows a selection of vehicle components and additional equipment and their weights researched on the Internet. While individual sensors weigh only a few grams (without wiring), other components weigh in the upper two-digit kilogram range. Some of these are optional extras (e.g. trailer coupling, third row of seats) that are not fitted as standard and are not included in the official kerb weight of the model, but have to be added on. Compared to the weight differences between alternative vehicle sizes, the weight ranges considered due to additional vehicle equipment are very small. In addition, the number and variety of equipment components are very high. An in-depth analysis of individual additional vehicle equipment would therefore be very time-consuming compared to the analysis of generally reduced car sizes, while at the same time offering less potential. For this reason, this study focuses on the weight savings achieved by switching between vehicle segments.

Table 12: Weights of various equipment components*

Component	Weight	Source
Wiring harness	Up to 70 kg	(Hammerschmidt 2018)
Air conditioning	15-40 kg	(Heise Online 2024)
Trailer coupling	Standard: 24 kg Detachable ball head: 48 kg Electrically extendable: 80 kg	(Heise Online 2024)
Large wheels	+40 kg	(Heise Online 2024)
Third row of seats	70 kg	(Heise Online 2024)
Spare wheel	15-20 kg	(Heise Online 2024)

Component	Weight	Source
Parking heater	6 kg	(Heise Online 2024)
Leather seats	6 kg	(Heise Online 2024)
Electric seat adjustment	14 kg	(Heise Online 2024)
Automatic start-stop system	14 kg	(Heise Online 2024)

* Some of the equipment components are not included in the empty weight

Source: own table Oeko-Institut / ifeu

Existing downsizing approaches in the vehicle market

In the passenger car market, there is a wide range of vehicle sizes from mini cars to very large all-terrain vehicles. At the same time, there are existing vehicle concepts with significantly smaller vehicle sizes and weights, but these are not yet widespread in the European passenger car market. This is because they have been developed for legal frameworks in other countries or for special usage niches with different technical requirements. Interesting approaches for future downsizing in the German and European passenger car market include, in particular, kei cars, which are widespread in Japan, and light vehicles in the EC vehicle class L7E.

Kei cars are a special vehicle category in Japan, characterized by their compact dimensions, low engine power and special tax advantages. Originally designed to provide space-saving and cost-effective mobility, these micro cars have become an integral part of the Japanese car market. According to current legislation, kei cars must be no longer than 3.40 meters and no wider than 1.48 meters. The engine capacity is limited to a maximum of 660 cubic centimetres and the engine power must not exceed 64 hp. These restrictions ensure that kei cars remain compact and lightweight, which has a positive effect on fuel consumption and emissions (Geiger 2019).

The success of kei cars in Japan can be attributed to several factors. Firstly, they offer a cost-effective alternative to conventional cars, in particular through tax breaks and lower fees for tolls and parking spaces. In contrast to normal cars, in many cities they are exempt from the requirement to have their own parking space (Geiger 2019). In addition, despite their compact size, kei cars offer a high level of comfort and modern equipment comparable to larger cars, e.g. air conditioning, electric sliding doors, cruise control and distance control.

Kei cars make up a considerable proportion of the vehicle population. In 2016, over 30 million kei cars were registered in Japan, accounting for almost 40 percent of the total vehicle population (Geiger 2019). Even today, their market share is at a similar level. Despite their success in Japan, their breakthrough in international markets has so far been limited due to stricter safety and emissions regulations as well as technical conversion requirements.

The EC vehicle category L7E comprises four-wheeled light motor vehicles whose empty weight must not exceed 450 kg (600 kg for vehicles for the carriage of goods), not including batteries of electric vehicles. This vehicle class was regulated by EC Directive 2007/46/EC and EU Regulation 2011/678/EU. The engine power is limited to a maximum of 15 kW. As a rule, they only reach speeds of 45 to 80 km/h. In terms of safety, they only meet minimal standards; airbags, ABS or comprehensive stability systems are usually not available, which makes them less safe.

These light motor vehicles are greatly reduced and only offer basic functions. They usually only have two seats, are slow and offer hardly any comfort or safety features. In summary, it can be said that L7E microcars lag well behind regular cars in terms of comfort and safety. Only a few thousand L7E microcars are sold in Germany each year (Deutscher Bundestag 2020) (compared to 2.5 to 3 million new cars per year).

3.3.3 Legal framework

There is no specific legislation on passenger car weights, except for the 3.5 tons maximum permissible mass limit. Vehicles above this weight fall under other categories such as trucks with stricter regulations regarding driving license classes, tolls and other operational requirements.

The **European CO_2 emission performance standards** for cars and light commercial vehicles (Regulation (EU) 2019/631) regulate the average CO_2 emissions of a car manufacturer's new vehicle fleet. In principle, they can act as an efficiency standard for cars with combustion engines and, thus, promote vehicle downsizing. However, the key lever is the electrification of new cars. Higher shares of new registrations of electric vehicles reduce the efficiency requirements for new vehicles with combustion engines. With the amendment in 2023, a CO_2 target of 100% compared to 2021 will apply from January 1, 2035, which means that no more new petrol or diesel vehicles will be registered from this year onwards (Regulation (EU) 2023/851). With regard to electric vehicles, the EU regulation does not create any incentives to reduce weight for new cars, as they relate exclusively to direct CO_2 emissions during vehicle operation and therefore electric cars are counted equally with zero emissions regardless of their size.

In some European countries, there are new registration taxes or bonus-malus regulations with high malus for new cars with high specific CO_2 emissions. In France, a weight-based penalty charge was also introduced on new petrol and diesel cars from 2022 (Bensalah 2025; Kreye et al. 2024). However, for electric cars, these national regulations do not provide any legal leverage for lightweighting.

Further weight increases are to be expected as a result of new **vehicle safety regulations**. Many of these new requirements, such as additional vehicle safety systems, necessitate the installation of cameras and radar equipment. In addition, improved head impact protection for pedestrians is expected to further increase vehicle safety, which may also have an impact on vehicle weight (BMDV 2024).

3.3.4 Foreseeable development trends

In recent years, a clear trend towards larger vehicle segments has been observed worldwide. Even in countries where smaller vehicle classes traditionally dominate, there has been an increase. There are no clear forecasts on how this trend will develop, but it is unlikely to end abruptly in the near future. Various sources (e.g. GFEI 2023; Transport & Environment 2024) expect further increases of vehicle sizes, though without detailed conclusions. A look at the newly announced vehicle models shows that SUVs will continue to play a significant role and increasingly displace smaller vehicle segments (ntv 2023). In urban areas, these large vehicles create problems as they are too wide for roadside parking, blocking emergency lanes and are often difficult to accommodate in parking garages. Interestingly, this seems to have little impact on purchasing behaviour, and instead revisions of current guidelines are attempting to adapt parking spaces to the new vehicle dimensions (FGSV 2023).

With the increasing spread of electric cars, vehicle weights continue to rise, which is mainly due to the heavy batteries and the growing battery capacity. However, this is a battery-specific issue (see chapter3.2) and is therefore not the focus of this chapter. Small vehicle concepts, on the other hand, are unlikely to gain significant market share without special measures. The legal framework does not give manufacturers any incentive to bring smaller vehicles onto the market. In contrast, new vehicle safety regulations could in addition to customer requests for larger cars additionally cause further increasing vehicle weights.

3.3.5 Fields of action and issues

The analysis shows that the increasing vehicle weights and sizes within the segments are not only determined by safety requirements and original equipment manufacturer specifications, but also to a large extent by the customers' demand for more comfort, additional equipment and larger vehicles. Purchasing behaviour - of both private and commercial customers - plays a decisive role here. Downsizing is therefore less of a technical challenge and more a question of market demand and preferences.

The analyses of greenhouse gas and material savings potential through downsizing in AutoRess therefore focus on a shift in the new car market towards smaller vehicle segments that are already available today. Weight and energy consumption-related differences for the following vehicle concepts compared to average passenger cars were researched:

- Small/mini-cars: this segment is already established on European market and accounts for around 5% of new registrations in Germany, although its share is trending downwards (see chapter 3.3.2). Vehicles in this category have a significantly lower weight compared to average new vehicles, which leads to considerable savings in GHG emissions and materials.
- Japanese kei cars: Kei cars are fully-fledged micro cars that are particularly popular in Japan due to their compact dimensions and complete comfort features (see chapter 3.3.2). These vehicles offer interesting potential for the European market, as they offer good performance not only in urban environments but also on long journeys.
- L7E light motor vehicles are lighter and less expensive, but do not currently meet the requirements to be perceived as a fully-fledged car alternative (see chapter 3.3.2). They are limited in their possible uses, e.g. in terms of maximum speed and vehicle equipment such as safety features or heating.

Table 13 provides an overview of the technical parameters of the respective vehicle classes in terms of weight, range and technical equipment for current BEV models in the mini, kei-car and L7E segments.

Table 13: Exemplary configurations in small vehicle segments

	Empty weight without battery (kg)	Engine power (kW)	Usable battery capacity (kWh)	energy consumption WLTP (kWh/100km)
Small/mini cars	851 - 1073	33 - 87	21 - 37	13 - 18
Kei cars	880 - 933	47 - 50	14 - 29	12 - 13
L7E	416 - 464	8 - 17	5 - 11	5 - 7

Sources: (ADAC o.J.; AutoData o.J.; Carwow o. J.)

L7E microcars can only gain market attractiveness through substantial adjustments to safety requirements and legal framework conditions. However, if such adjustments are made, it is to be expected that they will become larger and heavier and then only show slight differences in size to kei cars. The following modeling therefore focuses only on the potential of minicars and kei cars, which are already fully-fledged passenger cars.

3.3.6 Modelling

Several factors play a role in modeling the GHG and material effects of downsizing strategies:

- Weight/size and material composition of vehicle components (glider, powertrain, battery)
- Specific energy consumption
- New registration shares

Our focus in this modeling is on battery electric vehicles (BEV), as microcars in particular (e.g. kei cars) are not yet represented on the European market. It is no longer worthwhile for manufacturers to develop new microcars with combustion engines as current legislation means that no new cars with combustion engines will be registered in the EU from 2035. Table 14 shows the specific differences of **vehicle configurations** for the two downsizing concepts considered in the model. These were derived from the literature research results as a percentage change compared to new electric cars in the baseline development. As the vehicles under consideration are fully equipped and do not contain any special material innovations, the **specific material composition** of the vehicle components remains the same as in the baseline development. Changes in material requirements due to downsizing are scaled solely on the basis of the reduced size for the individual vehicle components.

Table 14: Vehicle configurations for downsized vehicle concepts compared to new electric cars 2030 in the baseline development

	Empty weight without battery	Battery capacity	Specific energy consumption
small/mini car	59%	39%	75%
kei car	51%	32%	59%

Source: own assumptions, ifeu

The **new registration shares** of downsized vehicles have a direct impact on GHG emissions and material requirements in vehicle production. The higher the proportion of these vehicles in the new fleet, the greater the reduction in annual GHG emissions. Increasing market penetration also reduces energy consumption and, thus, GHG emissions in car operation. However, this development is heavily dependent on political measures and the resulting changes in purchasing behavior. To assess the impact of different policy instruments and market mechanisms, we consider two levels of ambition:

- Moderate: we assume a ramp-up to 15% share of new registrations by 2035 (in addition to the mini cars entering the fleet anyway).
- Ambitious: Here we model a ramp-up to an additional 33% share of new registrations, which roughly corresponds to the share of kei cars in the Japanese car market.

This results in a total of four modelling variations for downsizing:

- V1: Moderate ramp-up – mini cars
- V2: Moderate ramp-up – kei cars
- V3: Ambitious ramp-up – mini cars
- V4: Ambitious ramp-up –kei cars

3.3.7 Results

As explained in this chapter, the weight of new cars has increased continuously in the past and is expected to continue to do so in the future. In addition to legal requirements for car manufacturers in terms of vehicle safety and exhaust aftertreatment, this trend is mainly influenced by customer demand for larger vehicles and more extensive equipment. One possible approach to counteracting increasing vehicle masses is to shift future new registrations towards smaller segments such as mini or kei cars. These vehicle classes are significantly lighter and therefore cause fewer GHG emissions both in production and in use. Material requirements in car production can also be significantly reduced.

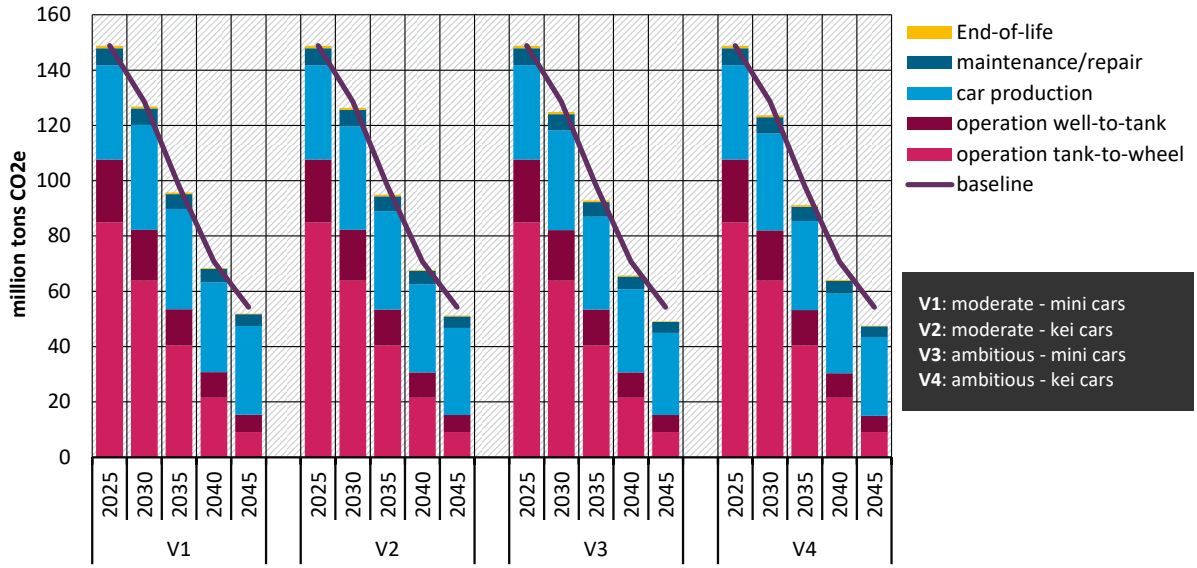
Comparison of GHG emissions

The results in Figure 45 and Figure 46 show the potential GHG emission savings from increasing the share of minis or kei cars in the total vehicle fleet. Four scenarios are shown in the graph for different ambition levels of market ramp-up and different downsized vehicle sizes.

Downsizing is only considered for new BEVs; accordingly, the direct GHG emissions from car operation (tank-to-wheel) do not change. The upstream emissions from the provision of electricity (well-to-tank) are 1-3% lower in 2035 and 2-8% lower in 2045 than in the baseline development. Overall, downsizing can reduce GHG emissions from car operation by up to 1% in 2035 and 1-3% in 2045 compared to the baseline.

The GHG emission savings in car manufacturing are significantly greater. Even a moderate ramp-up with an additional 15% new registrations share of mini cars, which are already represented on the German market today, can reduce annual GHG emissions from car production by 6%. Downsizing with kei cars would achieve a 7% reduction in emissions. With a significantly more ambitious new registrations share of 33% downsized cars, 13% (min cars) to 16% (kei cars) of annual emissions from car production can be avoided compared to the baseline development.

Figure 45: GHG emissions for cars for the different variations (downsizing)



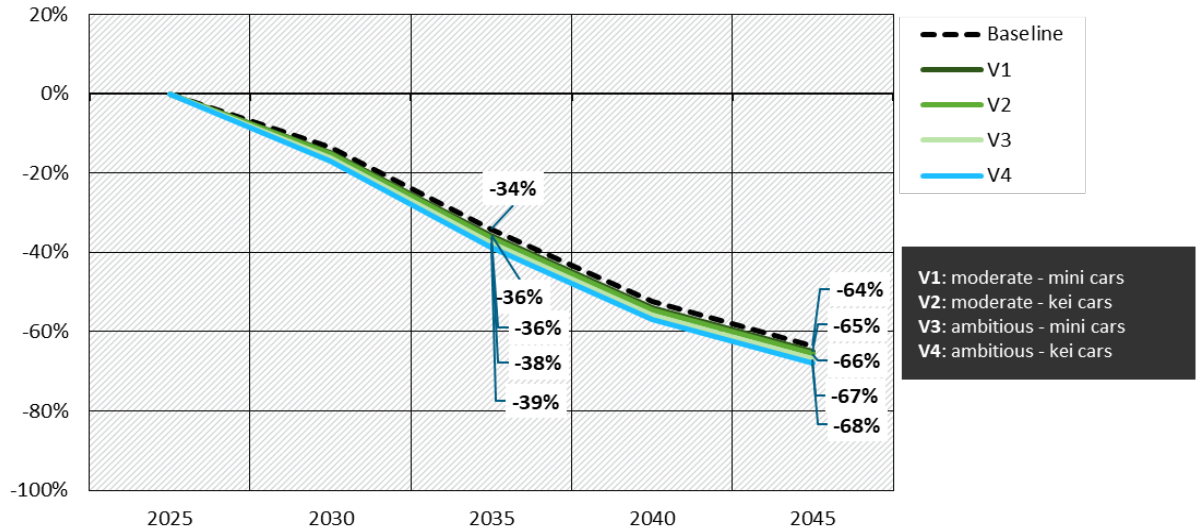
Source: own figure, ifeu/ Oeko Institute

The overall development of GHG emissions shows that downsizing can significantly increase future emission reductions (Figure 46). By 2035, GHG emissions could fall by 36-39% compared to 2025 and thus by 2-5 percentage points more than in the baseline. By 2045, electricity generation is switched to renewables, so emissions from car operation and manufacturing

associated with electricity consumption are already very low in the baseline development. Additional GHG savings from downsizing come primarily from the reduced material requirements in car manufacturing as according to model assumptions, the material supply is not yet defossilised. Compared to 64% emission reduction compared to 2025 in the baseline development, 65-68% GHG reduction can be achieved through downsizing.

The results of the modelling thus show that smaller and lighter vehicles such as mini and kei cars could make a relevant contribution to GHG savings in passenger car traffic. The example of kei cars, which are widespread in Japan, shows that this does not necessarily mean that vehicle users have to sacrifice comfort.

Figure 46: Change in GHG emissions for cars for the different variations compared to 2025 (downsizing)



Source: own figure, ifeu/ Oeko Institute

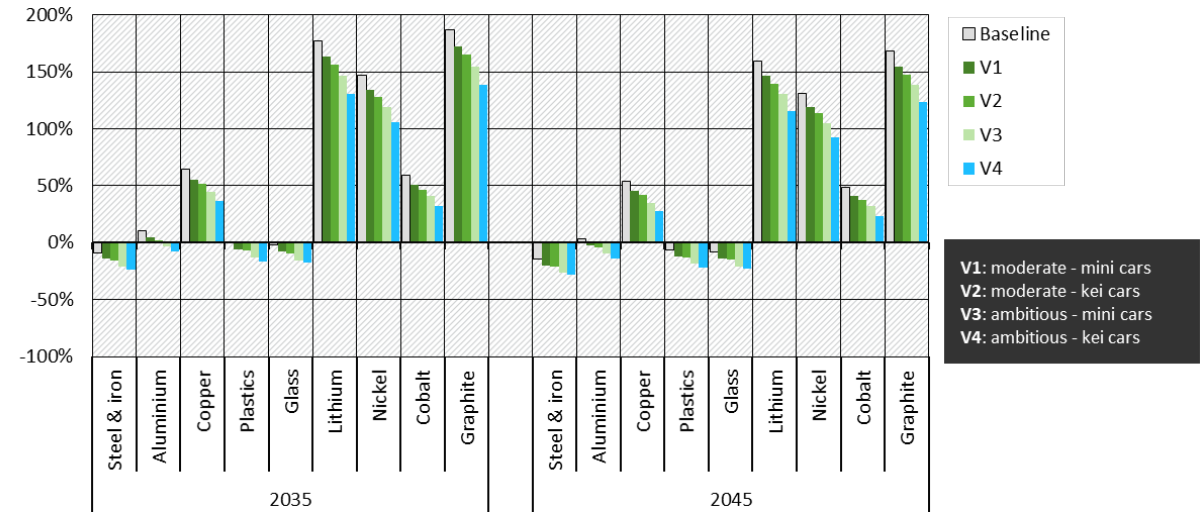
Comparison of material demand

Changes in the annual **total material demand** for car production up to 2035 and 2045 compared to 2025 are shown in Figure 47. As expected, downsizing means that the annual demand for all material groups is lower than in the baseline development.

The demand for steel already falls in the baseline by 9% (2035) and 15% (2045) compared to 2025 as a result of the lower total number of newly registered passenger cars per year (see chapter 3.1.2). With downsizing, steel demand will fall by 14-24% by 2035 and by 20-28% by 2045. The picture is similar for plastics and glass. The demand for aluminium increases slightly in the baseline development compared to 2025. However, downsizing can also lead to a slight reduction in annual demand for aluminium.

The demand for copper and battery cell materials will rise sharply after 2025 due to the ramp-up of electromobility. However, downsizing can significantly reduce this additional demand for materials. While lithium demand in the baseline development will almost triple by 2035 compared to 2025 (+177%), ambitious downsizing (33% kei cars in annual new registrations) will only increase demand by 130%. The situation is similar for the other battery cell materials.

Figure 47: Changes in material demand (total) for cars for the different variations compared to 2025 (downsizing)

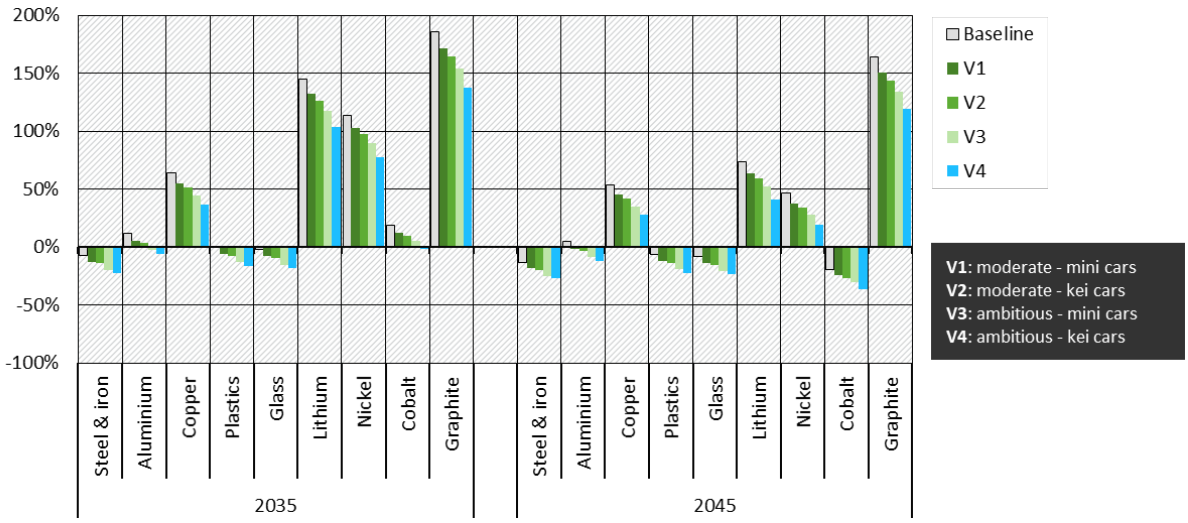


Source: own figure, ifeu/ Oeko Institute

In terms of annual primary material demand (Only battery cell materials show a slight effect of downsizing on recycled contents (Figure 49, middle+right). There is hardly any recycled material available from other sectors in baseline development, so the recycled content is determined by closed-loop recycling within the automotive industry. On the one hand, car downsizing with smaller battery sizes means that fewer battery cell materials are required in car production. On the other hand, the later decommissioning of downsized cars also means that smaller battery capacities are recycled, leading to a reduced amount of recovered materials. In the years 2035 and 2045, downsizing will lead to a slight overall increase in recycled contents for battery cell materials. The proportion of new registrations of downsized cars will reduce material requirements, while at the same time the proportion of downsized cars in decommissioned cars is still low. After 2045, when the share of downsized cars in decommissioned cars also increases, this will again lead to a reduction in the recycled contents achievable with closed-loop recycling, all other assumptions remaining the same.

Figure 48, the picture is basically similar to that of overall material demand, as downsizing does not result in any additional changes to the targeted recycled contents per material group. It is interesting to take a look at cobalt. By 2045, the demand for primary cobalt in the baseline development will already have fallen by around 20% compared to 2025 due to technical developments in vehicle batteries (see chapter 3.2). With downsizing, the demand for primary cobalt can be reduced by 27-36% by 2045 compared to 2025.

Figure 48: Changes in material demand (primary) for cars for the different variations compared to 2025 (downsizing)



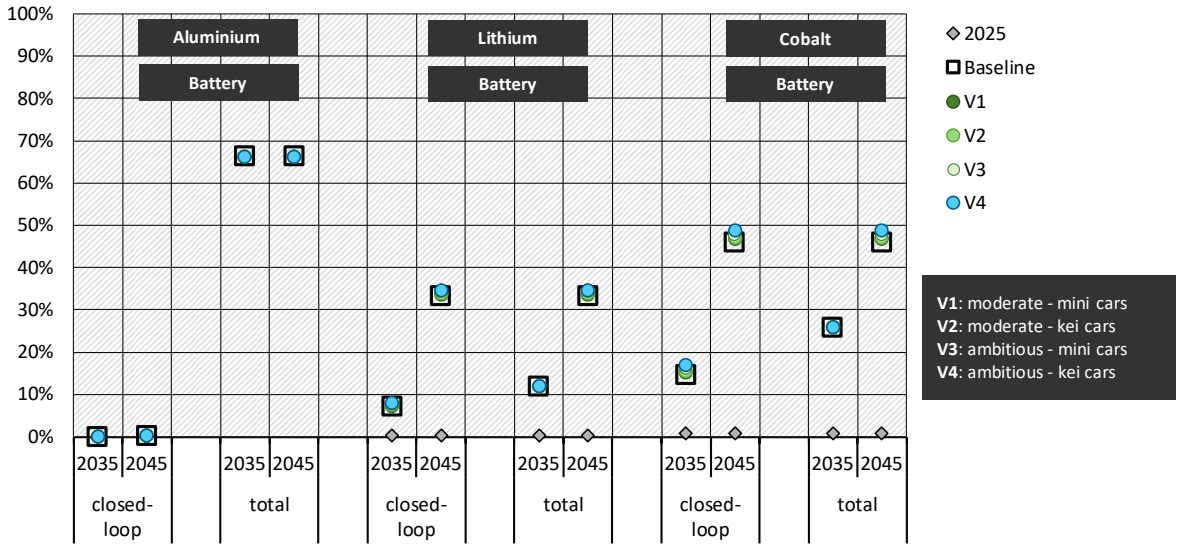
Source: own figure, ifeu/ Oeko Institute

Comparison of recycled content

Downsizing alone has hardly any effect on the recycled content of materials in car production, as in most cases the recycled material in baseline development comes mainly from other sectors and not from vehicle recycling. Figure 49 shows this as an example for aluminium (left).

Only battery cell materials show a slight effect of downsizing on recycled contents (Figure 49, middle+right). There is hardly any recycled material available from other sectors in baseline development, so the recycled content is determined by closed-loop recycling within the automotive industry. On the one hand, car downsizing with smaller battery sizes means that fewer battery cell materials are required in car production. On the other hand, the later decommissioning of downsized cars also means that smaller battery capacities are recycled, leading to a reduced amount of recovered materials. In the years 2035 and 2045, downsizing will lead to a slight overall increase in recycled contents for battery cell materials. The proportion of new registrations of downsized cars will reduce material requirements, while at the same time the proportion of downsized cars in decommissioned cars is still low. After 2045, when the share of downsized cars in decommissioned cars also increases, this will again lead to a reduction in the recycled contents achievable with closed-loop recycling, all other assumptions remaining the same.

Figure 49: Recycled material content for cars for the different variations (downsizing)



Source: own figure, ifeu/ Oeko Institute

3.4 Lightweighting

3.4.1 Background

Over the past decades new passenger cars in Germany have become increasingly heavier (see chapter 2.1.1.13.3.2). As a result, efficiency improvements in the powertrain have been offset and potential GHG savings in operation are not achieved. At the same time the material requirements of passenger cars are also increasing with rising vehicle masses. Reducing vehicle weight is an important lever for increasing vehicle efficiency and thus for reducing energy consumption and GHG emissions during the utilisation phase. Electric cars with lower specific energy consumption achieve the same range with smaller batteries and thus reduce the need for critical battery materials. In addition to vehicle downsizing (see chapter 3.3), technical lightweighting in the vehicle industry is a possible approach to achieving weight reductions. By using specifically lighter materials or material composites or through special design processes, the vehicle weight can be significantly reduced while maintaining (or in some cases improving) the functionality of the relevant components. However, lightweighting does not necessarily lead to GHG savings over the entire life of the vehicle. Additional GHG emissions in vehicle production through the use of energy-intensive materials and manufacturing processes can offset or exceed the GHG savings in the use phase (see chapter 2.2.2 and 2.3.6). Lightweighting can also have an impact on the recycled content in car production and on the possible recovery of materials in vehicle disposal.

In AutoRess, we analyse the potential of lightweighting for established but less widespread approaches as well as for selected prospective new drivers. We focus on the vehicle body, which determines the weight of the vehicle across all drive trains. In addition, we also analyse lightweighting potentials of batteries for electric cars.

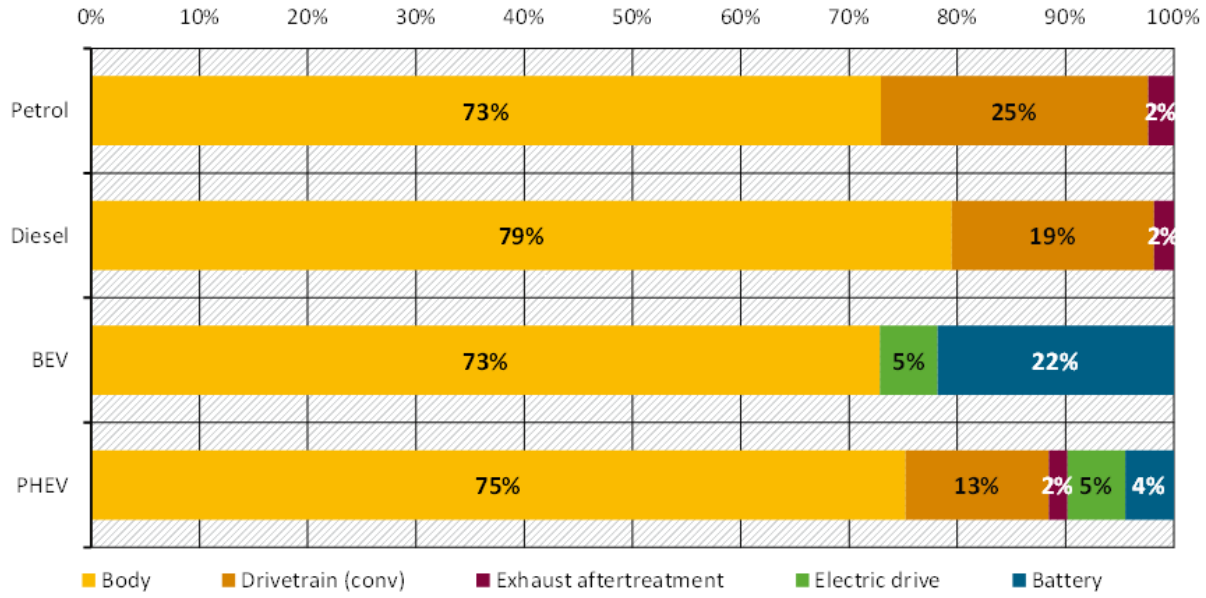
3.4.2 Status quo

Weight composition of passenger cars

Lightweighting in vehicle construction can start with many individual components. In AutoRess, we focus on components that account for a high proportion of the total vehicle weight and are therefore most effective for specific energy consumption and for material requirements in

vehicle production. The contributions of various components to the empty weight of new cars in the model baseline are shown below. Regardless of the drive concept, 70-80% of the vehicle weight is accounted for by the vehicle glider. In the case of petrol and diesel cars, a further 18-25% is accounted for by the powertrain (engine, transmission), plus 2% for exhaust gas aftertreatment. In hybridised cars, the electric drive and battery also each account for around 5% of the weight. In electric cars, the battery accounts for over 20% of the empty vehicle weight.

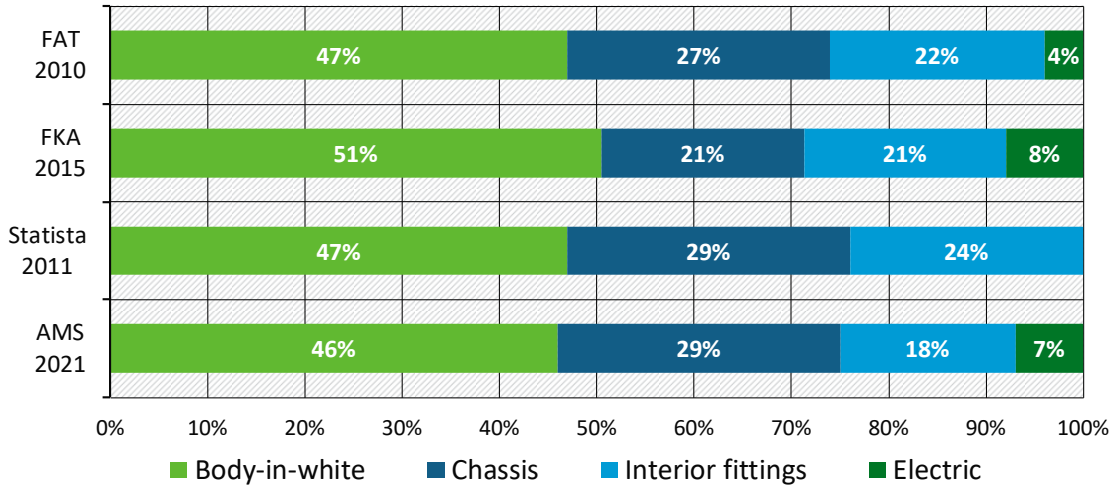
Figure 50: Weight composition of new passenger cars 2020 and 2030 by component



Source: own figure, ifeu

The vehicle glider, which dominates the vehicle weight, is made up of numerous individual components, mainly the body (body-in-white, closures), chassis and interior and exterior fittings. According to different data sources (Figure 51), about half of the glider weight is accounted for by the vehicle body, consisting of the body-in-white, closures and other exterior fittings. A further 20-30% is accounted for by the chassis. The various interior fittings (including comfort and safety equipment, electrics) account for around 20-30% of the glider weight.

Figure 51: Average weight composition of the car glider in different data sources



Source: own illustration, based on (FAT 2010; FKA 2015; Statista 2011; Weitbrecht 2021)

With the aim of technical weight reduction through lightweighing, the focus is therefore primarily on the vehicle glider. In particular the body and chassis. In electric cars, the battery is also a relevant starting point for lightweighting. According to (Meyer 2020) around a third of the battery is accounted for by battery housings and add-on parts, which are already the focus of lightweighting activities.

Lightweighting materials and technologies

Lightweighting has regularly been an important field of activity in the automotive industry in recent decades. Accordingly, there are a large number of different materials and design approaches that are being trialled and used to varying degrees. Table 15 shows an overview of different material classes and their degree of maturity as well as innovation potential from 2015 according to the VDI Centre for Resource Efficiency (VDI ZRE 2015). These are also referred to in an analysis of fields of action for increasing resource efficiency in (Jacob et al. 2021). A similar overview of main lightweighting materials and also structural lightweighting is given in a study for a European lightweighting research project (Reiland et al. 2019), see Table 16.

Table 15: Lightweighting innovation potential of different material classes (state of knowledge 2015)

Material class	Innovation potential	Maturity level
Aluminium alloy	Medium	High
Magnesium alloy	Medium	Medium
High-strength steel	High	High
Metal foam	medium	Low
fiber-reinforced plastics	High	Low
Bio polymers	Medium	low
Natural fiber-reinforced plastics	high	low
Wood	Medium	Medium

Source: based on (VDI ZRE 2015)

Table 16: Overview of relevant lightweight materials and structures

Materials		Structures		
Inorganic - Metals	**Organic** - Polymers - Wood & Fibres	**Nanomaterials**	**Hybrid structures** - Sandwich structures - Composites (e.g. fibre-reinforced polymer)	**4D structures***

* 4D structures are three-dimensional structures that change their properties due to additional external stimuli (e.g. heat)
Source: (Reiland et al. 2019)

Status quo of lightweighting in car manufacturing

The following is a brief outline of relevant lightweighting activities in the automotive industry to date. The most widespread is the use of **aluminium** instead of steel. Aluminium is used in various components and to varying degrees in individual car models. Audi is particularly worthy of mention here. In the mid-1990s, Audi launched two models on the market, the A8 and the A2, in which the body was made almost entirely of aluminium, the body-in-white in space frame technology as well as the outer skin (doors, fenders, hood, decklid). This reduced the unladen weight by around 40% compared to conventional construction methods (Chen 2023). Other manufacturers also continue to use larger quantities of aluminium in selected models. Nevertheless, high aluminium content in the body is still not standard, but is rather found in sports cars and in the premium segment. In an overview of aluminium use in passenger cars (Ducker 2016), the range extends from 62 kg/car to 610 kg/car. In the vehicle glider, significant quantities of aluminium are only used in the Euro car segment D (large) and above. According to (Ducker 2023), the average aluminium content per vehicle has risen continuously in recent years. A further increase is expected, primarily due to the shift to electric cars (e-drive housing, battery pack housings, ballistic battery protection, and cooling plates) and, to a limited extent, the use of large and mega castings in the body structure.

Plastics and composites have been used for many years by car manufacturers and suppliers in a wide range of applications in the vehicle body (shock absorbers, roof) as well as in numerous equipment components and also in the drive train. In order to meet the very different technical requirements (ergonomics, vibration damping, rigidity, etc.), the use of plastics also goes hand in hand with special structures. One example is a lightweight roof with a combination of polyurethane fibre composite layers and a core honeycomb structure in sandwich construction, which, according to current manufacturer information, reduces the weight of the roof module by 30% compared to conventional solutions (Automobil Produktion Online 2014). According to (Taub et al. 2019) after a sharp increase in the average specific amount of plastic in vehicles in recent decades, it has not increased further since 2005. The use of carbon fibre-reinforced plastics is regularly mentioned as an important lightweighting option. BMW has been using a body made entirely of CFRP in the i3 electric model since 2013 (Plastverarbeiter 2013). In the environmental balance sheet for the R8, Audi refers to the use of CFRP in the body in a material mix with aluminium, which reduced the vehicle weight by 40 kg compared to the predecessor model (Audi 2015). At the same time, Audi refers to the very energy-intensive production of such lightweight materials, which is why the recycling and reuse of carbon fibres is very important for environmental and cost reasons. (Jacob et al. 2021) also refers to larger waste quantities depending on the manufacturing process. In current sources, CFRP will continue to play a role in weight reduction in car production in the future, but not as a single material used on a large scale, but as a component of coordinated material mixes (Deleker 2023).

In principle, all German car manufacturers as well as the supplier industry are working on lightweighting. At the same time, the priority of lightweighting is rated significantly lower compared to other fields of action (digitalisation, electrification and autonomous driving) (Meyer 2020). This is also reflected in the current research in AutoRess - in-depth literature on lightweighting in particular is often already several years old, e.g. (Hottle et al. 2017; Taub et al. 2019; VDI ZRE 2015).

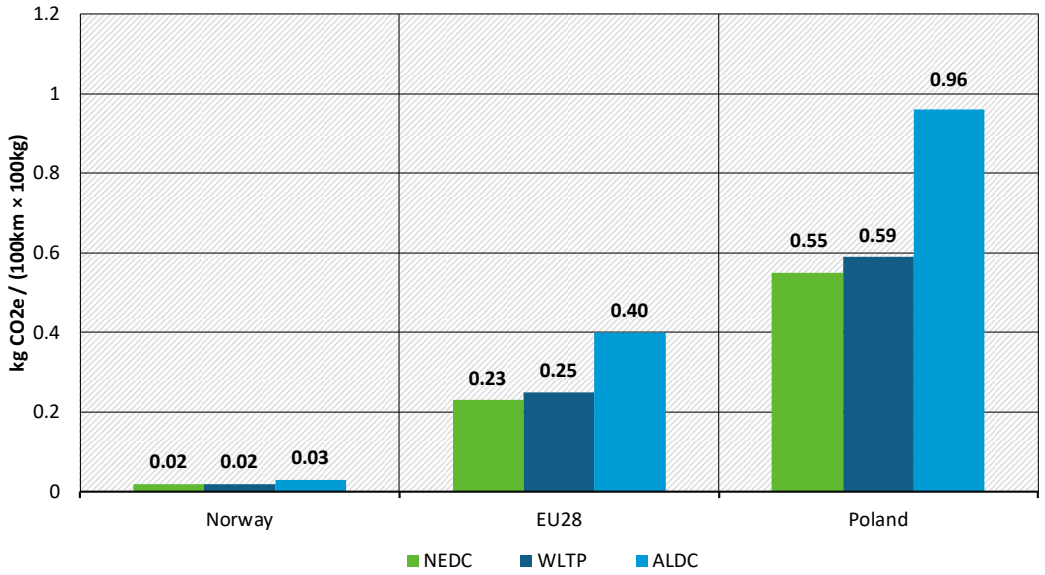
Impact of lightweighting on GHG emissions from vehicle operation

For cars with internal combustion engines, 100 kg weight reduction can reduce fuel consumption by 0.1-0.3 l/100 km. The fuel consumption savings are higher in urban traffic with many braking and acceleration processes than at high constant speeds. In hybrid cars with partial recuperation of braking energy, the efficiency potential of lightweighting is somewhat lower (Helms, Kräck 2016).

Lightweighting also reduces energy consumption in electric cars, although energy losses can also be limited here through regenerative braking. There are no legal incentives for car manufacturers to improve the energy efficiency of electric cars. The primary aim of increasing efficiency in electric cars is to increase the range and thus limit the required battery capacity. (Czerwinski 2021) states the potential of lightweighting for electric cars as an increase in range and mentions an increase of 13.7% with a 10% weight reduction.

In (Del Pero et al. 2020) a series of analyses were carried out on the effect of weight reduction in electric cars on energy consumption and greenhouse gas emissions in the use phase. A reduction in consumption of between 0.47 and 1.17 kWh/(100 km x 100 kg) was determined for various vehicle sizes in different driving cycles. The associated GHG savings potential varies considerably depending on the electricity mix (Figure 52). With an almost completely renewable electricity mix (e.g. Norway), the GHG savings from lightweighting are very low, whereas significant GHG savings can be achieved with a predominantly fossil electricity mix (e.g. Poland). As the proportion of renewable energy sources in the German and European electricity mix continues to rise in the future, the GHG savings potential in the car operation through lightweighting in electric cars will fall significantly. However, the lower specific energy consumption of electric cars limits the demand for electricity and thus the requirements for the expansion of electricity generation capacities from renewable energies.

Figure 52: Specific GHG reduction for electric cars in the use phase through lightweighting for different driving cycles depending on the electricity mix



NEDC: New European Driving Cycle [test cycle in EU type approvals until 2017]; WLTP: World Light Test Procedure [current test cycle in EU type approvals], ALDC: All-Long Driving Cycle
Source: own illustration, based on (Del Pero et al. 2020)

Relevance of conventional lightweighting for environmental impacts and material requirements over the entire vehicle life cycle

In addition to energy and emission savings in vehicle operation, lightweighting also has an impact on vehicle production, maintenance/repair and vehicle recycling. This can lead to synergies, but also to conflicting objectives. Depending on the technical lightweight design concept, energy consumption in vehicle production increases significantly and can significantly overcompensate for the energy savings and GHG savings in the utilisation phase. In (Zottler 2014) it is estimated for electric cars that the additional emissions from the production of aluminium or CFRP bodies are not offset by GHG savings during use, even after 200,000 km of lifetime mileage. In contrast, (Monteiro et al. 2022) concludes based on the evaluation of various studies that the use of lightweight materials with high embodied energy in production can lead to overall primary energy savings in the case of high lifetime mileage. (FVV 2021) has investigated various defossilisation paths for road transport in Europe, including additional GHG potential of aluminium lightweighting. This study comes to the conclusion that with increasing defossilisation of the energy supply in vehicle operation as well as in vehicle production, additional GHG emissions in the car production will be higher than GHG savings in the car operation.

End-of-life vehicle recycling must also be taken into account in the assessment of life cycle impacts of lightweight materials. GHG emissions from vehicle disposal in relation to total life cycle emissions are very low (approx. 1%). Accordingly, lightweighting has no relevant direct GHG impact on lifetime emissions. However, the materials and construction methods used influence the recovery of used parts and recycled materials. In some cases, there are still no established recycling processes and material cycles for new materials, especially composite materials. At the same time, considerable energy and cost potential for vehicle production is seen in material recovery. High proportion of reuse and high recycling efficiency reduces the need for primary materials and, thus, primary energy demand in vehicle production and repair (Monteiro et al. 2022). (Hottle et al. 2017) indicate an almost 90% lower energy requirement for

recycled cast aluminium. (Taub et al. 2019) points to a 70% cost reduction and up to 98% lower energy requirements for recycled CFRP compared to virgin material.

3.4.3 Legal framework

The **European CO_2 emission performance standards** for cars and light commercial vehicles (Regulation (EU) 2019/631) regulate the average CO_2 emissions of a car manufacturer's new vehicle fleet. In principle, they can act as an efficiency standard for cars with combustion engines and, thus, encourage vehicle lightweighting. However, the key lever is the electrification of new passenger cars. Higher CO_2 emissions are permitted for heavier vehicles. At the same time, higher shares of new registrations of electric vehicles reduce the efficiency requirements for new vehicles with combustion engines. With the amendment in 2023, a CO_2 target of 100% compared to 2021 will apply from January 1, 2035, which means that no more new petrol or diesel vehicles will be registered from this year onwards (Regulation (EU) 2023/851). With regard to electric vehicles, the EU regulation does not create any incentives to reduce weight for new cars, as they relate exclusively to direct CO_2 emissions during vehicle operation and therefore electric cars are counted equally with zero emissions regardless of their size.

In some European countries, there are new registration taxes or bonus-malus regulations with high malus for new cars with high specific CO_2e. In France, a weight-based penalty charge was also introduced on new petrol and diesel cars from 2022 (Bensalah 2025; Kreye et al. 2024). However, for electric cars, these national regulations do not provide any legal leverage for lightweighting.

Lightweighting can also have an influence on the achievable recycled content of selected materials in new cars. In the **EU Proposal for a regulation on circularity requirements for vehicle design and on management of end-of-life** (European Commission 2023a) the feasibility of requirements on minimum shares of recycled aluminium shall be assessed. However, there are no legal requirements as yet.

Lightweighting is also a topic at a political level. In summer 2023, the German Federal Cabinet adopted a new **lightweight construction strategy for the federal government** based on the 2021 coalition agreement, which was developed under the leadership of the Federal Ministry for Economic Affairs and Climate Protection and with the participation of seven other ministries (BMWK 2023). The aim of the lightweight construction strategy is to systematically activate the potential of lightweight construction across all departments for the first time. It is based on the lightweight construction strategy for Germany as an industrial location from January 2021 (BMWi 2021). Five programme lines were announced in a Lightweight Construction Technology Transfer Programme (TTP LB):

- Technology development to strengthen the German economy in lightweight construction
- CO_2 saving and CO_2 binding through the use of new construction techniques and materials
- CO_2 savings through resource efficiency and substitution
- Demonstration project
- Standardisation

A total of 109 million euros from the Climate and Transformation Fund (KTF) was available to the TTP LB in 2023. With the entry into force of the 2024 federal budget, the Lightweight Construction Technology Transfer Programme expired due to the austerity measures resulting from the ruling of the Federal Constitutional Court of 15 November 2023 (BMWK 2024).

However, the lightweight construction strategy is being continued in principle, currently primarily through networking activities in a strategy advisory board with representatives from the federal states, industry and associations, as well as an exchange with other European countries via the European Lightweighting Network (ELN) (Lohschneider 2023).

3.4.4 Foreseeable development trends

In principle, all German car manufacturers as well as the supplier industry are working on lightweighting. At the same time, the priority of lightweighting is rated significantly lower compared to other fields of action (digitalisation, electrification and autonomous driving) (Meyer 2020). This is also reflected in the current research in AutoRess - in-depth literature on automotive lightweighting in particular is often already several years old.

A key focus of lightweighting in the automotive industry is on improving the range of electric cars and thus limiting the cost of batteries (Ducker 2023). A wide variety of materials (high-strength steels, aluminium, magnesium and composite materials) are used for this purpose (Automobil Produktion Online 2022) not only in the glider, which dominates the vehicle weight, but also in many individual components (e.g. aluminium or composite materials in battery housings, lightweight construction through optimised cooling systems for the electric motor and battery). In addition to reducing vehicle weight and production costs, the possible recovery of materials in car disposal is also taken into account.

Aluminium will continue to be the dominant lightweighting material in the future. Its use is being promoted in literature for conventional aluminium lightweighting (in particular the replacement of steel sheets with aluminium sheets). In a study by organisation Alumobility (Alumobility 2021), lightweighting potential in body construction was identified for a current electric SUV model. According to the study, the use of aluminium can achieve weight savings of over 80 kg compared to the steel sheets used (Table 17).

Table 17: Weight reduction potential with aluminium for different components of the body structure

in kg	Rear end panel	A-Pillar	C-D-Pillar	B-Pillar	Rocker	Bodyside oute rpanel	Roof and roof rails
Steel	10.2	18.7	28.6	20.0	42.7	24.9	48.7
Aluminium	4.4	9.7	19.9	15.9	29.5	13.3	20.4
Weight reduction	5.8	9.0	8.7	4.1	13.2	11.6	28.3

Source: (Alumobility 2021)

New powertrain technologies and manufacturing processes also rely on aluminium. (Ducker 2023) expects a further increase in the amount of aluminium per car in the future up to 2030 though dedicated lightweighting activities only account for a limited part of the overall expected increase in aluminium demand. The electrification of the car fleet is identified as the main driver. However, (Ducker 2023) expects also a significant increase in the aluminium content in the vehicle body, primary due to an increase in aluminium die casting.

Current press reports on the use of aluminium in the automotive industry refer to the use of aluminium die casting for large body parts, so called mega- or gigacasting. After Tesla, other manufacturers (Toyota, Hyundai, Ford, Volvo, VW) have also announced to use gigacasting in new vehicle models (ANP 2024; Konstruktionspraxis 2023; Schönfeld 2023). By reducing the

number of individual parts to be joined together from several hundred to just a few cast parts, development and production times are to be significantly shortened and considerable energy and cost savings achieved in production. In addition, there should be hardly any material waste compared to sheet steel (Steigmaier 2022). It is still unclear to what extent gigacasting will lead to a reduction in vehicle weight. Although aluminium is significantly lighter than steel, significantly thinner wall thicknesses can be achieved with steel sheets than in aluminium die casting. Therefore, the minimum goal is not to become heavier and ideally to reduce some weight (Cooke 2023; Konstruktionspraxis 2023). Another important argument in favour of gigacasting is that with cast aluminium a significantly higher quantity of recycled content can be used compared to wrought aluminium alloys. This also raises the question of the extent to which additional recycled aluminium is available for vehicle production. Currently, the demand for secondary aluminium significantly exceeds the supply (Krall et al. 2024). However, with the elimination of combustion engines in new cars and the aluminium casting alloys used in the engine block (Bookhagen, Mählitz 2023) these quantities could be used in car bodies in the future. It remains unclear what risks gigacasting poses for the repairability of cars in the event of an accident and therefore for the service life of the vehicle. While some publications warn of "disposable cars", other experts believe that if the cast parts are structurally protected by other upstream components, repairability will not differ from conventional construction methods (Prengel 2024; Schönfeld 2023; Schwarzer 2024).

Battery housings for electric vehicles are a current field of activity in automotive lightweighting. Very different material concepts are being pursued here, e.g. special plastics, glass fibre nonwovens or sandwich construction with aluminium foam (Edag 2023; Envalior 2024; Koblmiller 2021; Pfeiffer 2022a; Quitter 2021), which should make it possible to halve the weight of the housing. The most common approach today is that battery cells are integrated into small modules, and the modules are then connected to make the final battery pack. Many battery manufacturers already take an advanced approach, eliminating the modules and integrating many battery cells directly into packs inside the battery housing (cell-to-pack CTP) increasing the energy density of the battery pack. Developing this approach further, manufacturers intend to integrate battery cells directly into the underbody structure (cell-to-chassis CTC), achieving a complete elimination of the battery housing (Barrier 2023; Köllner 2024). This would reduce the battery weight by about a third.

To summarise, according to current estimates, the main drivers of future lightweighting activities are electrification, but also developments in body construction. Conventional lightweighting in the vehicle body continues to offer greater potential for weight reduction, but the trend is not showing any significant increase. Gigacasting could become more important in future vehicle generations. However, it is unclear to what extent gigacasting will be used and whether it will lead to weight savings at all compared to previous design concepts. A special field of action in current lightweighting activities is the reduction of battery weights through different lightweighting concepts up to the complete elimination of battery housings.

3.4.5 Fields of action and issues

With the aim of technical weight reduction through lightweighting, the potential analyses in AutoRess focus primarily on the vehicle glider, in particular the body and chassis. Considering the development periods for new vehicle models, we only look at electric cars, as according to current legislation new petrol and diesel cars will be registered from 2035 onwards. Additionally, the battery housing is also a relevant starting point for analysing lightweighting. There are a multitude of possibilities for lightweighting with different materials and construction methods for various individual components. This diversity cannot be covered in

AutoRess. In order to evaluate the general effectiveness of lightweighting in comparison to other topic areas, we focus on the following three major levers that we identified in the previous chapter:

1. Conventional aluminium lightweighting in the vehicle glider
2. Gigacasting in the body-in-white
3. Cell-to-chassis design of batteries to completely save the battery housing

Conventional aluminium lightweighting in the vehicle glider

The large-scale use of aluminium in vehicle bodies is not currently mainstream and will not be in the foreseeable future. Nevertheless, it is constantly being discussed and promoted. A comparison of the GHG and material effects with new developments in lightweighting is therefore helpful - especially against the backdrop of increasingly decarbonised vehicle operation. Aluminium can replace steel in many components in the Glider and lead to weight savings. The use of aluminium in doors is already common in higher price segments. In (Alumobility 2021), the complete replacement of steel in the upper structure of the body with aluminium was considered for an electric SUV. Aluminium can also be used in the chassis, for example in wheel suspensions, drive shafts, steering axles and brake systems. In AutoRess, similar to (FVV 2021), we evaluate what the maximum theoretically possible replacement of steel components with aluminium components would bring. Rolled and forged aluminium is mainly used, with cast aluminium also being used to a lesser extent.

Gigacasting

With gigacasting, individual parts of the body-in-white are manufactured from large aluminium die-cast parts. One gigacasting component replaces many individual components. The gigacasting design can be limited to individual parts of the underbody. Theoretically, the complete body-in-white can also be manufactured from a single piece. (Fiedler et al. 2022) describe various stages of gigacasting (see overview in Table 18). Several manufacturers have announced Gigacasting for future car models, but so far the use has been limited to individual components (ANP 2024). Tesla had announced that it would manufacture the entire underbody from a single piece (1+1 piece). However, it was recently decided to stick with the approach already used and continue to manufacture only the rear and front body in gigacasting construction (2+2 piece) (Donath 2024).

Table 18: Gigacasting concepts

	1+3 piece	2+2 piece	3+1 piece	1+1 piece	1(+0) piece
Gigacasting	Rear underbody	Rear and front underbody	Rear, front and middle body	One-piece underbody	One-piece body-in-white
Conventional	Front and middle underbody, upperbody	middle underbody, upperbody	upperbody	upperbody	-

Source: (Fiedler et al. 2022)

Two main aspects play a role in the evaluation of the gigacasting approach in AutoRess, which will be addressed in the modelling for this topic area:

- How much steel in the body-in-white will be replaced by cast aluminium and how will this change the vehicle weight? It is currently unclear whether Gigacasting will lead to weight savings at all, as cast aluminium parts must have significantly greater material thicknesses than sheet metal to achieve the required technical properties. Nevertheless, some manufacturers expect weight savings of up to 15% (Ducker 2022; Fuchslocher 2022).

- Will gigacasting affect reparability of cars and, thus, vehicle lifetime? While some publications warn of "disposable cars", other experts believe that if the cast parts are structurally protected by other upstream components, repairability will not differ from conventional construction methods (Prengel 2024; Schönfeld 2023; Schwarzer 2024).

Cast aluminium uses significantly higher recycled contents than rolled aluminium. With the elimination of combustion engines in new cars and the aluminium casting alloys used in the engine block (Bookhagen, Mählitz 2023), an important sink for recycled aluminium will disappear. Gigacasting could offer the possibility of continuing to use high proportions of recycled aluminium in vehicle construction.

Batterie cell-to-chassis design

As a third lightweighting approach, AutoRess is investigating the effects of a cell-to-chassis design for batteries. This is the most comprehensive approach to lightweight battery design. The battery cells are integrated directly into the body structure, eliminating the battery housing completely. Chinese battery manufacturer CATL plans to launch a cell-to-chassis concept before 2030 (Barrier 2023; Köllner 2024).

The elimination of the housing also eliminates the materials required for vehicle production. The battery system weight is reduced by a third. This reduces the specific energy consumption, which in turn enables reducing battery capacities for the same range. The effects of a cell-to-chassis design on the repairability and replacement of batteries and on the possible reuse of functional batteries at the end of the vehicle's life are unclear. In AutoRess, we assume in the baseline development that the battery will normally last for the whole life of the car. Some of the batteries that are still intact when cars are decommissioned are reused in vehicle repairs or as stationary energy storage. This could be made more difficult if the battery cells are integrated directly into the vehicle frame. As a result, the complete batteries would end up directly in recycling.

3.4.6 Modelling

As explained in the previous chapter, we model three different forms of lightweighting: (1) Conventional aluminium lightweighting in the vehicle glider, (2) gigacasting in the body-in-white and (3) cell-to-chassis design of batteries. Considering the development periods for new vehicle models, we only look at electric cars, as according to current legislation new petrol and diesel cars will be registered from 2035 onwards. All three approaches are aimed at different car components. This means that the GHG and material effects of the individual approaches can also be added together to determine combined potentials.

In the modelling, we primarily evaluate changes in the material compositions of new electric cars as well as energy and GHG savings in car operation achieved by reducing the vehicle weight. In the case of gigacasting, there is also the question of reparability and a potentially shortened service life. In the lightweighting of batteries, an additional question being investigated is the restriction of possible reuse of used batteries. In total, we model the following 5 lightweight variations:

- V1: Conventional aluminium lightweighting in the vehicle glider
- V2: Gigacasting in the body-in-white
- V3: Gigacasting in the body-in-white + Average car lifetetime decreases by 3 years
- V4: Cell-to-chassis design of batteries
- V5: Cell-to-chassis design of batteries + No reuse of batteries from decommissioned vehicles

For specific vehicle compositions and the impacts of various lightweighting options, there are large bandwidths and correspondingly high uncertainties for detailed modelling. We therefore use simplified approaches in AutoRess, which should nevertheless provide a reliable representation of the magnitude of the THG and material effects. The material and weight proportions of the individual body parts can only be estimated approximately. We have derived average weight proportions and material compositions of other components in the glider based on our own LCA data sets in eLCAr (Helms et al. 2024) and additional information, e.g. from the GREET lifecycle model (Kelly, Winjobi 2020). Based on weight data for individual components in (Alumobility 2021) and from Tesla gigacasting (Electrified 2023), we also assume that around 40% of the body-in-white is accounted for by the upper body (V1) and 45% by the front and rear underbody (V2).

According to various sources, normal lightweighting using aluminium reduces the weight of the components concerned by around 30-50% (Alles über Alu 2024; Alumobility 2021; Weitbrecht 2021). In V1, we therefore assume a specific weight reduction of 40% by switching from steel to aluminium. In the case of gigacasting, on the other hand, it is still unclear whether it will lead to weight savings at all or if low weight savings up to 15% can be achieved (Ducker 2022). To evaluate possible GHG savings in car operation, we assume a specific weight reduction of 10% in the model.

The annual **new car registration shares** with additional lightweighting cannot be reliably estimated. In principle, market penetrations of up to 100% are possible. Even though various manufacturers are pursuing gigacasting, the current view is still that gigacasting will play a greater role, but will not completely replace the previous design concepts. We make the simplified assumption for all variations that 10% of all new registrations in 2030 and 30% from 2035 onwards will include additional lightweighting.

Table 19 provides an overview of selected model parameters in the topic area lightweighting.

Table 19: Main modelling assumptions for vehicle lightweighting

	V1 Glider Conventional	V2 Glider Gigacasting	V3 Battery cell-to-chassis
Weight reduction per car	247 kg* (11%) * -220 kg glider, -27 kg battery	33 kg* (1.5%) * -29 kg glider, -4 kg battery	150 kg (8%)
Specific fuel reduction	6.6%	0.9%	4.1%
New registration shares	2030: 10%, 2035+: 30%		

Source: own table Oeko-Institut / ifeu

3.4.7 Results

Comparison of GHG emissions

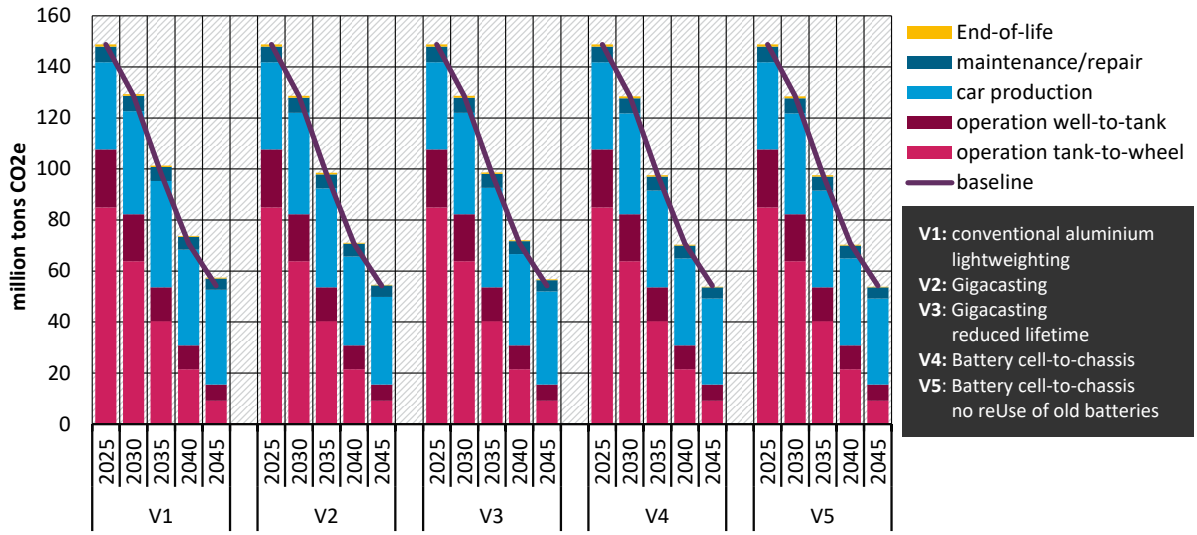
The various lightweighting variations have only a very minor impact on the development of GHG emissions from passenger car transport. The effects are greatest in V1 with conventional aluminium lightweighting of the glider. Lower energy consumption in vehicle operation leads to a 1% reduction in GHG emissions from car operation from 2040. This contrasts with a 9% increase in GHG emissions from vehicle production. This means that the total GHG emissions from car transport in this variation are 3% (2035) to 6% (2045) higher than in the baseline development. This confirms the results of other analyses. As already described in chapter 3.1.2.1, the model assumes a decarbonisation of the energy supply in car operation and production processes, but not in the provision of materials for car production. In the event of

additional defossilisation, including in the provision of materials, the additional GHG emissions in the year 2045 would be lower. Nevertheless, lightweighting has no significant additional GHG potential in this case either.

The effects of gigacasting depend in particular on possible reductions in vehicle lifetime. Gigacasting has no relevance for emissions from car operation due to the very small changes in vehicle weight. The emissions from car production increase by 1% if the lifetime of cars remains the same. If car lifetimes are shortened by 3 years, more cars are produced and newly registered each year. GHG emissions from production are 1% higher in 2035 and 7% higher in 2045 than in the baseline development.

Lightweighting through cell-to-chassis design of batteries leads to minor GHG savings compared to baseline development both in vehicle production (elimination of the battery housing) and in car operation (reduced energy consumption). Overall, however, the savings are almost negligible at less than 1%.

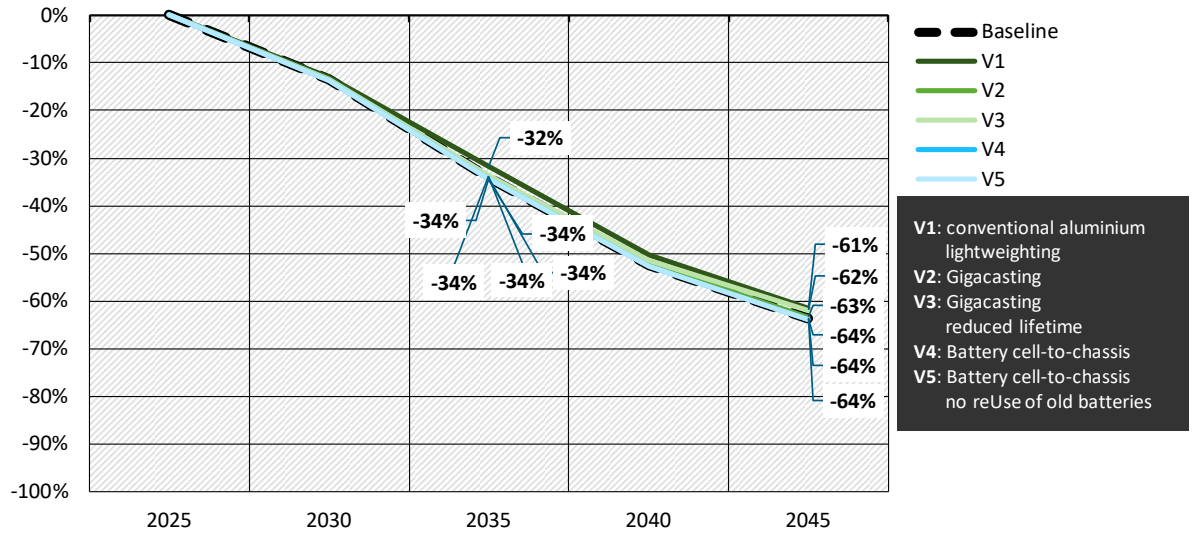
Figure 53: GHG emissions for cars for the different variations (lightweighting)



Source: own figure, ifeu/ Oeko Institute

Figure 54 shows the GHG emission changes compared to 2025. Overall, the GHG developments are very similar to the baseline in all lightweighting variants analysed. No significant additional reduction is achieved with any lightweighting option; some variants (conventional aluminium lightweighting, gigacasting with shortened car service life) lead to a weaker emission reduction.

Figure 54: Change in GHG emissions for cars for the different variations compared to 2025 (lightweighting)



Source: own figure, ifeu/ Oeko Institute

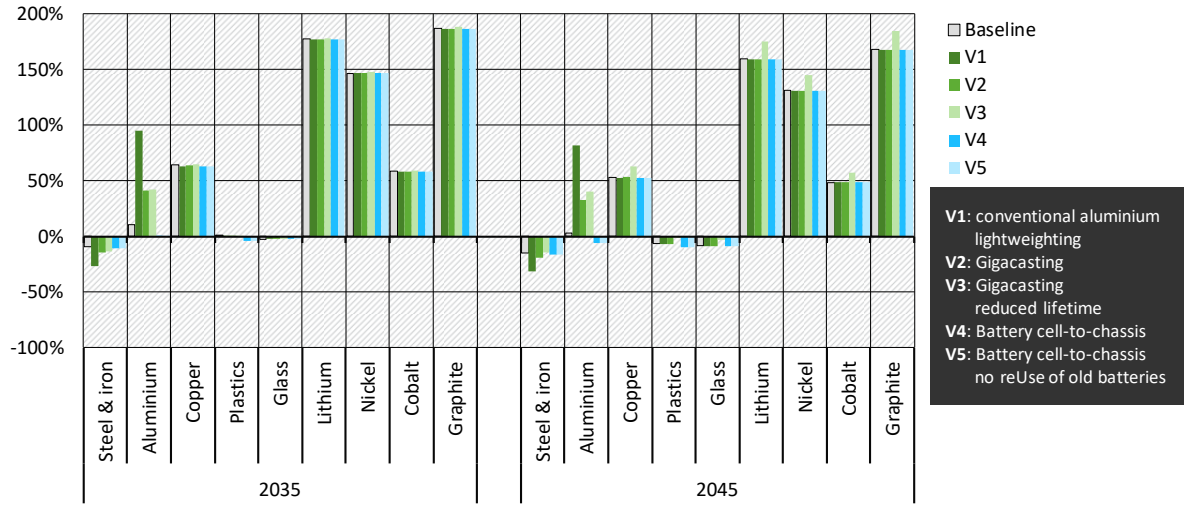
Comparison of material demand

We compare the effects of lightweighting on the demand for selected material groups in Figure 55 for total annual material demand and in Figure 56 for the demand for primary materials.

Conventional aluminium lightweighting and gigacasting only directly affect steel and aluminium consumption in the glider. In the baseline, steel consumption will fall by 9% by 2035 and by 15% by 2045 compared to 2025, due to the overall decline in new car registrations. With the lightweighting variations on the glider, a significantly greater reduction in steel demand of 13-27% (by 2035) and 14-32% (by 2045) is achieved. At the same time, the demand for aluminium will rise sharply due to lightweighting. Gigacasting will require 42% more aluminium in 2035, while conventional lightweight aluminium construction will almost double aluminium consumption compared to 2025. Even in 2045, aluminium consumption will be 33-82% higher than in 2025, despite a further reduction in the number of new car registrations. In conventional aluminium lightweighting, the requirements of other material groups also fall slightly due to the reduced battery capacities. Gigacasting has a particular impact on other material groups if the car lifetime is reduced. In this case, all material requirements increase due to higher numbers of new car registrations.

In the battery lightweighting under consideration, the effects on the material side are smaller, they affect all materials used in the battery housing; in addition to steel and aluminium, there is also a slightly reduced need for plastic compared to the baseline.

Figure 55: Changes in material demand (total) for cars for the different variations compared to 2025 (lightweighting)

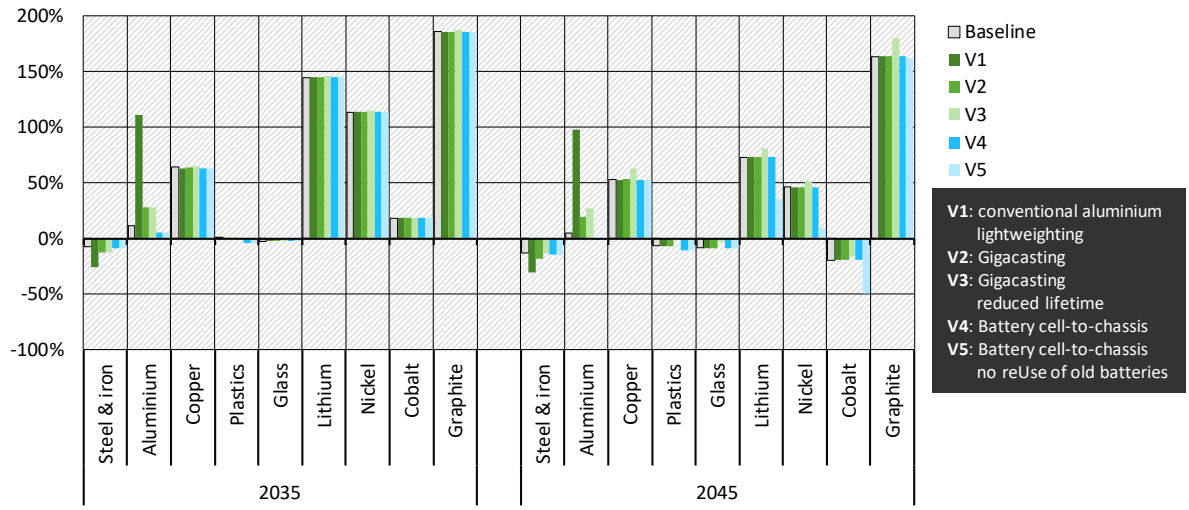


Source: own figure, ifeu/ Oeko Institute

The effects of lightweighting on primary material requirements for new cars are largely similar to those of overall material requirements. Two deviating developments should be emphasised:

- Conventional aluminium lightweighting: The demand for primary aluminium increases disproportionately because rolled aluminium is primarily used here with relatively low recycled content.
- Battery lightweighting: Without the reuse of functional batteries from decommissioned cars in 2045, this will have a significant impact on the primary material requirements for battery cell materials. Primary material requirements for lithium and nickel will increase significantly less, and cobalt requirements will even decrease compared to 2025. The reason for this is that without the reuse of batteries, a higher quantity of cell materials can be recovered in recycling and used in vehicle production.

Figure 56: Changes in material demand (primary) for cars for the different variations compared to 2025 (lightweighting)



Source: own figure, ifeu/ Oeko Institute

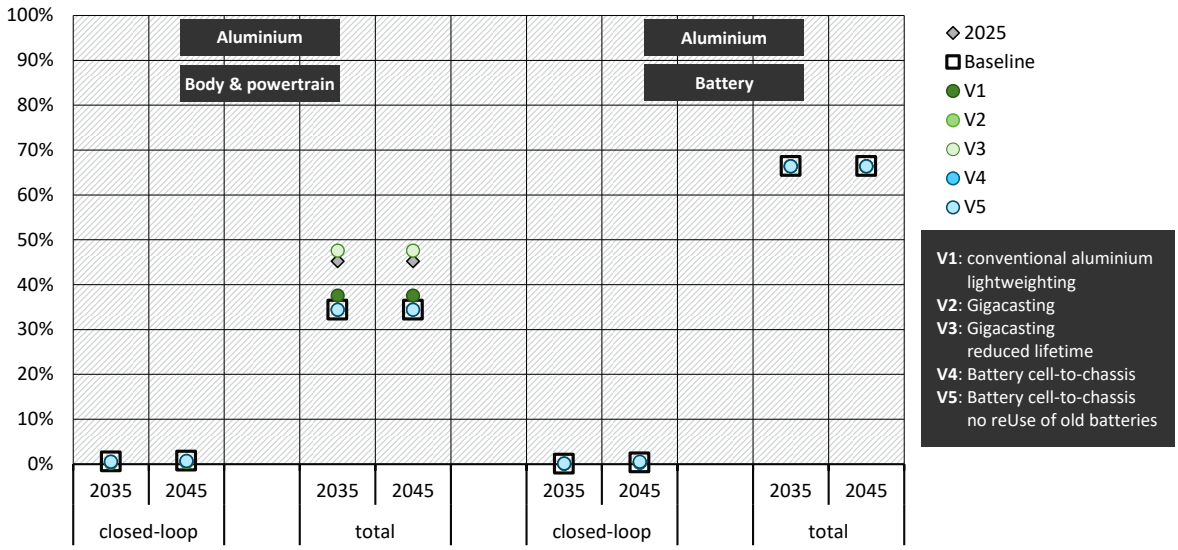
Comparison of recycled content

Lightweighting only has an indirect effect on the recycled contents of materials in car production if there is a shift in quantity ratios between individual material types with different recycled contents. As shown in Figure 57, the recycled content of cast iron and cast aluminium is significantly higher than that of rolled materials.

Accordingly, lightweighting does not result in any changes in the recycled content of steel & iron, as only steel, but not cast iron, is affected. In the case of aluminium, the effects depend on the specific lightweighting measure.

- Firstly, a look at the baseline development is helpful. Between 2025 and 2035, the recycled content in the glider will fall from 45% to 34%, as no new petrol and diesel cars with large quantities of cast aluminium in the engine block will be registered from 2035 onwards.
- With conventional aluminium lightweighting, the recycled content in the body increases slightly. In addition to the sharp increase in the amount of rolled and forged aluminium, cast aluminium is generally added and thus gains percentage shares of the total aluminium demand.
- With Gigacasting, only the amount of cast aluminium with a high proportion of recycled aluminium increases, bringing the total recycled content of aluminium to 48%.

Figure 57: Recycled aluminium content for cars for the different variations (lightweighting)



Source: own figure, ifeu/ Oeko Institute

3.5 Design for Circularity

3.5.1 Background

The design of vehicles sets the fundamental basis for saving materials and greenhouse gases throughout the entire life cycle. Design for circularity is a cross-cutting issue and can contribute to achieving goals such as durability, upgradeability, reparability, recyclability, refurbishment, reuse, repurpose, dismantlability and raw material savings in vehicle production (Mesa 2023). In consultation with UBA, the focus of this option was set on the following design goals:

- Longevity, including upgradeability,

- Dismantlability

An increase in **longevity** can lead to a reduction in GHG emissions, provided that the efficiency gain in the utilisation phase is not outweighed by fleet renewal. The switch to e-mobility and the increasing share of renewable energies in the electricity mix are increasingly emphasising the production phase as a greenhouse gas-intensive phase in the life cycle.

Increasing **upgradeability**, i.e. the possibility of upgrading or customising the product in terms of hardware or software components, can make an indirect contribution to reducing GHG emissions, as modular upgrades allow the vehicle to meet the user's requirements longer, thereby extending its utilization phase. Design for upgradeability thus supports the goal of longevity. As the level of electronic components increases, so does the relevance of upgradeability. Experience from the electronic appliances sector shows that software obsolescence can lead to premature disposal of appliances.

Increasing the **dismantlability** of vehicles helps to make repairs potentially easier if vehicle components are more accessible (e.g. not glued). Dismantlability therefore also supports the goal of reparability. At the end of life, easy dismantling supports good and clean sorting of parts so that selected components can be used for second-life applications (e.g. batteries see 3.7) or as spare parts (see chapter 3.6). Parts that are no longer used are sent to recycling. Certain construction methods in the automotive industry have so far made end-of-life (EoL) recycling more complex and therefore more expensive (e.g. fixed welds but also screw connections in some cases). Easy dismantling of different materials and alloys can make an important contribution to recycling with high-quality secondary materials. Design for dismantling thus supports several objectives, including reparability, re-manufacturing, second life and recycling.

3.5.2 Status quo

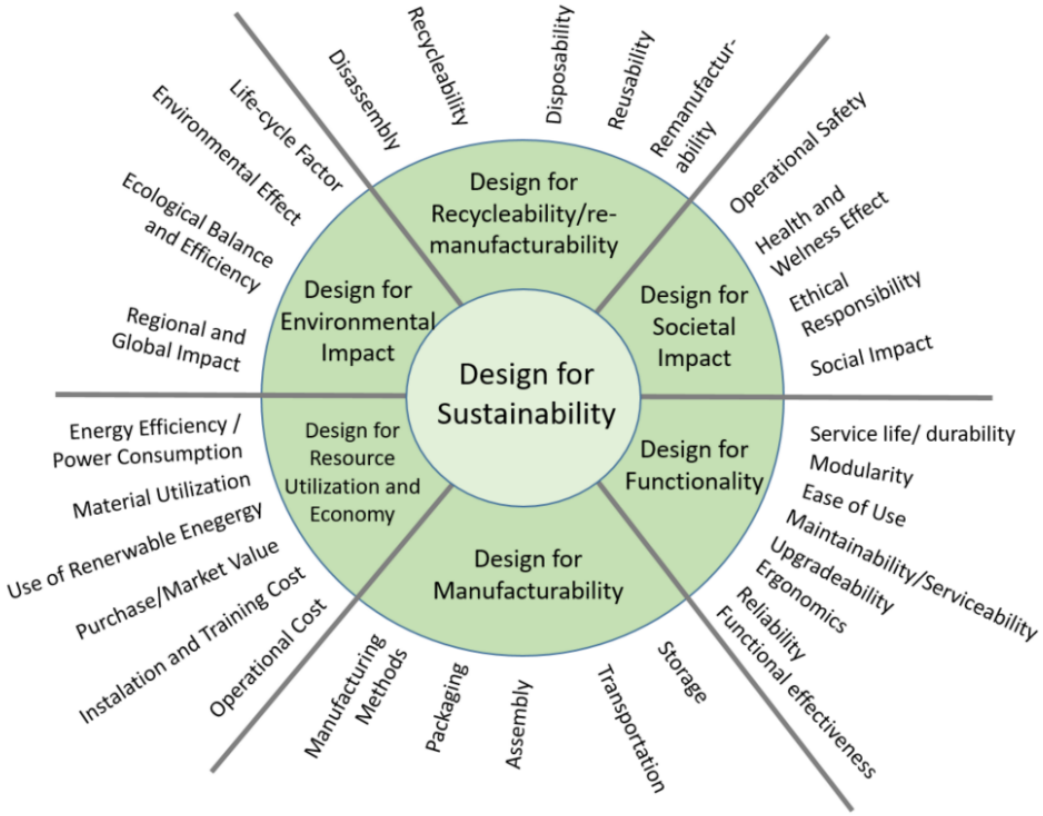
Elements of design for circularity

Design for circularity is a cross-cutting issue with various different objectives. Figure 58 displays a schematic framework of design for sustainability, as developed by (Jawahir et al. 2007). The framework's core elements are referenced by further studies examining the design for sustainability in the automotive industry (Mayyas et al. 2012).

Design for Sustainability (DfS) comprises a multitude of different core elements (inner circle), that are differentiated into further sub-elements. Examples directly linked to circularity include amongst others recyclability, remanufacturability, reusability, disassembly, durability, upgradeability, or environmental effect.

Within the project, the focus is set on the objectives design for longevity (incl. upgradeability) and design for dismantlability. With regard to the framework, these are categorized under the core design element Design for Recycleability/Remanufacturability and Design for Functionality, respectively.

Figure 58: Core elements of Design for Sustainability (DfS)



Source: own illustration Oeko-Institut / ifeu, based on(Jawahir et al. 2007)

Design for longevity (or design for durability / service life, as referenced by Jawahir et al. (2007)) focuses on increasing the probability that a car will work to the full extent of its basic functions over a certain period of time (Mayyas et al. 2012). The product lifetime of a vehicle is an important factor in order to determine the stock and flow of vehicles and those vehicles reaching end-of-life. With regard to the lifetime of electric vehicles, long-term data is still rare. Considering the life curve of ICEs, PHEVs, EVs and HEVs it can be stated that most cars of the EU fleet that have been registered 15 years ago will reach their end-of-life (European Commission 2023c). In the baseline of the AutoRess model for BEVs it is assumed that the average lifetime is 15.8 years based on the ELV-assessment (European Commission 2023c). With regard to the product lifetime one can differentiate between the physical lifespan (PHL), which describes the survival span from production to final disposal, and the possession lifespan (POL), which is the span of possession from purchase of the product to replacement (Nakamoto, Kagawa 2022). (Nakamoto, Kagawa 2022) analyse that in Japan the POL of the first owner is approximately half the PHL. In Germany the average POL is between 6-7 years (DAT Report 2021), and thus also approximately half of the physical lifetime (of EU fleet).

Design for dismantlability (or disassembly) describes the difficulty or complexity of dismantling components or assemblies. This is influenced, among other things, by joining techniques, i.e. the way in which parts or components are joined in the vehicle (e.g. glued, riveted, welded). The level of equipment is also relevant, as is the provision of information on material composition, among other things (Mayyas et al. 2012). The disassembly of BEVs is addressed in various studies (Baazouzi et al. 2021; Gerlitz et al. 2021; Tan et al. 2021)

As the illustration of the core elements (Figure 58) suggests, individual design goals can cause conflicts with other goals. For instance, focusing on a design that makes the car last longer, will

on the one sight reduce waste generation and raw material use; yet an adverse effect of a long service life is that older, less efficient vehicle technologies will then remain longer in the fleet, causing higher fuel consumption compared to newer, more efficient vehicles. Consequently, this could impact the overall environmental impact of the sector or product (Mayyas et al. 2012).

Longevity can also stand in contrast to the recovery of material for recycling e.g. due to later availability of end-of-life vehicles, or if enhanced durability was achieved by employing substances that restrict recycling (e.g. non-detectable pollutants in plastic components).

Further, a reduction in component complexity, e.g. for vehicle chassis, could require less welding, industrial adhesives and other joining techniques which will have an advantageous effect on the economy of assembly and disassembly of vehicles. At the same time, this might reduce the possibility to repair individual parts in case of an accident and thus decrease service life. Also, if the reduction in complexity is achieved by moulding, for instance in the case of moulded batteries, this again leads to a conflict of objectives with recycling (second life) and dismantling.

Nevertheless, individual design elements can also support each other: Decreasing the effort and time for assembly and likewise disassembly will most likely have a positive effect on operational costs.

Problems that are currently being reported and that go back to production design decisions concern batteries and their lack of modularisation. Manufacturer employ different battery geometries and screw connections. Due to this heterogeneity, recycling companies salvage processes for returned batteries are difficult to standardise and cost-intensive manual work is required. The question therefore arises as to whether increasing quantities of End-of-Live electric vehicles will solve this challenge or whether the problem can be better addressed with standardisation (e.g. for geometries, connections).

Design decisions and concepts generally go through a long process until they are implemented. In this project, the focus is thus set on the design of electric vehicle (BEV). Likewise, it should be mentioned that electric cars do not yet play a major role in the current business of recycling companies. However, it can be expected that the continuous switch from combustion engines to electric cars will provoke a change in material composition as well as a reduced number and weight of cast parts. These changes in general car design will affect the end-of-life management in the foreseeable future (Mauer, Kallien 2018).

3.5.3 Legal framework

"Since 2005, the EU Ecodesign Directive has provided the framework for standardised, binding minimum eco-design requirements for products within the EU. This directive strengthens the market for efficient and environmentally friendly products. At the same time, considerable potential for saving energy and resources in the appliance and product sector is being realised. The directive starts at the product design stage, as this is where the majority of the environmental impacts of products are predetermined" (BMWK 2024).

Vehicles are not yet part of the 29 product groups[10] for which implementing regulations are in force.

The Joint Research Centre (JRC) conducted a preliminary study on new product priorities for the Ecodesign Regulation in 2023. The products examined include used tyres: As far as the

[10] These include product groups for lighting equipment, televisions, domestic refrigerators, domestic dishwashers, domestic washing machines and dryers, hoovers, as well as electric motors (for heating and ventilation technology), external power supply units, transformers and fuel boilers.

collection of waste tyres is concerned, 40% are currently destined for co-incineration. However, it has been estimated that the recycling of EOL tyres could save 700 kg of CO_2 per tonne of tyres. Further research should be conducted in the areas of retreading, new uses for end-of-life rubber, recycling and targets for recycled content, sustainable sourcing and deforestation-free supply chains (JCR 2023a).

The proposal for a regulation on requirements for the circular design of vehicles and the disposal of end-of-life vehicles submitted by EC has the primary objective of dovetailing the design requirements for vehicles more closely with the provisions for the disposal of end-of-life vehicles. The vehicle design requirements are formulated in such a way that they constitute an effective prerequisite for the proper implementation of the end-of-life vehicle management provisions (European Commission 2023a).

Design for longevity and upgradeability are, however, not specifically mentioned in the proposal.

With regard to the design of products the current developments of the new EU Ecodesign Directive are of high priority. Vehicles are not in the frame of the directive. However steel is the first intermediate product for which a proposal for a product-specific regulation is currently being drafted as part of the new European Ecodesign for Sustainable Products Regulation (ESPR) (European Commission 2024a; UBA 2024). The aim of the ESPR is to create a broad legal framework for a wide range of products (including textiles, mattresses and aluminium) in order to make products sold on the EU market more sustainable. The ecodesign requirements for products include the criteria of recycled content, durability, reusability, upgradability and reparability, but also the creation of a CO_2 and environmental footprint, as well as making extensive product information available in the form of a digital product passport (European Commission 2024b). Product-specific requirements for the individual criteria are adopted as part of separate delegated acts (UBA 2024).

For steel, ecological and technical-economic aspects of iron and steel products are currently being examined as part of a preparatory study. The study provides a basis for the future legal act for iron and steel products and is intended to identify corresponding measures for optimization potential (European Commission 2024a). The workplan on steel started in June 2024 and should be completed by June 2025. The requirements for a digital product passport also include the development of a label. According to the Commission, this includes "*an easily accessible label on products that provides immediate access to information on the sustainability of the product. It will be useful not only for consumers, but also for customs and market surveillance authorities*." (European Commission 2024b).

3.5.4 Foreseeable development trends

Insights from the expert workshop

As part of this project, various issues related to the design for circularity were discussed with experts and stakeholders from industry, science and civil society at an expert workshop on June 27, 2024. The Workshop insights related to foreseeable design trends are summarized in this chapter.

Design for longevity is not a new topic and has been pursued for a long time by the industry. The focus of current design developments is almost exclusively on e-mobility. This finding is an important parameter used for modelling (see chapter 3.4.6). The extension of usage time and service life gain even more importance against the background of the switch to electronic cars, which shifts the emission-intensive life cycle phase from the usage- to the production phase.

According to participants potential technical and design aspects that can improve circularity in general include, amongst other things, the reduction of model variants, the use of more mono-material, segment suitable components (e.g. shock absorbers), the incorporation of predetermined breaking points; using other painting techniques, as well as durable bodywork and upgradeability (e.g. interior parts). Further, it was mentioned that new business models, such as Mobility as a Service, could create incentives for reuse and refurbishment.

To improve recyclability already in the design stage of car production, attention should be paid to the recyclability of the components / materials used, e.g. composite materials should be questioned for each component. The variety of materials used for plastics should be reduced.

Concerns were raised about the durability in the context of the switch to e-mobility. Open questions are the influence of the (possibly lacking) modularity of the battery. Further, it remained unclear to some participants if the dependence on software and special components lead to premature obsolescence. However, regarding the battery, the fact was highlighted that there is still a lot of development potential remaining. Battery life should foreseeably correspond to that of the vehicle and therefore not be a reason for obsolescence. Also, improvements in cell chemistry could enable batteries to have a Second life (see chapter 3.7).

Standardization is considered an instrument that could help to create a business case here and in general reduce the variety of materials and thus increase / facilitate recyclability. At the same time, there may also be conflicting goals if the standardization of batteries leads to a slowdown in the spread of new efficient technologies or if innovations are generally slowed down due to the specifications.

From the expert workshop, it was not possible to predict whether the service life of electric cars will change in the period under consideration. Likewise, no clear trend could be identified for dismantlability.

Gigacasting

As already highlighted in chapter 3.4.4, currently so called mega- or gigacasting is a topic that is affecting the automotive industry globally (Fuchslocher 2022; Schwarzer 2024). The new aluminium die-casting process allows key body structures to be cast as one large part. This means that around 70 or more components can be replaced. Tesla has already implemented the process in the Model Y, Toyota will do so from 2026, Volvo, Hyundai, Ford and perhaps the rest of the car industry are involved or will follow. Toyota assumes that gigacasting could halve the body assembly time from 20 to ten hours per vehicle (Schönfeld 2023). The Fraunhofer IWS is conducting further research into this technology (Fraunhofer IFAM 2024). To date, the process has mainly been used for electric vehicles.

Gigacasting influences the goal of dismantlability, which tends to be facilitated by a significant reduction in component parts. At the same time, however, there could be a conflict of objectives with repairability (and durability). Insurers currently assume that damage to a load-bearing part will result in more total losses (ecomento.de 2024). Unfortunately, there is little empirical data on this. Yet, for instance, SIXT USA has sold its Tesla fleet for this reason (Klender 2024). On the other hand, according to Tesla, single structural casting absorbs the impact force of an accident much better. In addition, the die-cast parts are mounted inside and secured by replaceable crash elements (Pfeiffer 2022b; TFF Forum 2022).

According to the experts from the workshop, the comprehensive use of gigacasting is not currently on the horizon for German OEMs, as there are already established production processes in place. In addition, high reject rates are to be expected and e.g. cast components require thicker walls. At the same time, the casting process allows a higher use of secondary

material. Nevertheless, a change in production technology is not (yet) driven by recycling or design aspects. At present, it is unlikely that there are many accidents (in Germany) in which the entire structure would be affected. A carbon footprint of the process (or of cars with large die-cast aluminium components) could provide important additional insights.

Given the insights from the expert workshop and because gigacasting is not mainly driven by design concept aspects, gigacasting was not considered as a foreseeable trend that is included in the modelling of this option. However, it is considered in the lightweight subject area (see chapter 3.4).

3.5.5 Fields of action and issues

Many important issues and fields of action were discussed at the expert workshop on "design for circularity".

- A car design that focuses on separability is highly relevant for end-of-life vehicle recycling, this involves e.g. the consideration of suitable predetermined breaking points for components as a design component. The car design must consider a quick dismantling process, as effort and costs involved is high. Modularity and standardisation are potential drivers for better recyclability (dismantlability) and longevity and could also strengthen the second-hand market. The mandatory provision of basic dismantling information for recyclers, as demanded by the proposal for the European Commission's Directive (European Commission 2023a), could be an appropriate instrument here.
- In addition, securing a large quantity of end-of-life vehicles (no illegal exports) is an important issue in order to establish efficient structures. As recycling technologies will be developed further in the future, it will also be possible to better process end-of-life vehicles through pre-sorting. Yet, experience with BEVs is still limited. Composite materials, bonding and a wide range of variants are a general challenge - these aspects make automation, the selection of instruments and tools more difficult and require a lot of manual (non-destructive) intervention[11]. Destructive disassembly is also difficult, as the materials may be contaminated.
- Plastics are considered to hold a lot of potential for improved recycling, compared to metal or glass. Mix plastic clusters cannot be recycled together. Multi-layer components (e.g. surface cover, foamed layer, hard bottom layer) could instead be produced/foamed from plastics of the same family in one component. Another possibility is the use of a mono-material, where applicable.
- Although not yet ready for the market, recycling technologies for components with protective coating (e.g. paint, metallization, chrome-plated parts, e.g. to protect against corrosion) are improving.
- Reduce approaches (smaller cars) have not yet been taken into account or not taken into account enough (see also chapter 3.3)
- Reuse of EoL components is preferable to recycling and should be expanded where possible
- Longevity as a goal was discussed controversially. One open question was whether recycling might be more efficient than long-term use in the foreseeable future. In order to get a better

[11] Practical examples: recycling company Herfel uses handling excavators with tweezers (e.g. for wiring harnesses) or BMW dismantling center: circular.economy.erleben@bmw.de

understanding in this regard, the modelling focusses on comparing the effect of an increased recycling (due to improved dismantlability) against longer car service life (see chapter 3.5.6)

- Further concerns for the longevity of vehicles are raised with regard to the increased dependency on proprietary special components and software, due to the shift to electric vehicles. As a consequence, repair and maintenance become more complex and therefore expensive. Further, a temporarily limited provision of software updates could lead to premature obsolescence. This dependency could also lead to restrictions with respect to the second-hand market for vehicles and car components. An Instrument to alleviate these concerns could be mandatory software-updates and lifetime guarantees for vehicles.
- Further, standardization and modularity of components (especially batteries) were seen as major tools to increase repairability and therefore longevity. Standardization and modularity were also seen as appropriate approaches for an increase in the dismantlability of vehicles. For the latter, the mandatory provision of basic dismantling information for recyclers, as demanded by the proposal for the European Commission's Directive (European Commission 2023a)
- The key point about design for circularity is that it is an investment in the distant future. This raises the general question of who bears the costs of this enabler of the circular economy. The costs should not only be borne by the end-of-life phase and recycling companies. The EU's extended producer responsibility is therefore an important instrument for taking the costs of recycling into account from the outset and ensuring that end-of-life vehicles are returned to the cycle. Appropriate policy measures can ensure that investments pay off in the long term.
- Design decisions in the past lead to problems today: End-of-life vehicles contain plastic parts containing pollutants (not subject to verification prior to 2003), which are likely to limit circular use. Fundamental challenge of temporal inertia: newly developed vehicles are not quickly end-of-life vehicles. Development work (approx. 2 years) and use phase (approx. 15 years) means that significant high-quality recyclates would not be available until 2040. However, an earlier effect may occur in the use phase (repairs).
- Used parts market: whether a new or used part is used for repairs depends on various factors:
  - Central register: used parts are not centrally organized / registered in Germany. The interest of insurance companies, which bear the costs, is therefore to use new parts, as these are available more quickly and thus minimize expensive downtimes. A central and supra-regional register for used parts could remedy this situation and reduce the need for new car parts
  - Role of insurance: In Germany, it is the car owner who decides whether a new part or a used part is fitted for repairs, but in the event of an accident (or a corresponding insurance package) this is paid for by the insurance company. The owner therefore has an incentive to opt for the more expensive new part. The opposite example is Sweden: Here, the insurance company decides which replacement part is used and also bears the costs. This creates an incentive to opt for the cheaper and more environmentally friendly option of a used spare part (as long as there are no excessive costs for a longer service life, see above).

Glass

Glass recycling in vehicles is an interesting field of action. However, the recycling of glass is not the focus of this option and is therefore only described in qualitative terms here in agreement with UBA.

Car windscreens are coated and bonded with various plastics and tinting films. This makes recycling very challenging, as the individual components cannot be separated again. EoL vehicle glass (e.g. windscreens or panoramic roofs) is therefore largely recycled into bottles or insulating materials. The manufacturer Audi is now planning and testing a closed-loop recyclate utilisation of 30-50% for the Q4 E-Tron electric crossover. This is made possible by a process developed with Reiling Glas Recycling, Saint-Gobain Glass and Saint-Gobain Sekurit: the car windows are shredded in a special process and then broken down into their components. The partners melt down the resulting glass granulate and feed it into the manufacturing process for automotive flat glass (MediaInfo Audi 2022).

3.5.6 Modelling

In the previous chapter 3.5.4 we elaborated that no clear trend could be identified for the longevity or dismantlability of future cars. The modelling for this subject area aims at examining the effects a change in vehicle design with respect to longevity and dismantlability have on GHG emission and raw material demand. In order to do so, flat-rate percentage increases in the respective design targets were assumed.

This subject area primarily concerns vehicle production with subsequent effects on other stages of the life cycle. As the registration of conventional cars is due to expire by 2035 and it can be assumed that manufacturers will spend more time developing electric cars, for the modelling we chose to focus on the design of electric cars only. This assumption was supported in the expert workshops (see chapter 3.5.5).

Several parameters were adjusted, compared to the baseline, for modelling an increase in longevity and dismantlability, respectively (Table 20). The main purpose of modelling the four variations is to assess the magnitude of the effect improvements in longevity and dismantlability have with respect to THG-emissions and the reduction of the demand for (primary) resources. Results are then used to compare the effectiveness of improvements in either of those dimensions.

For longevity, a new vehicle class with extended longevity is introduced gradually. This new class is assumed to make up 25% of newly registered vehicles in 2035, increasing its share in new registration finally up to 100% in 2050. This approach takes into account that currently no foreseeable trends could be identified on a design level and the fact that there will likely be a significant delay before changes in design will evolve from conceptualization to implementation and affect the automotive fleet (i.e. temporal inertia). Two variations for the newly introduced vehicle class were modelled: V1 extends the baseline lifetime by 10 percentage points, V2 by 20 percentage points.

For dismantlability, first the rate for reuse and repurpose of the battery is gradually extended: in the option V3 by 10%, in V4 by 20%, by 2050. The rate of reuse and repurpose in the model describes the share of material in different parts of the vehicle (in this case the battery), which can be recovered and reused as a finished component in a new vehicle or other sectors (see chapter 3.1). Furthermore, material-specific recycling rates are gradually increased: for V3 by up to 10 percentage points, for V4 by up to 20 percentage points for each material until 2050. However, since recycling rates for several materials are already on a high level (see chapter 3.1.2.2), the difference in recycling rates between the two variations is not as significant, since a 100% recycling rate represents the threshold value here. Finally, the rate of high-quality

material that is recycled in closed loop is gradually increased: for V3 by up to 10 percentage points, for 4 by up to 20 percentage points for each material until 2050. The recycling input rates were partly adjusted to reflect the additional availability of (high quality) secondary material due to higher recycling rates.[12]

Table 20: Overview of adjusted parameters for the variations

Parameters / Variation	longevity V1	longevity V2	dismantlability V3	dismantlability V4
Share of more durable (more repairable) vehicle concepts	2030: 12.5% 2035: 25% 2040: 50% 2045: 75% 2050: 100%	2030: 12.5% 2035: 25% 2040: 50% 2045: 75% 2050: 100%	2030: 0% 2035: 0% 2040: 0% 2045: 0% 2050: 0%	2030: 0% 2035: 0% 2040: 0% 2045: 0% 2050: 0%
Increased longevity	+10%	+20%	+0%	+0%
Share of material reuse & repurpose (battery)	Baseline	Baseline	up to +10% in 2050	up to +20% in 2050
Material-specific recycling rates	+0%	+0%	up to +10% in 2050	up to +20% in 2050
Rate of high-quality closed-loop recycling	+0%	+0%	up to +10% in 2050	up to +20% in 2050

Source: own table Oeko-Institut / ifeu

The four variations and their general characteristics can be summarized as follows:

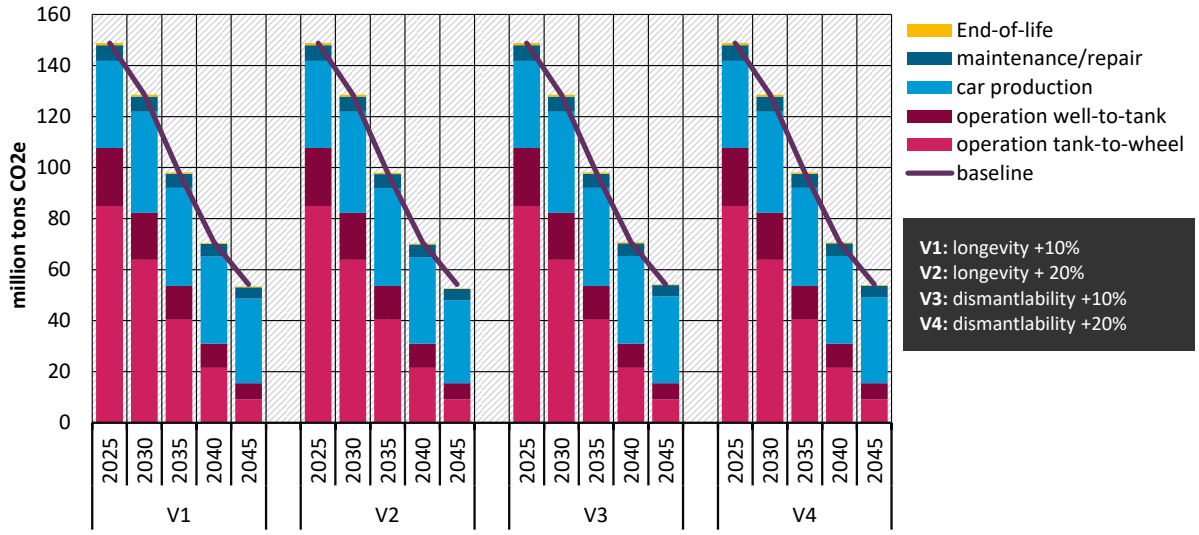
- V1: longevity + 10%; gradual increase of market share of cars with increased lifetime
- V2: longevity +20%; gradual increase of market share of cars with increased lifetime
- V3: dismantlability +10%; gradual increase of market share of cars with improved dismantlability
- V4: dismantlability +20%; gradual increase of market share of cars with improved dismantlability.

3.5.7 Results

The variations of the car design in terms of longevity and dismantlability, modelled here, are described in the previous chapter (chapter 3.5.6). Figure 59 shows the development of GHG emissions for the variation 1 to 4. It displays that none of the four variations has significant impacts on the GHG emissions along the whole life cycle in the considered time period compared to the baseline.

[12] Here the recycling input rates are determined endogenously by the availability of materials: only those recycling input rates for materials were changed, where the available closed-loop secondary materials exceed the total secondary materials needed to satisfy the baseline recycling input rate. This means that, mathematically speaking, the recycled content of these materials can be covered entirely by closed-loop recycling. In contrast, the modelling approach applied for modelling the subject area in Chapter 3.9 determined the recycling input rates exogenously.

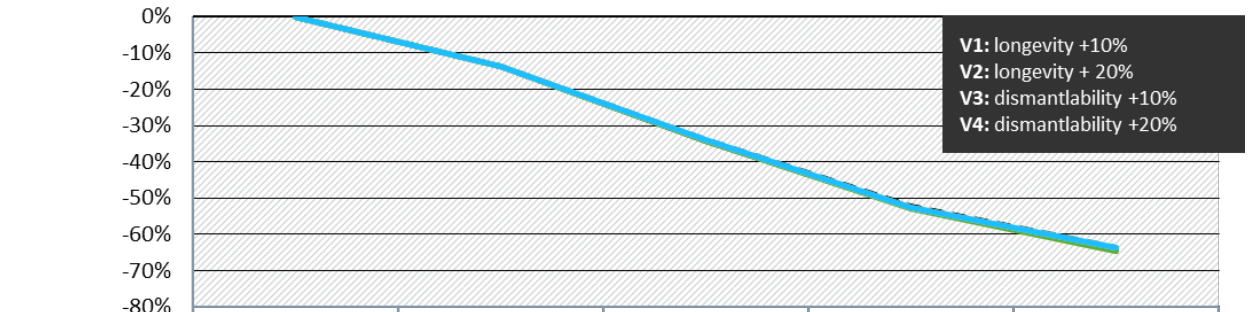
Figure 59: GHG emissions for cars for the different variations (design for circularity)



Source: own figure Oeko-Institut / ifeu

The results in Figure 60 show that the gradual introduction of a durable car (V1 and V2) has only marginal impact on the GHG emission development compared to the baseline. The introduction of a car with an increased lifetime of 1.6 years on average (17.4 years average lifetime instead of 15.8 years average lifetime in the baseline) does not have significant impacts in the considered time period; GHG emissions decrease by an additional 0.6 percentage points in 2045 compared to the baseline. The same applies for the even more durable car introduction in V2 with an average of 3.2 years longer lifetime. GHG emissions in 2045 decrease by an additional 1 percentage points compared to the baseline development. The lack of a significant impact on GHG emissions is partly due to the gradual market launch and the delayed effect on car registration and production. The introduction of durable cars in V1 does decrease the registration of new cars in 2035 by -0.1%, in 2045 by -3%; in V2 car registrations decrease by -0.3% in 2035 and by -4% in 2045. The effect of more durable long living cars gains further significance only after 2045.

Figure 60: Change in GHG emissions for cars for the different variations compared to 2025 (design for circularity)



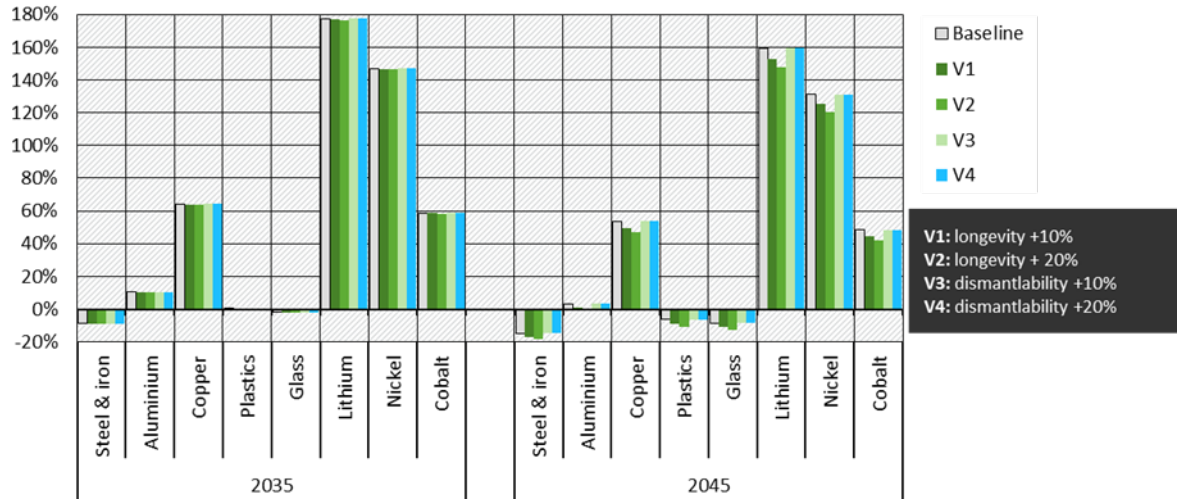
	2025	2030	2035	2040	2045
Baseline	0,0%	-13,6%	-34,1%	-52,5%	-63,6%
V1	0,0%	-13,6%	-34,1%	-52,7%	-64,2%
V2	0,0%	-13,6%	-34,1%	-52,8%	-64,6%
V3	0,0%	-13,6%	-34,1%	-52,5%	-63,6%
V4	0,0%	-13,6%	-34,1%	-52,5%	-63,8%

Source: own figrue Oeko-Institut / ifeu

The gradual introduction of easily dismantlable cars (V3 and V4) only has a marginal effect on GHG emissions of approx. -0.2 percentage points of additional reduction for V4 in 2045, compared to baseline. This reduction is caused by a reduction in the demand for primary materials for some material groups (see below) and the substitution with secondary materials, which display lower emission-intensities.

The changes of total material demand for V1 and V2 are marginal in 2035 and become slightly more pronounced in 2045 (see 3.5.6). For all materials, total material demand decreases slightly compared to the baseline in 2025. For V1, in 2035 changes are in the amplitude of -0.1 to -0.4 percentage points relative to the baseline. In 2045, when less cars need to be registered due to the growing share of longevity cars, material demand of car production decreases around 2.2-6.8 percentage points. Assuming that the average lifetime of a vehicle increases by +20% compared to the baseline (V2) results in an additional reduction of material demand that is twice as high as for V1 (assuming a 10% increase in lifetime).

Figure 61: Changes in material demand (total) for cars for the different variations compared to 2025 (design for circularity)

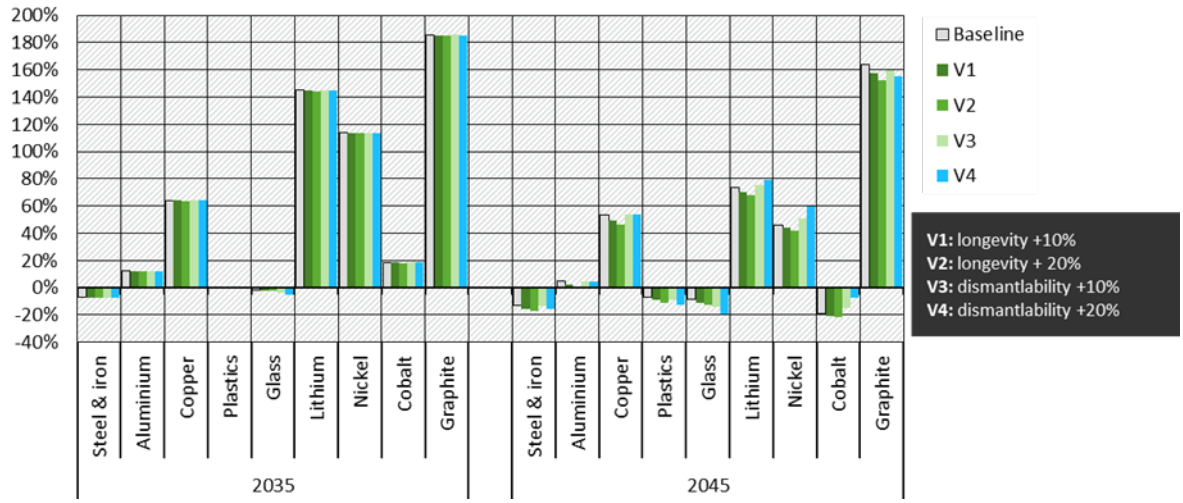


Source: own figure Oeko-Institut / ifeu

As illustrated in Figure 61, for V3 and V4 there is no change in total material demand compared to the baseline, there is however a change in composition of open-loop and closed loop recycling material used for car production. As noted before, we generally see that the effect on changes on primary material demand (Figure 62) is delayed given the gradual introduction of longevity and dismantlability designs of cars. In 2035, there is hardly any effect on primary material demand, while in 2045 for all four variations a reduction becomes visible for some materials.

In 2045, for the longevity variations (V1 and V2) primary material demand decrease proportionally to the decrease of total material demand. There are no changes in the rates of closed loop recycling. Given the assumptions in V3 and V4 that cars are more easily dismantled, more reuse of batteries is assumed, as well as an increase of recycling rates and the share of high-quality recycling materials and thus secondary material that is suitable for closed loop recycling. The newly available closed-loop recycling material substitutes primary raw material demand in V3 and V4 for some materials. The strongest effects can be observed for plastics, glass and cobalt, where in V4 we can observe an additional reduction of primary material demand of -5.6%, -11.0% and -8.6% respectively.

Figure 62: Changes in material demand (primary) for cars for the different variations compared to 2025 (design for circularity)

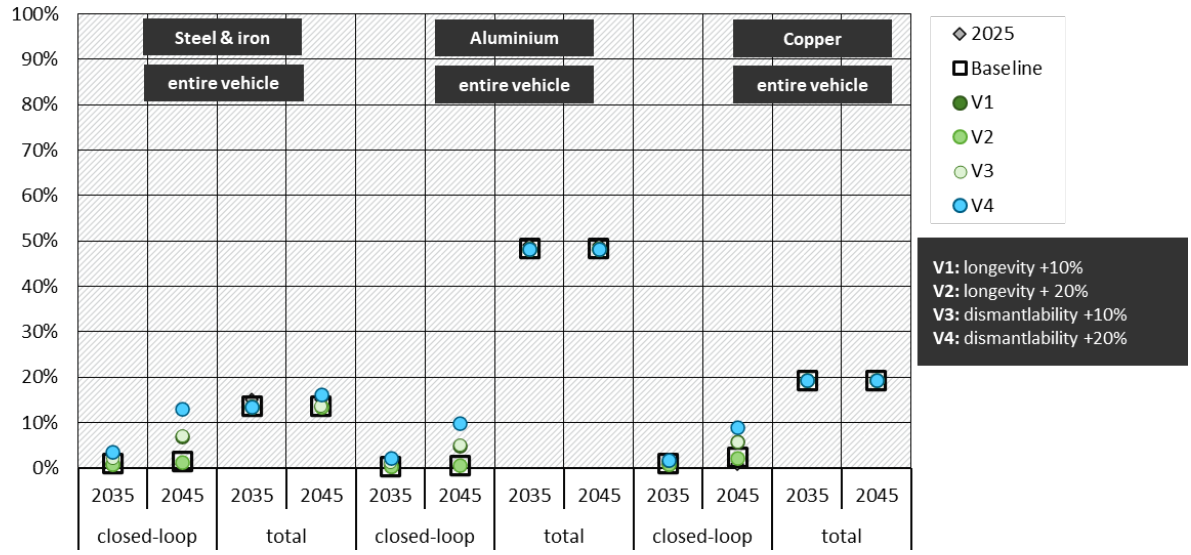


Source: own figure Oeko-Institut / ifeu

In general, it can be noted that a 10% (20%) increase in longevity has similar effects on primary raw material demand as an increase of dismantlability of 10% (20%) for several materials, e.g. for steel and iron and plastics. In V3 and V4, given the higher reuse rates assumed for batteries, primary material demand for battery materials increases compared to the baseline: 5.8% for lithium, 13.8% for nickel and 12.0% for cobalt. The reason for this is materials flowing into second life applications are not available for (closed loop) recycling, since they are still in use.

Looking at the entire vehicle, steel and iron, aluminium and copper closed loop recycling rates still increase (Figure 63). The more the design concept increases dismantlability, the higher the increase in closed-loop recycling and possible recycled contents. For iron and steel 13% in 2045, for aluminium 10% and for copper 9% closed loop are achieved in the ambition design variation V4.

Figure 63: Recycled content for cars for the different variations (design for circularity)



Source: own figure Oeko-Institut / ifeu

3.6 Repair and remanufacturing of EV batteries

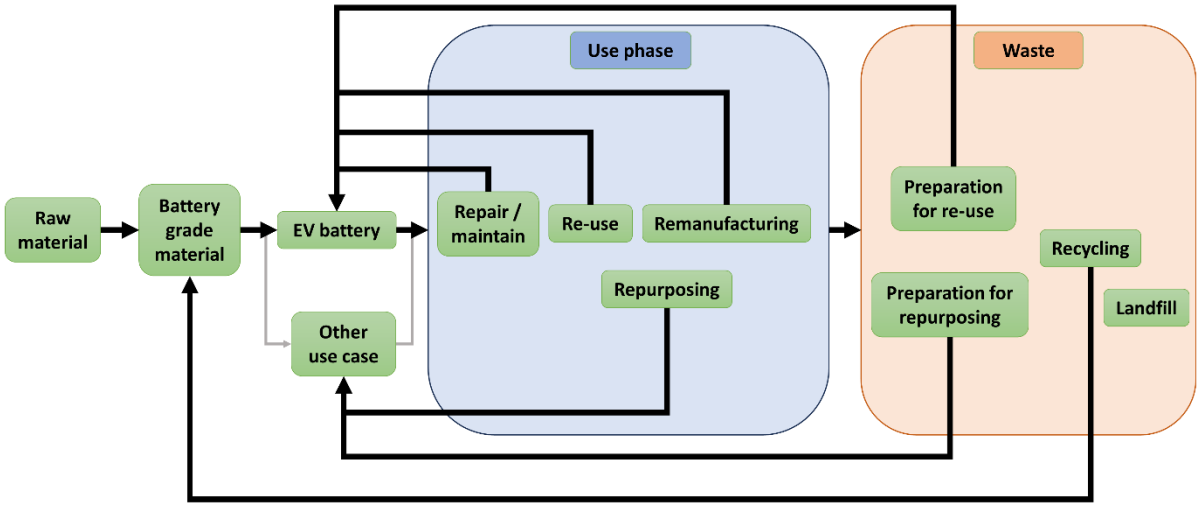
3.6.1 Background

The purchase cost of electric vehicles is high compared to conventional internal combustion engine vehicles, with the battery being one of the biggest cost drivers. Over the life cycle of a vehicle, the higher initial cost is not offset by lower running costs. A longer vehicle life of around 16 years is one possible solution to this problem, but this is offset by the limited life of the lithium-ion battery, among other things. Therefore, extending the service life of the lithium-ion battery has cost reduction potentials for the costumer. In addition to extending the life of traction batteries, components can also be reused in new products at the end of their useful life. As a result, there is potential for cost reduction through the purchase of the used battery, but also through the discounted purchased parts in the production of traction batteries. From an economic point of view, remanufacturing can therefore increase the economic viability of electric vehicles and thus their uptake. Another economic benefit is the development of new business models through the sale of used and remanufactured components (*Elektromobilität* 2024).

A longer service life is also particularly desirable from an environmental point of view: a longer period of use reduces waste and conserves resources by reusing components, a fundamental building block of a circular economy. The aim is to achieve the highest possible level of energy and material recycling at the end of a product's life—which is precisely the aim of re-use, repurposing, repair and remanufacturing (*Elektromobilität* 2024).

Generally, by extending the use phase of a product the input of new material and energy is reduced throughout a product's life cycle Figure 64 gives a schematic overview of the options of used and waste batteries. The benefits are usually considered to be higher for approaches like reuse, repair, redistribution, refurbishment and remanufacturing than for recycling and energy recovery. Repurposing (cascaded reuse) delays the need for recycling and end-of-life treatment and allows the benefits before disposal to be maximised. One of the main environmental benefits of repurposing is aiding grid integration of renewables. The use of electric vehicle batteries in renewable energy storage systems could increase the lifetime of the battery by 72% and result in a reduction in GHG emissions of 42% for whole vehicle emissions, based on emissions per kilometre. This application could also have indirect environmental benefits, as the development of a second-hand battery market could reduce the cost of electric vehicles (European Environment Agency 2018).

Figure 64: Schematic illustrating options for the end-of-life stage of batteries



Source: own figure Oeko-Institute / ifeu

3.6.2 Status quo

In their book "Elektromobilität—Grundlagen einer Fortschrittstechnologie" Achim Kampker and Heiner Hans Heimes identify a number of technical issues that need to be addressed for remanufacturing to be successful (*Elektromobilität* 2024). They group them into product, process and market challenges. The product side requirements are defined by existing research. These include the manufacturability of a product in a mass production environment, the construction of the product from interchangeable components, or the absence of disruptive technology changes. In addition, challenges in production planning and control arise in the context of remanufacturing processes in comparison to a linear value chain. With regards to the process, remanufacturing requires similar safety measures and equipment to those in battery manufacturing. The costs are further increased by the need for expensive specialised plants as well as skilled labour. Process cost reduction and efficiency gains through automation can be achieved through the use of appropriate technologies. A major obstacle in the automation of the disassembly process is the extreme diversity of battery designs at pack, module and cell level. Therefore, it is important to consider battery disassembly at the design stage. Examples include the use of detachable connectors and the ability to disassemble without destroying components that can help facilitate an economically feasible disassembly. To enable remanufacturing, the battery packs should have a modular structure and standardised interfaces, both within the pack and towards the vehicle, this also enables future replacement with new battery technologies. The market needs to ensure a clear traceability of battery components. Another challenge are the varying conditions of the returned batteries, which require customised preparation and assembly processes. Due to individual customer return policies, the supply of used batteries is likely to fluctuate. The same applies to the demand for reconditioned batteries. If it is not possible to match this return flow with demand, this can lead to high stock levels and the need for a sophisticated logistics network (*Elektromobilität* 2024).

To build trust in BEVs car manufacturers provide customers with warranties and guarantees for the batteries in their cars. They usually guarantee, that the batterie capacities remains above a threshold of 70 to 80% of the original capacity. Depending on manufacturer, vehicle and battery type these warranties span periods from 5 to 10 years or a distance of 160,000 to 200,000 km. If the battery capacity falls below the threshold or shows a fault within the warranty period, the

manufacturer is obliged to repair or replace it (ADAC 2022). The Euro 7 norm from April 2024 also defines minimum performance requirements (MPR) for battery durability. These are based on the battery energy and set specifications in % for rest energy left in the battery in two steps. Up to 5 years of life or 100 000 km (whichever comes first) the rest energy of the battery needs to be above 80% of the original battery energy for vehicles used for carriage of passengers, comprising not more than eight seats in addition to the driver's (M1). After 5 years or 100 000 km, the second step is for vehicles of up to 8 years or 160 000 km, whichever comes first. The remining required battery energy is set at 72%. For vehicles used for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes (N1). The steps are the same, but the remaining battery energy is set at 75% and 67% (European Parliament, Council of the European Union 2024b).

As the amount of BEVs in use is increasing drastically, warranty cases will occur more frequently in the coming years and manufacturers will be faced with a growing number of batteries in need of repair. Currently, there is no extensive experience or defined standards for setting up and operating battery repair lines. Therefore, manufacturers have to establish functioning service concepts and efficient repair lines for batteries.

At the moment, repair of EV batteries is primarily organized centrally by the manufactures, this requires a high logistic effort as the entire battery pack is sent to the repair centre. The customer receives a replacement battery locally. Once the battery pack is functional again it is returned to the workshop. For repairs outside the warranty period, however, this replacement procedure appears to be time-consuming, and workshops should also be able to gradually carry out battery repairs on site. But instructions and precise criteria on how to deal with damaged BEVs as well as for the repair and partial replacement of damaged batteries are not yet established. Therefore, there is still a great deal of uncertainty when dealing with damaged electric cars, which is why they are sometimes stored in quarantine for a long time or become total losses due to precautionary measures such as immersion baths in extinguishing containers. An evaluation by the German insurance industry (GDV) found that in the event of damage repairing an electric car is significantly more expensive than for a comparable combustion engine at an average of 30% to 35% (GDV 2023). At the same time maintenance and service costs are half for an EV compared to an ICE according to Detlef Peter Grün from the Zentralverband Kraftfahrzeughandwerk (Rosen 2024).

While 8%-10% of car workshops have the expertise and equipment to work on EVs, very few can work on the EV batteries themselves. With regards to the batteries, most workshops are limited to reading out failure codes from the Battery Management System (BMS) and refer the battery to the manufacturers in case it needs service. Problems are that measurement hardware and procedure are not standardized and might wield different results. Furthermore, manufacturers specifications with regards to how to handle damage on the batteries are very different (Schaal 2023).

Regardless, repairing a module is of course much cheaper than replacing the entire battery. The repair of defective batteries should generally not take longer than 72 hours in order to avoid long vehicle downtimes. A module repair takes about one day, including the removal and installation of the entire battery housing and testing. In terms of time and cost, a module repair is therefore comparable to an engine repair but can vary depending on the design (Rosen 2024).

Batteries arrive at repair centres with diverse fault patterns such as (Schaal 2023):

- Defective battery management systems

- Failure of electrical components such as current sensors or power electronics
- Defective cells or modules
- Damaged seals, insulation, or housings

The specialized equipment needed for handling and working with batteries is very expensive. On the other hand, there is yet not much demand. An additional burden is the lack of proper training and know-how. These present some of the hurdles for smaller workshops.

A survey by Roland Berger (Tim Hotz 2023) asked workshops around the world which where the top 3 failure modes they observed. Failure in the battery modules was the named must often in the top 3, by 53% of the workshops. Named the second and third most often were the Battery Management System (BMS) and Battery Disconnect Unit (BDU) with 49% and 38% respectively. 29% of the repair shops named structural components in their top 3. An array of electrical components was also named as well as thermal components, Table 21 gives an overview of the results.

Table 21: Main observed technical failure modes by workshops

Component	Failure	Rate
Modules	Battery Modules	53%
Battery Components	Battery Management System (BMS)	49%
	Battery Disconnect Unit (BDU)	38%
Electrical	Sensors	33%
	Wiring	19%
	Contactors	20%
	Connectors	20%
	Relays	12%
Thermal	Thermal Components	26%
Structural	Structural Components	29%

Source: (Tim Hotz 2023)

Some examples of repair and remanufacturing centres in Germany have been identified:

- Opel: "Battery Refurbishment Center"
- Volkswagen has 450 repair centres for high-voltage batteries
- MAN battery repair centres
- Replacement and repair of high-voltage batteries as a contractual partner of STREETSCOOTER (Dittmar & Stachowiak GmbH 2013)
- Leadec has been repairing defective traction batteries from light commercial vehicles centrally in Hoyerswerda since December 2022 (Schaal 2023). Leadec expects the cost of

transporting and repairing a battery to be 30% to 50% less than the battery's new value (Jaschinski et al. 2023).

Another example from Japan concerns the Nissan Leaf. Here the used batteries are dismantled in the new factory. Modules that have lost 20% or more of their original capacity are disposed of and replaced with modules from other batteries. Modules that are no longer suitable for use in vehicles can be reused for stationary energy storage or batteries for electric forklift trucks and other heavy equipment. Reconditioning is done centrally, but the "replacement batteries" can be installed by independent garages. The cost of remanufactured batteries is at around 52% of the new value (new battery cost: 5,499 US dollars, remanufactured 24 kWh battery: 2,855 US dollars) (Hanley 2018).

Nio is a Chinese EV manufacturer that relies on swappable battery packs. At 'swapping stations', customers can swap their current battery pack for a fully charged one. Nio claims that they only need 3% of extra batteries, and the batteries that are not used in the swapping station can act as grid storage. The batteries can be charged slowly, sustainably and flexibly. It is also possible to upgrade the battery packs in use. While the battery itself is not easier to repair than most other EV batteries, it is possible to run diagnostics in the swapping station and identify problems (Nio 2024).

When it comes to **repair**, the nature of the failure determines how it is handled. Complex problems at module level require specialist handling in repair centres. Less complex repairs, such as the replacement of standardised electronic components, can be carried out in local workshops. An overview of possible battery failures, the associated repair difficulty and the appropriate repair location is shown in Figure 65.

Figure 65: Overview over possible battery failures the associated repair difficulty and the suited repair location

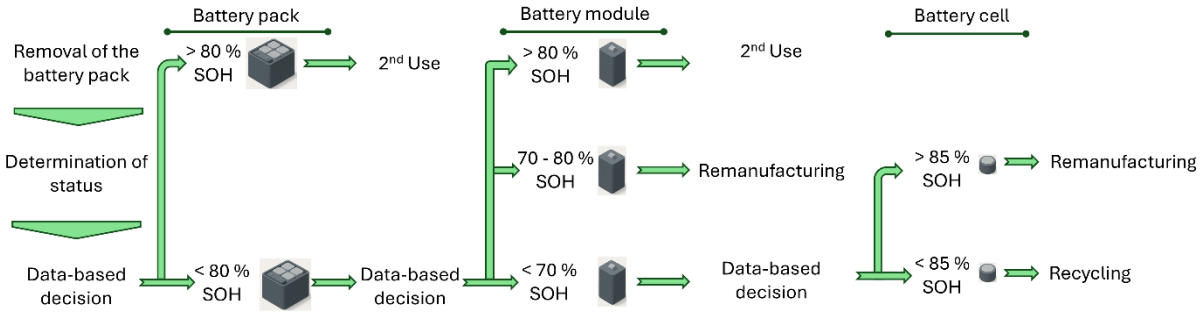
Component level	Fault Group	Repair requirements	Repair difficulty	Repair location: Local Workshop	Repair location: Regional repair center	Repair location: Refurbish center
Pack-level	BMS	• High-voltage training • BMS/diagnosis software success		Only select locations	Capable	Capable
	Electrical comp.	• High-voltage training • Spare parts availability		Only select locations	Only select locations	Capable
	Thermal mgmt.	• May require module servicing or replacement • Spare parts availability		Usually not capable	Only select locations	Capable
Module-level	Module	• Module repair: Module access, connector repair		Usually not capable	Only select locations	Only select locations
		• Module exchange: Module inventory for SoH balancing • BMS software access		Usually not capable	Usually not capable	Capable
	Cells 	• Module (re-)manufacturing capabilities		Usually not capable	Usually not capable	Only select locations

Source: own illustration Oeko-Institut / ifeu, based on (Tim Hotz 2023)

Heimes et al. (Heimes et al. 2021) describe a possible route and procedure of handling used EV batteries, as depicted in Figure 66. First, the battery pack is removed from the vehicle and some rapid tests are carried out (visual inspection, internal resistance), these are used to determine

the battery condition and pre-sorting is carried out. If the quick tests indicate that the battery pack is in a good condition, the SoH is determined. On average the SoH of a LIB is at 80% after the first utilisation phase. The following procedure can then be followed. If the SoH is still above 80% the pack can be used in a "2nd use" without further treatment. Otherwise, the battery packs are dismantled and characterised at module level. Battery modules with a SoH of over 80% can be transferred to a "2nd use" with little effort. Modules with a SoH between 70% and 80% are suitable for rebuilding battery packs. If the modules have a SoH of less than 70%, they could be dismantled further and characterised at cell level in case the battery module design permits that. Battery cells with a SoH of more than 85% can be rebuilt into battery modules. Cells with a SoH of less than 85% are sent for recycling. For economic reasons, the battery classification process should be carried out within short test times and with low equipment and labour costs.

Figure 66: Handling of used EV batteries



Source: own illustration Oeko-Institut / ifeu, based on (Heimes et al. 2021)

As Heimes et al. (Heimes et al. 2021) describe, dismantling EV LIB packs is a complex, time-consuming and cost-intensive process due to the wide variety of battery pack designs and the connection technologies used. Depending on the manufacturer and vehicle model significant differences in battery pack design occur, therefore different special tools and a high degree of flexibility in the disassembly process are required. At the beginning of the dismantling process, the battery pack is discharged, and the electricity is temporarily stored or fed into the grid. Next, the housing of the battery pack is opened, for example by removing the cover by loosening the screws along the edge of the cover. As the sealing rings between the battery cover and housing differ depending on the battery type, high forces must sometimes be exerted to remove the cover. Depending on the sealing material, the seal may be damaged during removal. The battery modules and other components such as the cooling system and power electronics are located inside the housing.

The removal of these components from the battery pack is now considered in more detail. After removing the housing cover, the battery components can be removed from the battery pack. To do this, first remove the wiring, then remove the cooling system and the high-voltage module and finally remove the battery modules. The cabling of the BMS master with the cooling system, the module slave board and the high-voltage module are removed first. The high-voltage (HV) and low-voltage (LV) wiring harnesses for connecting the modules to peripheral devices are then removed. The screwed, complex high-voltage module is then removed using an insulated screwing tool. To remove the cooling system, it is first separated from the cooling elements of the pack housing. In the case of liquid-cooled battery packs, the coolant should first be removed from the system using an extraction system to prevent the coolant from leaking and causing potential short circuits. The metal cooling plates and the cooling system components can be easily recycled due to their composition. The battery modules are attached to the battery pack housing via screw connections. Additional fixation using adhesives, foams or wax is optionally

used by the manufacturers and is correspondingly difficult to remove. Depending on the design, the battery packs consist of fewer than ten to 48 modules.

For further disassembly, the battery module must now be opened so that the battery cells can be removed. The module cover is either screwed or pressed in place. It is removed using insulated screwdrivers or a force/pressure insert. Depending on the battery design, the module housing is made of different materials (e.g. metals or plastics). The design of the housing also depends on this. Metal housings consist of a deep-drawn housing tray and a cover. Plastic housings usually have an end plate and are clamped to the battery cells. After opening the module, the cell contacts can be separated to remove the cells. For safety reasons, the cell contacts are covered or taped with insulating material. In most cases, the cells in the module housing cannot be removed without damaging them, as they are glued for thermal and electrical insulation.

Partially automated disassembly steps using human-robot collaborations have already been used to date, as they are easier to implement than fully automated disassembly.

The publication from Graner et al. (Graner et al. 2023) identifies several requirements for a functioning remanufacturing process, as well as existing challenges for the remanufacturing of EV Battery Packs andgives an overview of a functioning remanufacturing process. The SOH and aging condition of single cells determine about their further use. The same applies to the functionality of the e-parts, some of which could use an overhaul. The process sequence depends on the same business model or remanufacturing strategy. There are two strategies indicated in (Graner et al. 2023) in which either aged modules or aged cells are exchanged and replaced. Furthermore, in another strategy the whole system is disassembled and components are used as spare parts or in newly reassembled packs. Also, a combination of these strategies is possible: if a module contains a single or few degraded cells they are replaced, otherwise the whole module is exchanged. Some of the remaining cells from the removed module then might serve as spare parts. The strategy on mudul level is similar to the business model of the Nissan Leaf, where aged modules of LIBs can be replaced which is enabled by a special design with very small modules and bolted connections.

With regards to the remaining remanufacturing challenges Graner et al.; (Graner et al. 2023) identifies the wide variety of cell, module and pack types as the main reason the dismantling of LIB systems is time-consuming manual work. Nevertheless, considering the rising amount of returning LIBs, the remanufacturing process needs to be partially or fully automated to implement it industrially and economically. It must be further investigated whether a flexible line in terms of variants and quantities is better than an automated sub system separated by cell type (cylindrical, pouch or prismatic) or process steps (e. g. glued or screwed connections).

The main difficulties of disassembly of state-of-the-Art LIBs to cell level are listed as:

- Welded electrical connections between cells and welded busbars are difficult to separate without removing material (such as drilling or milling the contacts).
- Adhesive insulation between cells and between cell blocks and the cooling plate makes it very difficult to loosen and separate the cells without damaging them.
- The cells must not be damaged in any way (e. g. by penetration or destruction of the outer casing, short circuits and deformation due to excessive pressure).
- To replace a single cell in the module frame, the compression within the block should be maintained as the cells expand during use.

- The overall SOH within a block should be balanced, so the SOH of the inserted cells should match the SOH of the remaining cells.
- Corrosion, distortion due to thermal and mechanical loads, altered tolerance chains and induced residual stresses make disassembly complicated.

Acceptance of reuse batteries in EVs is seen as stumbling block as it largely influences consumer decisions. Here the condition of the battery is often seen as a "great unknown" and plays a major role in the purchase decision (ADAC 2022). The ADAC now offers a manufacturer-independent and neutral battery check in cooperation with its partner Aviloo (Schaal 2024). Standardized test procedure as well as the EU Battery Passport might ease doubts of costumers in the future.

The second lifespan of batteries can make sense from both an economic and ecological perspective: use in two consecutive applications reduces the costs for the first user due to the resale value and at the same time provides a battery that is cheap for second-life applications. Second-life solutions thus offer a unique value proposition for the three stakeholder groups that are regularly involved in interactions with used batteries: the vehicle OEM that supplies the used battery and the equipment manufacturer that stores the battery in a second-life application, as well as the customer who uses the second-life battery. There is also the possibility of improving the ecological and energy balance of battery-electric applications due to the reduced need for new batteries (Heimes et al. 2021).

There are already some major projects on repurposing of used EV Batteries as can be seen in Table 22. Further larger examples are a cooperation between RWE and Audi (RWE 2021) as well as Mercedes and Battery Loop (Hartmann 2022).

Table 22: Examples of battery second life pilot and commercial projects between 2012 and 2017

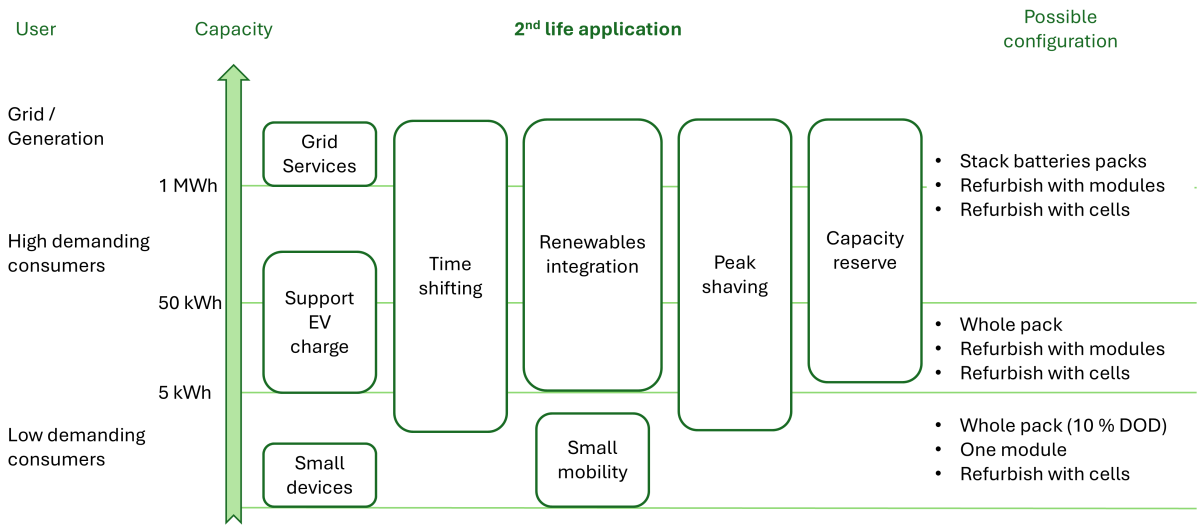
OEM	B2U Partner / Service Provider	EV Model	Capacity	B2U Application	Country
Daimler	GETEC, The Mobility House, Remondis	Smart	13 MWh	Renewable energy	Germany
GM	ABB	Volt	50 kWh / 25 kw	Power supply	USA
GM	ABB	Volt	n/a	Renewable energy	USA
Renault	Eco2Charge	Kangoo ZE	66 kWh	Renewable energy	France
Nissan	Eaton	Leaf	4.2 KWh	Residential energy storage	UK
Nissan	Eaton, The Mobility House	Leaf	4 MWh / 4 MW	Peak shaving, Backup power	Netherlands
Nissan	Sumitomo	Leaf	400 kWh / 600 kW	Renewable energy	Japan

OEM	B2U Partner / Service Provider	EV Model	Capacity	B2U Application	Country
Mitsubishi, PSA	EDF, Forsee Power	Peugeot Ion, C-zero, iMiev	n/a	Renewable energy	France
BMW	UC San Diego	Mini-E	160 kWh / 100 kW	Renewable energy	USA
BMW	Vattenfall, Bosh	ActiveE, i3	2.8 MWh / 2 MW	Renewable energy	Germany
BMW	Vattenfall	I3	12 kWh / 50 kW	Fast charging	Germany
Renault	Connected Energy	Zoe	50 kWh / 50 kW	Fast charging	UK

Source: (Zhao et al. 2021)

Batteries that can no longer meet automotive purposes still have the prospect of profitable operation in less demanding applications whose requirement profile they can meet. Batteries can be used in a broad number of applications. The most discussed applications for second life batteries are: time-shifting (energy arbitrage), peak shaving, grid services, renewables integration, support EV charging stations, capacity reserve, personal e-mobility and small electronic devices. The above-mentioned applications require different battery characteristics and can vary, even within the same application. That is why, for each specific case, the requirements need to be analysed. Figure 67 gives an overview over possible applications as well as possible configurations in which the batteries can be utilised (Montes et al. 2022).

Figure 67: Overview of possible applications and possible configurations for repurposing



Source: own illustration Oeko-Institut / ifeu, based on (Montes et al. 2022)

While the environmental benefits of extending the life of a battery in another application are considered to be very high, there still seem to be many obstacles and unknowns at a practical level [13], (Biemann et al. 2024; Richa et al. 2017). Some OEMs are exploring ways to reuse their

[13] Stakeholder feedback from the workshops organised in the frame of this project.

batteries themselves in second life applications, limiting open access to used batteries. Interviewed stakeholders admitted that at the moment the demand for used vehicle batteries is very high, and access to the EV batteries can be problematic, as there are no established systems for distribution yet.

Whether second-life batteries make sense from an economic point of view depends on various factors (Neubauer et al. 2015):

- Current new price of batteries
- Type of use and location (1st and 2nd life)
- Raw material prices
- Costs for reprocessing

The **costs** for refurbishment or remanufacturing of batteries are influenced by several aspects. The main cost comes from the battery itself, followed by the labour cost for refurbishment. Zhao et al. (Zhao et al. 2021) gives an overview of the relationship between the factors that influence the cost of bringing batteries into a usable condition for a second life application. While this is will certainly differ from business case to business case, it is clear that the main cost is the battery itself (its acquisition) with 56%, followed by the labour cost (13%), general and administrative expenses (13%), packaging material (7%) and other (warranty, testing, insurance etc.) (11%). At the same time there are stark contrast in the literature with regards to costs for remanufacturing of batteries. This can be down to many reasons like the general conditions assumed, examples could be (EV) fleet development, development of the battery market, demand for second life batteries and effects of scale, as well as differences in the way the terms “remanufacturing” or “refurbishment” are defined (Zhao et al. 2021).

As shown Table 23 reuse and repurposing are under strong price pressure. The table com-piles prices from various literature sources to give a range for the cost of repurpose operations.

Table 23: Price range for re-use and repurpose operations

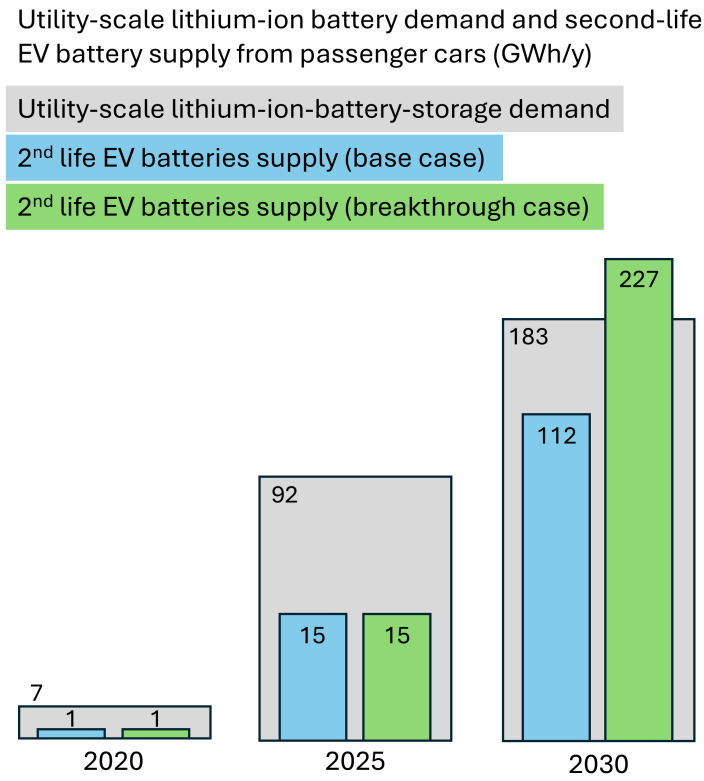
	High [€/kWh]	Low [€/kWh]
Future costs for new EV batteries	200	80
Selling price for used EV batteries	100	20
Repurposing costs	90	15
Purchase price for remanufactured batteries	190	35
Battery price for stationary applications	120	40

Sources: own table based on (Biemann et al. 2024; Neubauer et al. 2012; Richa et al. 2017)

Most publications project a big and growing demand for stationary energy storage in the future. Opening a big potential market for old batteries as stationary energy storage systems (Hauke Engel et al. 2019). An example of a study predicting the development until 2030 can be found in Figure 68. This demand opens the door for batteries to be repurposed after their first life in an EV in a second life in a different application. Examples of possible applications for used EV batteries include power grid services, Renewable Sources Integration, Reserve Capacity,

integration in EV Charging stations, low power consumer electronics or small mobility applications.

Figure 68: Demand for utility-scale lithium-ion battery storage and supply of second life EV batteries until 2030



Source: (Hauke Engel et al. 2019)

3.6.3 Legal framework

The defining legal framework regarding EV batteries and waste EV batteries (among other battery types) is the Battery Regulation (European Parliament, Council of the European Union 2023), which came into force in July 2023. The Regulation adopts the definitions of the terms re-use and preparation for re-use from the Waste Framework Directive (2008/98/EC). In addition, it defines the following three terms: repurposing, remanufacturing as well as preparation for repurposing.

The terms preparation for re-use and preparation for repurposing both refer to waste batteries, while re-use and repurposing refer to used batteries that that have not received waste status. All include operations like checking, cleaning or repairing with the aim of using the battery again for the same purpose or application as the one for which the battery was originally designed (re-use) or for a purpose or application other than that for which the battery was originally designed (repurpose). Remanufacturing can apply to both batteries and waste batteries, in the case of waste batteries it can be considered to be preparation for re-use and preparation for repurposing. Remanufacturing has the objective of restoring the original performance of a used battery and includes a wide range of operations that exceed more re-use and go as far as disassembling and evaluating the cells and modules of the battery and replacing a certain amount of these cells and modules. The target is to restore the battery capacity to at least 90% of the original rated capacity, in addition, the state of health of all individual battery cells should

not differ more than 3% between cells. An overview over the definitions can be found in Table 24.

Table 24: Overview over legal definitions

Term	Definition	Legal Document
re-use	're-use' means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived;	waste framework directive (2008/98/EC) – Article 3 13.
repurposing	'repurposing' means any operation that results in a battery, that is not a waste battery, or parts thereof being used for a purpose or application other than that for which the battery was originally designed;	Battery Regulation - Article 3 (31)
remanufacturing	'remanufacturing ' means any technical operation on a used battery that includes the disassembly and evaluation of all its battery cells and modules and the use of a certain number of battery cells and modules that are new, used or recovered from waste, or other battery components, to restore the battery capacity to at least 90% of the original rated capacity, and where the state of health of all individual battery cells does not differ more than 3% between cells, and results in the battery being used for the same purpose or application as the one for which the battery was originally designed;	Battery Regulation - Article 3 (32)
preparation for re-use or preparing for re-use	'preparing for re-use' means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing;	waste framework directive (2008/98/EC) – Article 3 16.
preparation for repurposing'	'preparation for repurposing' means any operation, by which a waste battery, or parts thereof, is prepared so that it can be used for a different purpose or application than that for which it was originally designed;	Battery Regulation - Article 3 (30)

Source: own table Oeko-Institut / ifeu

Since the Battery Regulation only recently came into force, the definitions provided in the Regulation have not yet been widely used in literature. Therefore, sometimes different terms are used, or terms are used to describe something else. Even before the Battery Regulation came into force, most terms were not uniformly defined and were often used differently by different authors. Here are some examples:

- 'Repurposing' is often also referred to as 'cascaded re-use'.
- The term 'remanufacturing' is often referred to as 'refurbishment'.
- There are no defined quality standards attached to the term 'remanufacturing', as is the case in the Regulation.
- During battery cycling side reactions can lead to the loss of active material and electrolyte and the formation and growth of unwanted material layers at the electrode/electrolyte

interfaces, resulting in a degraded capacity. In some publications, remanufacturing includes processes that reverse electrochemical cell degradation, in order to recover (some of) the original capacity of a battery. The distinction between remanufacturing in this sense and direct recycling is blurred. While this promises to have environmental and economic benefits, the technological feasibility (especially on a large scale) is unclear and still at an early stage of development (Ramoni, Zhang 2013).

The Battery Regulation further defines that an economic operator, that places a battery on the market or puts it in service as a result of preparation for re-use, preparation for repurposing, repurposing or remanufacturing shall be considered to be the manufacturer of that battery(European Parliament, Council of the European Union 2023)– Article 38 – 11. This also implies, that a battery that has been subject to re-use, is considered to have already been placed on the market when it was first made available on the market for use or distribution (European Parliament, Council of the European Union 2023)– Recital 16. This reduces the regulatory burden with regards to re-use without a change of purpose. Furthermore, economic operators placing on the market or putting into service batteries that have been subject to preparation for re-use, preparation for repurposing, repurposing or remanufacturing shall ensure that the examination, performance testing, packing and shipment of those batteries, and of such batteries' components subject to any of those operations, is carried out following adequate quality control and safety instructions as well as that the battery complies with the requirements of this Regulation, any relevant product, environmental, human health protection and transport safety requirements in other Union law, taking into account the fact that, as a result of those operations, the battery might fall under a different battery category. For remanufacturing operations, such economic operators shall provide, upon request, market surveillance authorities with the documentation necessary to demonstrate that the battery has been subject to remanufacturing in accordance with this Regulation. (European Parliament, Council of the European Union 2023)– Article 45.

The EU's Battery Regulation also introduces a digital battery passport (starting in 2027) that shall contain information on the battery's CO_2 footprint, performance class, origin of materials used and recycled content. The Regulation also defines minimum requirements for capacity, shelf life and performance.

3.6.4 Foreseeable development trends

In the study "Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy" by Richa et al. from 2017, the material flow analysis results were normalised to 1,000 LIB packs for a given year. This waste stream consisted of 25% battery electric vehicles (BEV), 36% long-range plug-in hybrid electric vehicles (PHEV) and 39% short-range PHEV LIB packs. The original study laying the foundation for this study is from 2014 and therefore relatively old and assumes a relatively high market share of PHEV. The study analyses the flows of these 1,000 EOL EV LIBs through different waste management pathways (Richa et al. 2017).

The Richa et al. (2017) (Richa et al. 2017) study finds that, for re-use of BEV and high-range PHEV battery packs in EVs, the avoided cumulative energy demand (CED) of LIB production exceeds the CED of charge-discharge losses, replacement cells, and LIB testing. As a result, the net benefit per pack for BEV batteries is 3,200 MJ and 73 MJ for high-range PHEV. However, no CED benefit was observed for short-range PHEV packs due to the lower avoided CED value for these smaller packs, compared to the CED impacts of electricity use and losses. The results suggest that, due to the small number of BEVs assumed in this model, there is minimal benefit from direct re-use of LIBs in EVs. It was also assumed that 37.2% of the 1,000 packs entering the waste stream are feasible for re-use in BEVs.

Furthermore, the Richa et al. (2017) study finds that re-use of EV LIBs in vehicles can provide an eco-toxicity benefit per pack of 430 (PHEV) to 3,100 (BEV) Freshwater ecotoxicity potential (CTUe). This benefit is due to avoiding the production of new LIB packs (as replacement EV batteries), which outweighs the potential eco-toxicity during the use phase. The re-use pathway has the potential to avoid approximately 12 t of metals: primarily aluminium, manganese and copper. Furthermore, the estimated economic benefit from LIB reuse in vehicles ranges from US dollars 330 to USD 3,000 per pack for short-range PHEV up to BEV battery. This results in a net benefit of 480,000 US dollar for the functional unit of 1,000 battery packs.

With regards to repurposing (cascaded use) of LIBs from EVs, it was assumed, that only 50% of the LIBs that outlived their usage capacity in EVs could be used in stationary applications based on expected cell failures during testing and technical limitations of repurposing with a 5-year service life. Some additional component input is required to refurbish and assemble these systems like wiring or the battery management system, while some components may be discarded. Per year, used LIB packs could be repurposed in stationary application over two cycles, immediately after entering the waste stream and after re-use in EVs. The study finds that, for a stationary energy storage system operating for 5 years, a net CED and eco-toxicity benefit of 1,330 MJ/kWh and 626 CTUe/kWh can be obtained through repurposing (cascaded use) of retired EV LIBs and by avoiding the production and use of PbA battery systems. Scaled to the entire 1,000 EOL battery stream, a potential net CED and eco-toxicity benefit of 9.6 million MJ and 4.5 million CTUe was estimated. Repurposing in stationary battery systems would potentially avoid 130 t of metal inputs, primarily by avoiding primary and secondary lead production). In addition, approximately 600,000 US dollars cost savings for the utility sector is estimated from installing these stationary energy storage systems with combined storage of 7,200 kWh. However, these estimates are based on low future LIB cost and comparisons made with valve regulated lead-acid (VRLA) battery systems. There is strong uncertainty in future LIB prices and the type of PbA battery systems that would be replaced by these retired LIBs.

It is also important to consider that developments in battery chemistry may reduce the incentive to recycle and increase the incentive to re-use and repurpose batteries. This can be illustrated by the impact of a higher rate of lithium ferrous phosphate (LFP) batteries compared to lithium nickel manganese cobalt oxide (NMC). This is because recycling is less attractive for LFP with lower material values. A high proportion of LFP in the lithium-ion battery waste stream also makes it difficult to archive the recycling targets set in the Battery Regulation. At the same time, LFP-based batteries are often more suitable for stationary applications as they tend to have higher cycle stability. Therefore, the trend towards LFP encourages re-use and repurposing in favour of recycling.

The State of Health (SoH) of a battery is a key factor in determining whether it is appropriate to reuse or recycle a battery. This depends on a number of factors and can vary. These include the number of charge cycles, the age of the battery and the owner's usage patterns, such as charging and driving. External factors such as temperature also play a role. In addition, batteries with a higher capacity tend to have a better SoH than smaller batteries (Canals Casals et al. 2022).

Another unknown in terms of user behaviour is the acceptance of a decrease in capacity (and range) as vehicles age. The threshold of 80% remaining capacity as an end-of-life criterion for batteries in electric vehicles is so far a theoretical value. It remains to be seen whether drivers themselves will use the batteries for much longer and accept a reduction in capacity and range. Early data also suggests that batteries tend to have a longer life and more stable capacity than expected. In addition, batteries are subject to rapid technological improvements that will lead to longer battery life and cycle stability. Car owners' awareness of battery-friendly usage and charging patterns can also counteract capacity loss (Ryan 2022).

Recurrent Auto looked at 20,000 EV batteries and found that, while battery replacement is common for older EVs launched before 2016, 13% of these EVs have reported battery replacement. For newer models from 2016 onwards, less than 1% have reported a replacement. For cars from 2011, the replacement rate was 30%, but the battery technology is hardly comparable to a state-of-the-art battery. Based on this data, it is not expected that whole battery replacements at an early stage will be common in EVs in the future (Najman 2024).

As a result, it is difficult to predict the state in which batteries will be available for re-use or re-purposing in the future. Assuming the same end-of-life characteristics for EVs as for ICEVs, Casals, L. C.; et al. (Canals Casals et al. 2022) predicted that less than 30% of EVs will have a SoH of less than 80% at end-of-life, making both re-use and repurposing viable in terms of SoH, as batteries with a higher SoH are more suitable.

Stakeholder feedback indicated that most repairs during the warranty period are not to the cells or modules themselves but to the other components of the battery, such as the BMS, power electronics or casing. These repairs are often very expensive as they are labour intensive and require specialised equipment, expertise and an environment suitable for working on high voltage systems. However, they are not very material-intensive and are therefore not taken into account separately in the model (Kurzmann et al. 2023).

Repurposed EV batteries have to compete with batteries that are specifically designed and optimised to meet the technical requirements of that application. In the case of stationary storage, this means batteries with good cycle stability and a relatively low specific capacity price [€/kWh], since weight optimisation is not as critical. In addition, consumer acceptance often favours new batteries specifically designed for stationary applications. At the same time, the innovation cycle is very high and battery costs are steadily decreasing, making older used batteries less attractive. In order to successfully reuse EV batteries, an inhomogeneous input stream of a wide range of different batteries has to be managed, which makes the process difficult to standardise and causes high labour costs. Therefore, developing flexible and modular second life solutions that can integrate a wide range of different EV battery types and utilise the existing battery, including BMS and power electronics, is essential. The importance of standardisation and automation as described above becomes even more apparent when looking at the cost of battery disassembly Table 25. As described by H. Rallo et al. (Rallo et al. 2020) for a relatively small battery pack of 17.6 kWh, the cost of disassembly at module or cell level can be up to 58.1% of the total disassembly cost. This underlines the importance of keeping the amount of effort required for repurposing as low as possible.

Table 25: Costs for the disassembly process for battery pack, modules and cells

Working step	Battery pack	Module	Cell	Share [%]
Removing the battery from EV [€]	117	117	117	8.8%
Post battery assessment [€]	442	442	442	33.2%
Disassembly battery to module [€]	-	500	500	37.5%
Disassembly battery to cells [€]	-	-	275	20.6%
Total [€]	558	1058	1333	
Cost [€/kWh]	32	60	76	

Source: H. Rallo et al.; Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries; Resources, Conservation & Recycling 159 (2020) 104785

Battery repurposing is further complicated by the different standards and norms that apply. EV batteries are designed to meet a number of formal requirements, such as safety, security, liability, reliability and fire safety. These requirements often vary by application. The standards identified in the course of the research on standards related to batteries and the circular economy identified standards that apply to different categories of batteries, a total of 100 in Germany. Of these, 51 applied to all types of batteries, 15 applied specifically to EV batteries and 17 applied specifically to stationary battery storage systems. This illustrates the different requirements that batteries must meet for specific applications, which can create obstacles for repurposing (DIN 2022).

Availability and access to essential information can also be a barrier to battery repurposing. The Battery Regulation aims to create transparency and reduce information asymmetries by introducing the Battery Passport.

3.6.5 Fields of action and issues

Table 26 provides an overview of possible measures that could be implemented to increase repair, re-use and repurposing of EV batteries. The impact on the input parameters for the modelling is described in following sub-chapter 13.

Table 26: Overview of measure

	Description
Measure I	**Standardization**
Description	As the Batteries Directive does not contain provisions to promote a standardised structure and design of EV batteries and components, further development of standardisation in the field of EV batteries and related components is necessary to improve resource efficiency. Development of standards for repurposed batteries, including conformity assessment of EV batteries for use in stationary applications and, such as assessment of SoH, performance and remaining service life.
Impact	Increased standardisation of EV batteries at pack, module and cell level is important to promote reuse and re-use, as similar designs and functionalities can significantly reduce process costs and make batteries suitable for a wider range of vehicle types and applications. Standardisation should therefore be promoted within manufacturers' product lines, but also across manufacturers. It can also encourage vehicle retrofitting with newly developed batteries, thus extending vehicle life.
Difficulty of implementation	
Importance	High
Timeframe	Short
Source	▶ Stakeholder Feedback ▶ Heimes, H., Kampker, A., Offermanns, C., Kreisköther, K., et al.: Recycling von Lithium-Ionen-Batterien. PEM RWTH Aachen University, BLB TU Braunschweig und VDMA, Frankfurt am Main (2021) (Heimes et al. 2021)

	Description
	▶ Normenrecherche Circular Economy; Schwerpunktthema 3: Batterien; https://www.din.de/de/forschung-und-innovation/themen/circular-economy/normenrecherche/batterien (checked: July 2024) (DIN 2022) ▶ Deutsche Umwelthilfe e.V.; Resource efficiency for electric vehicle batteries: Strengthening ecodesign, reuse, repair and high-quality recycling; Position paper; 2024 (DUH 2024a) ▶ Nationale Plattform Zukunft der Mobilitat, Arbeitsgruppe 6 „Standardisierung, Normung, Zertifizierung und Typgenehmigung“; 2020 (NPM 2020)
Measure II	**Incentives to lower repair, re-use and repurposing costs as well as incentives to promote repairable vehicles**
Description	Possible instruments in this field would be tax reductions for repairs and the use of reused or repurposed EV batteries. In addition, purchase incentives and lower insurance costs for repairable cars could make EVs more affordable and attractive to consumers.
Impact	Medium
Difficulty of implementation	Easy
Importance	
Timeframe	Short
Source	▶ Stakeholder Feedback ▶ Kurzmann, N.; Analyse von Kollisionsschäden bei Hochvoltfahrzeugen; AZT Automotive GmbH; Jan. 2023 (Kurzmann et al. 2023) ▶ Deutsche Umwelthilfe e.V.; Resource efficiency for electric vehicle batteries: Strengthening ecodesign, reuse, repair and high-quality recycling; Position paper; 2024 (DUH 2024a)
Measure III	**Minimum Targets for re-use and repurposing**
Description	In line with the waste hierarchy, which favours reuse and repurposing over recycling, separate targets for reuse and repurposing of automotive batteries will be introduced in addition to the recycling targets.
Impact	Fixed minimum amount of re-use and repurpose
Difficulty of implementation	High legislative burden and high resistance expected
Importance	Potentially high impact
Timeframe	Stepwise adoption of targets in the next 5-10 years
Source	Deutsche Umwelthilfe e.V.; Resource efficiency for electric vehicle batteries: Strengthening ecodesign, reuse, repair and high-quality recycling; Position paper; 2024
Measure IV	**Obligation to check for reusability**

	Description
Description	Introducing a mandatory check on the suitability for re-use or repurposing of EV batteries during dismantling. Promote the role of insurance companies to strengthen the spare parts market and cooperation between stakeholders.
Impact	Batteries suited for re-use or repurposing are detected with at a higher rate.
Difficulty of implementation	Easy
Importance	Medium
Timeframe	Short
Source	▶ Stakeholder Feedback ▶ Deutsche Umwelthilfe e.V.; Resource efficiency for electric vehicle batteries: Strengthening ecodesign, reuse, repair and high-quality recycling; Position paper; 2024 (DUH 2024a)
Measure V	**Easy access to sufficient information on how to repair and maintain EV batteries ‚Right-to-repair'**
Description	A right to repair ensures that independent repairers have access to the information, tools and parts necessary to repair and maintain EV batteries without legal or technical restrictions.
Impact	Enables independent workshops to repair EV batteries and help reduce costs.
Difficulty of implementation	High resistance by OEMs and licenced garages Legal and safety concerns
Importance	Medium
Timeframe	Instant
Source	▶ Stakeholder Feedback ▶ Hansen et al.; The Right to Repair of Electric Vehicle Batteries; GAIA; 2024 (Hansen, Davis 2024) ▶ Deutsche Umwelthilfe e.V.; Resource efficiency for electric vehicle batteries: Strengthening ecodesign, reuse, repair and high-quality recycling; Position paper; 2024 (DUH 2024a)
Measure VI	**Promotion of battery friendly user behaviour**
Description	Raising EV owners' awareness of "battery-friendly" usage patterns. Improve and deploy intelligent onboard battery management technologies to protect them from degradation.
Impact	Extends battery life and SoH and the end of the EVs life
Difficulty of implementation	Easy Medium
Importance	High
Timeframe	Medium

Source: (Canals Casals et al. 2022); (Ryan 2022); (Najman 2024)

3.6.6 Modelling

In order to model the impact of possible reuse and repurposing of electric vehicle batteries the parameter “Share of electric vehicle batteries being reused and recycled” has been developed.

The analysis was carried out for three variations next to the baseline scenario. Variation 2 (V 2) represents a trend towards an increase in the fleet of BEVs with a “High repairability and reuse potential” (BEV-Repair) over years. Variants 1, 3, and the baseline have no share of BEV-Repair in their fleet during the whole analysed time perspective. The proportions of EV batteries for reuse/repurpose vary between Variations 1 and 3.

The analysis considered the following aspects:

- Collection rate of electric vehicle batteries
- Remaining capacity of the collected EV batteries
- Average vehicle age
- Share of BEVs with "High repairability and reuse potential"

Once collected, EV batteries can have a second life in stationary storage applications. The number of EV batteries available for second life is determined by the number of EV batteries reaching the end of their first life and the collection rate. This study assumes a collection rate of 95% for all scenarios, similar to (Crespo 2022). According to different sources, the collection rate of EV batteries in Europe is between 90 and 100% (Abdelbaky et al. 2021; Bobba et al. 2020a).

As already mentioned in this report in chapter 3.7.2, several works show that the battery capacities remain above a threshold of 70 to 80% of the initial capacity when they reach their end-of-life stage, i.a. (Neubauer et al. 2015). The study of (Canals Casals et al. 2022) indicates that a small number of EVs batteries will arrive at SoH below 60% (as less than 30% of the EV at retirement will have a SoH below 80% at end-of-life). According to (Heimes et al. 2021), if an EV battery is still above 80%, the pack can be reused without treatment. Otherwise, the packs are dismantled and assessed at the module level. Modules with SoH above 80% can be reused easily, those between 70-80% can be rebuilt into packs, and those below 70% are further dismantled and assessed at the cell level. Cells with SoH over 85% can be rebuilt into modules, while those below 85% are recycled. The reused/repurposed has been modelled taking into account reused/repurposed components. For the moderate share of batteries for reuse/repurpose (Variation 1), the capacity of batteries for repurpose was assumed to be 60% and for reuse 90%. For the variations with a high share of batteries for reuse/repurpose (Variations 2 and 3), the remaining capacity of EV batteries was assumed to be 95% for reuse and 75% for repurpose.

The average vehicle age of BEVs with “High repairability and reuse potential” (BEV-Repair) is assumed to be higher than for current BEVs and close to the highest average vehicle age in the EU in 2022 of17.4 years (FAIST 2024).

Please refer to Table 27 for an overview of the assumptions made in this study. It is also assumed that the improvement in management strategies will contribute to a linear increase in the share of batteries that are reused and repurposed and the share of BEV-Repair between 2030 and 2050.

Table 27: Assumptions for the baseline and analysed variations V 1 to V 3: Share of electric vehicle batteries being reused and repurposed and Share of BEV with "High repairability and reuse potential" in the fleet.

Variation	Year				
Share of electric vehicle batteries being reused/repurposed					
	2030	2025	2040	2045	2050
Baseline	10%	30%	30%	30%	30%
V 1	10%	36%	42%	48%	54%
V 2	30%	59%	68%	76%	85%
V 3	30%	59%	68%	76%	85%
Share of BEV with "High repairability and reuse potential" in the fleet (BEV-Repair)					
	2030	2025	2040	2045	2050
Baseline	0%	0%	0%	0%	0%
V 1	0%	0%	0%	0%	0%
V 2	10%	30%	50%	70%	90%
V 3	0%	0%	0%	0%	0%

Source: own assumptions based on literature review

The model assumes only one lifetime of an EV battery for reuse or repurposing. Therefore, it only calculates the number of EV batteries that reach the end of their life for the first time.

3.6.7 Results

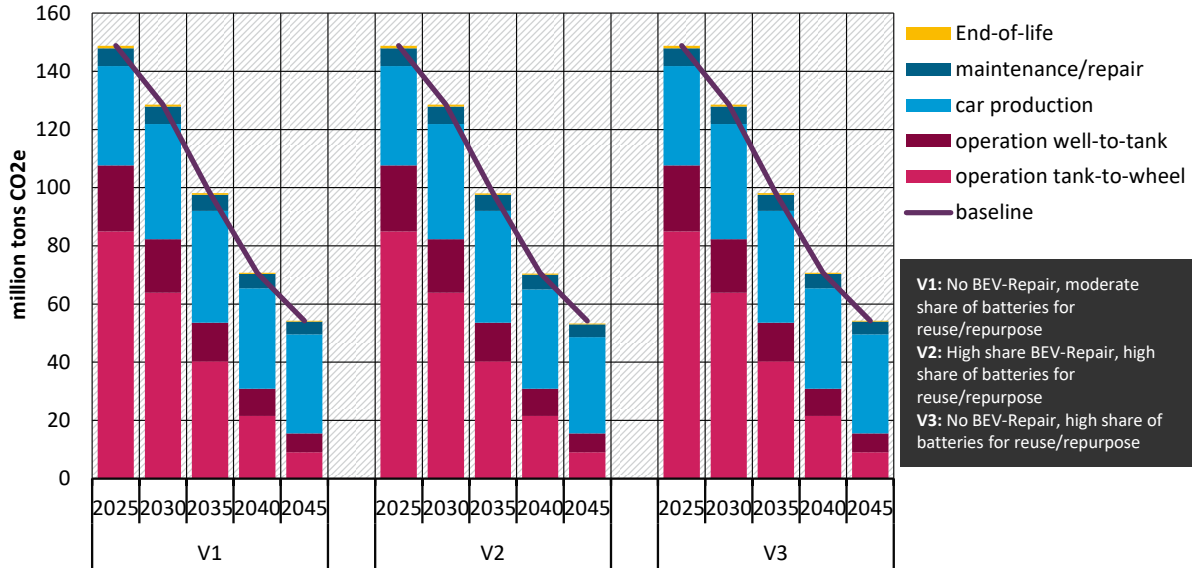
The model assumes that functioning batteries recovered during dismantling can be reused or repurposed (e.g. as stationary storage). The higher the reuse/ repurpose share, the lower amount of material that can be recovered in the subsequent recycling process.

The following two graphs (Figure 69 and Figure 70) show the GHG emissions from cars for different variations and the baseline of the "Reuse and repurposing of EV batteries" option. There is no change in the GHG emissions for operation tank-to-wheel, operation well-to-tank, and maintenance/repair, as changes in the analysed variations assumptions only affect the car production and end-of-life phases.

With the high share of BEVs with "high repairability and reuse potential" (V 2), the GHG emissions of the vehicle manufacturing and end-of-life phases decrease slightly compared to the baseline and other variations. This is due to the fact that the share of BEV-Repair is higher than in the other variations, which have a longer lifetime of the BEV in the fleet (about 2 years). The change in lifetime affects both the number of end-of-life vehicles and the number of new registrations.

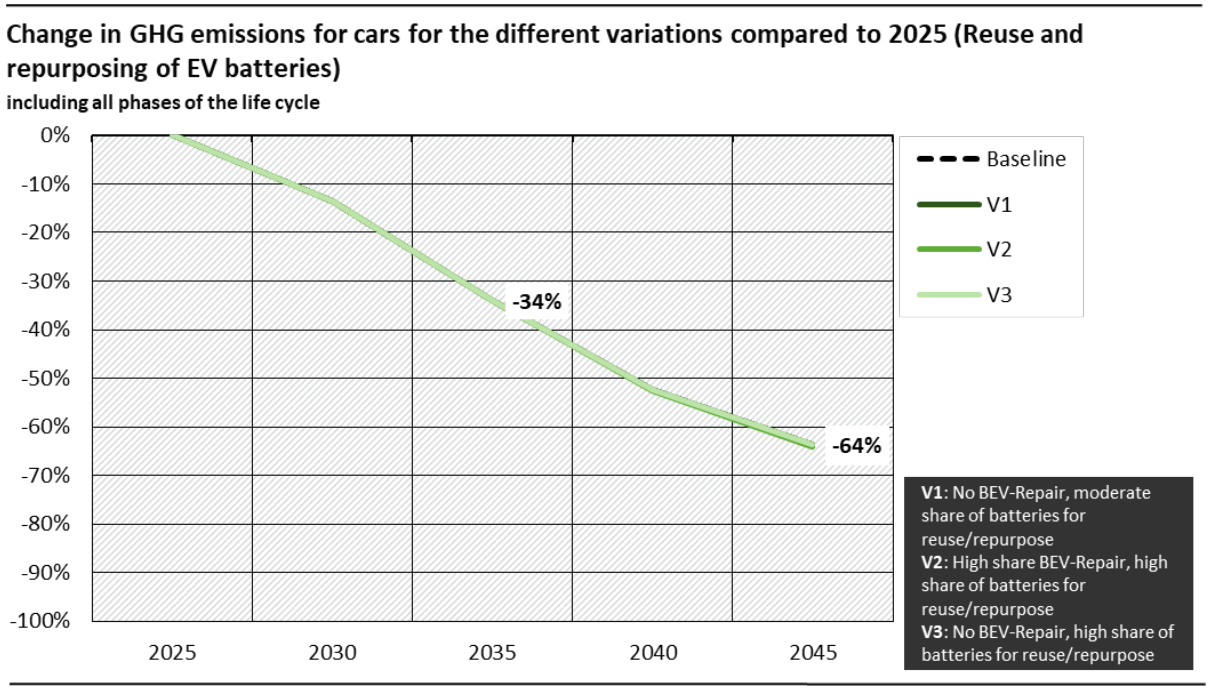
The share of BEV-Repair in V 1 and V 3 is the same as in the baseline (no share), so the GHG emissions are the same.

Figure 69: GHG emissions for cars for the different variations (Reuse and repurposing of EV batteries)



Source: own figure, ifeu/ Oeko Institute

Figure 70: Change in GHG emissions for cars for the different variations compared to 2025 (Reuse and repurposing of EV batteries)

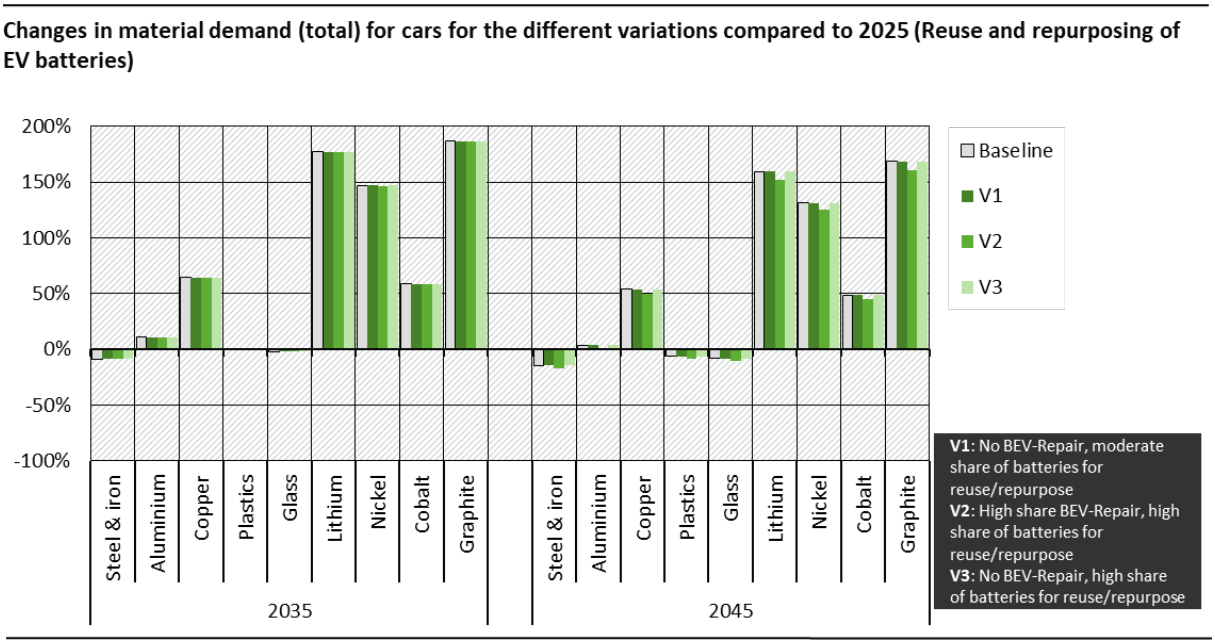


Source: own figure, ifeu/ Oeko Institute

Changes in the total material demand for cars for the different variations of "Reuse and repurposing of EV batteries" are not visible until 2035 (see the following Figures). In 2045, the long lifetime of BEVs with "High repairability and reuse potential" (V 2) shows impact changes in total material demand while the baseline and Variations 1 and 3 remain at the same level (see next Figure). The changes in primary material demand for cars compared to 2025 are more

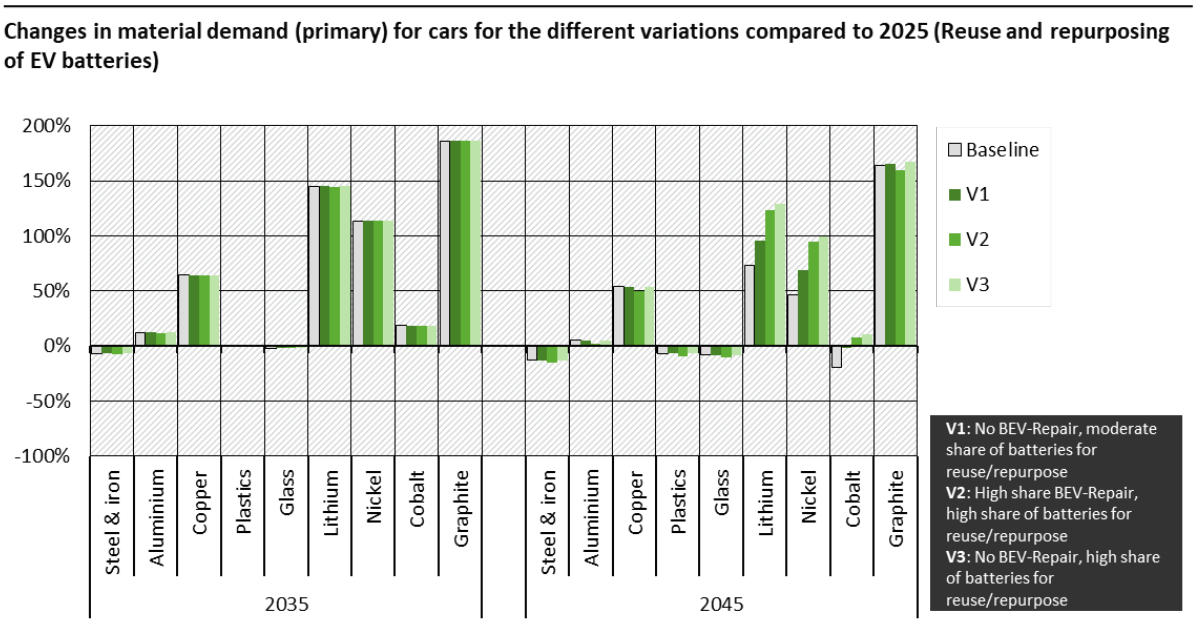
variable. The high share of batteries for reuse/repurpose (V 2 and V 3) has a significant impact on the demand for lithium, nickel and cobalt. It is highest for V3, which assumes no BEV repair in the fleet, resulting in a higher number of batteries for reuse/repurpose in 2045. However, the model does not take into account the use of primary materials that can be avoided by reusing EV batteries, e.g. for stationary energy storage or other possible applications.

Figure 71: Changes in material demand (total) for cars for the different variations compared to 2025 (Reuse and repurposing of EV batteries)



Source: own figure, ifeu/ Oeko Institute

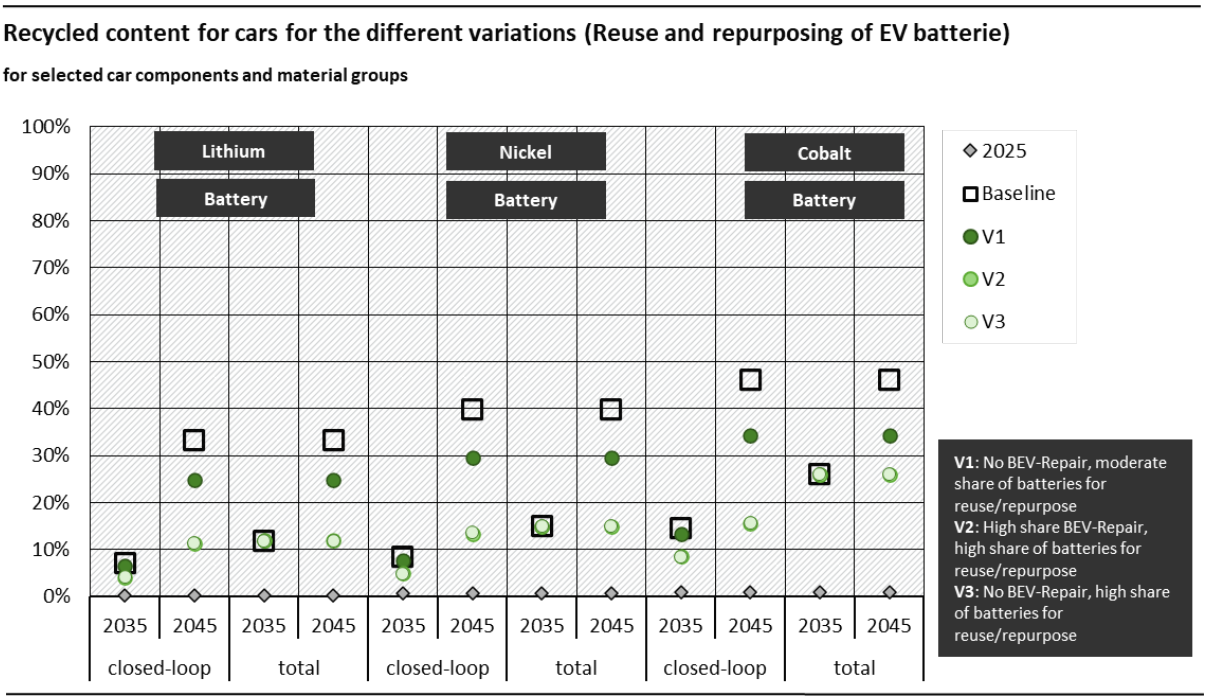
Figure 72: Changes in material demand (primary) for cars for the different variations compared to 2025 (Reuse and repurposing of EV batteries)



Source: own figure, ifeu/ Oeko Institute

The reuse/repurpose of EV batteries contributes to a reduction in the material stream at the recycling stage. This also has the effect of reducing the level of potential recycled content for cars. The following graph shows the calculated levels of recycled content levels for lithium, nickel, and cobalt for "closed-loop" and "total". For the majority of the calculated Variants, the values obtained are below the calculated baseline.

Figure 73: Recycled content for cars for the different variations (Reuse and repurposing of EV batterie)



Source: own figure, ifeu/ Oeko Institute

3.7 Repair and remanufacturing of parts and components, excluding batteries

3.7.1 Background

If items are repaired, this extends their service life, thus the functional life of vehicles. As a result, no new items need to be purchased, which means that (primary) raw materials and production related GHG emissions are avoided.

However, in the case of durable consumer goods such as cars, where technology is constantly changing, the advantage or disadvantage of a repair in terms of raw materials or emissions also depends on other factors such as the speed of diffusion of more efficient technologies.

Longer lasting repairs have an impact on fleet composition, e. g. keeping vehicles in the fleet longer in terms of emissions (e. g. Euro 5 to Euro 6 and to Euro 7) and vehicles registered until the EU7 emissions standard comes into force. In the medium to long term, however, this is of secondary importance, as the EU and vehicle manufacturers' roadmaps have set the course for e-mobility.

At the same time, the question arises as to whether the longer period of use and the resulting indirect scarcity of (secondary and critical) raw materials will not lead to increased pressure for innovation and efficiency, which will positively counteract the disadvantage of repairs that promote product longevity.

Similarly to repair, remanufacturing reduces the amount of waste and saves (primary) raw materials and energy expenditure that would otherwise have to be used to produce the part/component. The specific savings effects depend on the part/component that did not have to be produced thanks to remanufactured part/component. Contrary to repair, remanufacturing is understood as a standardised process, which is associated with additional economic and environmental costs. Also, a remanufactured part/component fulfils a function that is at least equivalent to the function of the original part, and a remanufactured part is given the same warranty as a new part, which increases the possibility of adopting remanufactured parts/components in manufacturing new vehicles.

As in the case of repairs, consideration should be given to which reuses are beneficial in terms of raw materials and greenhouse gas emissions, and at what point remanufacturing becomes detrimental overall due to the delayed introduction of new, more efficient technologies. Remanufactured parts/components could replace (avoid the production of) newly manufactured parts/components, but this needs to be aligned with the electrification of the vehicle fleet and the possible demand for parts/components from end-of-life vehicles, which are currently mainly ICE vehicles.

The authors are aware of the existence of various definitions describing operations aimed at increasing the reuse or prolonging the use of parts and components (see the following sub-chapter for more information).

3.7.2 Status quo

3.7.2.1 Environmental impacts

According to various, selected assessment studies, it appears that repair/remanufacturing can boost resource efficiency, circularity of raw materials and reduce environmental impacts.

For instance, according to (Bobba et al. 2020c), remanufacturing allows keeping within EU about 150,000 tonnes of materials, which is particularly relevant for Critical Raw Materials (CRMs), such as rare-earth elements (REEs). Examples of automotive CRMs include cobalt (in lithium-ion batteries, especially electric vehicles), PGMs (palladium, platinum and rhodium in catalysts and particulate filters) and rare earths (REEs) (in permanent magnets, auto-catalysts, filters and additives). The rapid growth in sales of electric vehicles (EVs) has important implications for the increasing demand for CRMs. Among these are REEs. CRMs are required for several applications in the automotive sector, but their functional recycling is very limited, e. g. for REEs. Typically, only about 1% of REEs are recycled from end products, the rest is waste and removed from the material cycle (Jowitt et al. 2018). Thus, the authors believe that more efficient strategies can help in boosting resources efficiency in the transport sector, e. g. by extending the lifetime of products through their reuse or remanufacturing.

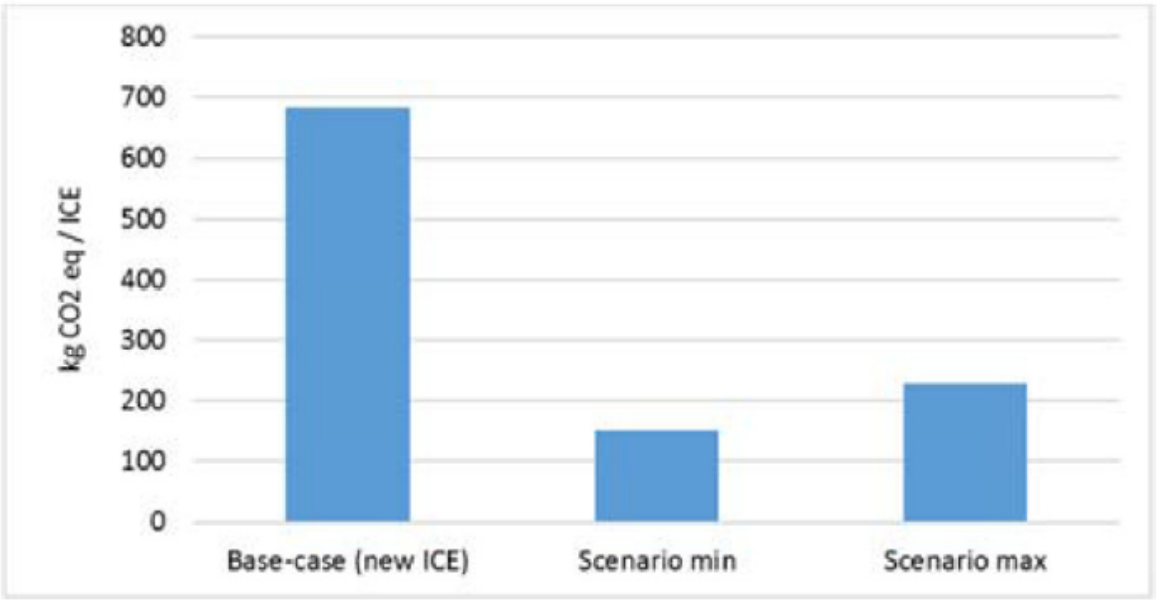
(Bobba et al. 2020c) assesses the weight of materials kept in the economy thanks to remanufacturing in 2012, using the MFA methodology (as a result above 150,000 tonnes of materials). (Bobba et al. 2020c) also assesses the potential reduction in the environmental impact of key vehicle components, such as the combustion engine, using LCA methodology.

To this end, the authors established three scenarios: 1. 'Base case', where ICE is manufactured using only new parts, 2. 'Scenario min', where ICE is remanufactured using a minimum number of new parts (i.e. maximising reused components), 3. 'Scenario max', where all ICE parts are replaced with new parts, except for the 3 main castings (aluminium, iron, steel), as they are generally remanufactured. The analysis assumes that remanufactured parts save 80% energy, 88% water, 92% chemical products and 70% waste.

The LCA results show that average GWP per ICE is 0.7 tonnes CO_2e. The main contributors are materials (69%), energy used to manufacture (24%) and mechanical shredding at the EoL (7%).

The figure below reports the comparison between the GWP of the assessed scenarios. It shows that remanufacturing helps to reduce the environmental impact of key vehicle component such as the internal combustion engine up to 77.9% ('Scenario min') of the global warming potential reduction. Exempted replacements ('Scenario max') brings to 66.4% of savings. This is mainly due to the reduced amount of energy for the processing, and thanks to the savings of primary resources. The conclusion is that the higher the percentage of remanufactured parts, the higher the GWP savings.

Figure 74: Global Warming Potential: results for the three considered scenarios



Source: (Bobba et al. 2020c)

Further examples show (see Table 28) that considerable savings can be achieved through remanufacturing (diesel motor, cylinder head, compressor, gear box, starter), but there are also examples in which the input increases, such as the oil consumption of 2,800 kg in the case study of the cylinder head (Lange 2017). On the one hand, this is due to the transport route to the reconditioning site (remanufacturing centre), which is more than 750 km long. On the other hand, approx. 4.5 kg of crude oil is used per cylinder head for pyrolysis to remove paint layers during the cleaning process. The remanufacturing of the cylinder head therefore increases the use of crude oil by a total of 43%. Nevertheless, the remaining savings replace the increased transport route and the use of crude oil in the cleaning process and reduce the overall environmental impact by around 40%.

Table 28: LCA results for new and remanufactured product parts – case examples

	New production	Remanufacturing	Savings in %
Case example 1: DIESEL MOTOR			
Energy consumption in megajoules	6,016.68 MJ	3,620.16 MJ	40%
Resource consumption of coal in kilograms	2,200 kg	590 kg	73%

	New production	Remanufacturing	Savings in %
Resource consumption of crude oil in kilograms	59.5 kg	48.5 kg	18%
CO_2 emissions in tonnes	3.9 t	1.02 t	74%
Case example 2: CYLINDER HEAD			
Resource consumption of coal in kilograms	320,175 kg	71,182 kg	78%
Resource consumption of crude oil in kilograms	6,468 kg	9,237 kg	-43%
CO_2 emissions in tonnes	534 t	126 t	76%
Case example 3: COMPRESSOR			
Emissions in kilograms of CO_2 equivalents	1,590 kg CO_2-eq	168 kg CO_2-eq	89%
Case example 4: GEAR BOX			
Energy consumption	Not specified	Not specified	33%
Case example 5: STARTER			
Energy consumption in megajoule equivalents	281.03 MJ-e	122.73 MJ-e	56%
Material consumption in kilograms	3.49 kg	0.43 kg	88%
Emissions in kilograms of CO 2 equivalents	17.01 kg CO_2-eq	8.03 kg CO_2-eq	53%

Source: (Lange 2017)

3.7.2.2 Existing barriers

Except studies that aim measure environmental remanufacturing benefits, expert recognise a list of barriers that affect remanufacturing market. Among others, the one that heavily impact the branch are access to appropriate core, software, and developing the appropriate operations to deal with future components (Waugh, Ramjee 2021). Table 29 below illustrates barriers to remanufacturing by actor and type of barrier.

Table 29: Barriers to remanufacturing, by actor and type of barrier

	Technical	Economic	Social	Political & Legal
OEM[14]	Developing remanufacturing operations		Increased labour costs	Obtaining core from non-EU countries
Tier 1[15]	Lack of access to sofware, original specifications and tolerances	Economics and logistics of core recovery	Increased labour costs	Obtaining core from non-EU countries
	Limited component availability	Cheap ‚copy' parts		Perception of core as a waste

[14] Vehicle manufacturers that may also undertake remanufacturing

[15] Component manufacturers that may also undertake remanufacturing

	Technical	Economic	Social	Political & Legal
Independent[16]	Lack of access to sofware, original specifications and tolerances	Economics and logistics of core recovery	Skills needed to deal with electrical components	Obtaining core from non-EU countries
	Limited component availability	Cheap ‚copy' parts		Perception of core as a waste
Core Brokers[17]	Limited component availability			Obtaining core from non-EU countries
	Determining the quality oft he core in real time			Perception of core as a waste
Triggers across different actors	Accessing software and core	Managing projects and communications	Upskilling the workforce to deal with electric components	Designation of core value globally
	Developing remanufacturing operations			

Source: (Waugh, Ramjee 2021)

Other sources (Bobba et al. 2021) and (Lange 2017) name further existing obstacles in the development of repair/remanufacturing facilitates. (Bobba et al. 2021) summarised the main barriers identified in various literature sources (see Table 30).

Table 30: Summary of the main barriers identified in some of the studies consulted in the literature review on remanufacturing of vehicles

Source / Type of barrier		Russel (2018)	Parker et al. (2015)	Kamper et al. (2019)	Nasr et al. (2017)				Weiland (2019)	Lange (2017)	Boustani (2011)	Matsumoto (2020)	Liu et al. (2018)	
Regu	Lack of a clear definition of terms	X	X						X					3
			Lack of standardisation		X				X					2
			Trade restriction			X			X			X		3
Te	Market competition	X	X						X			X		4
			Poor design for remanufacturing			X	X		X		X	X	X	6

[16] Remanufacturers that are not involved in the manufacturing of new components

[17] Intermediate company that sources core for a remanufacturer

Source / Type of barrier		Russel (2018)	Parker et al. (2015)	Kamper et al. (2019)	Nasr et al. (2017)				Weiland (2019)	Lange (2017)	Boustani (2011)	Matsumoto (2020)	Liu et al. (2018)	
			Low efficiency of remanufacturing-related processes			X		X	X			x		4
			Innovation of remanufacturing processes			X	X		X		X			4
			Fast technological changes				X		X	X	X			4
			Increases in components' complexity		X	X	X		X	X				5
Economic			Viable business model			x				X	X	X	X	5
			Access to cores and available volumes		X	X			X	X	X	X	X	7
Social	Perception/ acceptance of reuse from consumers	X	X						X	X		X	X	6
Knowledge			Lack of specific skills		X	X	X			X				4
			Lack of information		X	X			X					3

Source: (Bobba et al. 2021)

Authors of (Lange 2017) highlight current and future weaknesses in the remanufacturing industry (see Table 31).

Table 31: Current and future strengths and weaknesses in the remanufacturing industry

Current	Future
Image problems availability of high-quality spare parts legal framework	Availability of well trained personell
Variety of product and part variants	Rising product complexity
Access to product information	Knowledge in the filed of rebuilding of electronics
	Digitalisation

Source: (Lange 2017)

(Waugh, Ramjee 2021) in its report list selected barriers that have also been identified by various sources. Below can be find selected barriers named in (Waugh, Ramjee 2021) further supplemented by the opinions of the participants of the training organised within the framework of the AutoRess:

Transboundary movements seem of high important for the remanufacturing branch. Moving core and remanufactured products across borders hinder the growth of remanufacturing activities and access to new markets. These barriers also lead to higher costs for transporting and storing core products.

Independent remanufacturers face challenges due to **limited access to software**, original specifications, and components, which hampers their competitiveness. OEMs control software access, making it hard to develop viable remanufacturing programs without support. Independent remanufacturers must invest heavily in R&D to create their own software solutions, risking intellectual property issues from reverse engineering. Ensuring remanufactured parts meet original specifications is difficult without original software. Additionally, large minimum order quantities or lack of spare parts, especially for short-lived electronic components, further complicate remanufacturing efforts.

The suitability of EV components for remanufacturing is often limited by a **lack of design for disassembly**, such as the use of glue and spot welds instead of reversible fasteners in EV batteries. Increasingly complex and integrated component designs make disassembly more challenging and labor-intensive. While new EV component designs could incorporate remanufacturing-friendly principles, the business case for this has not yet been established, especially for OEMs.

Customers on **online sales platforms** often don't understand the differences between new 'copy' parts and remanufactured components. This lack of knowledge can lead them to prioritize price over performance and hesitate to buy what they perceive as "used" or "second-hand" parts.

Independent garages in Germany appear to prefer to use new components because of the higher profit margins, and often find the 1-2 day waiting time for remanufactured components too long. In addition, it appears that garages may be unaware of the possibility of returning used parts to manufacturers for remanufacturing.

OEMs also appear to favour the use of new parts due to higher customer expectations and the desire to return the vehicle immediately. The use of new parts also helps OEMs to sell the parts they manufacture.

According to **insurance companies** in Germany, many spare parts that could be remanufactured and reused are "lost" due to the fact that many used vehicles are exported from Germany. In addition, the use of used parts in the repair of vehicles is limited, since the insurance companies' policies require that only new parts be used in the repair of vehicles during the warranty period (4 years).

3.7.2.3 Vehicles' components/parts suitable for reuse

Remanufactured units account for 55% of the EU automotive aftermarket, with the remainder (45%) being new units; however, market growth may push demand for remanufactured parts to a market share of 80% in the future (Bartel 2016).

In principle, all parts of a car with a minimum value and complexity can be remanufactured (Bartel 2016). Parts that are often economical to remanufacture include many mechanical and hydraulic parts, as well as a growing number of electrical/electronic parts (Gaudillat et al. 2017). Examples include air conditioning components, air brakes, alternators, brake calipers, carburettors, clutches, cylinder heads, driveshaft, electrical units, instrument clusters and controllers, engines and engine components, fan motors, heater blowers, front axles, fuel pumps, fuel injectors and ignition, generators, gearboxes, master cylinders, pumps (hydraulic, oil,

water), rack and pinions, radiators, starters, alternators, steering units (manual, power), turbochargers, torque convertors, and transmissions (Optimat 2013).

Remanufactured parts and components are supplied to the aftermarket mainly as spare parts for repair and maintenance (Gaudillat et al. 2017). Between 80% and 90% of cores come from garages, with the remainder from ELVs (Weiland 2019).

Parts/components from ICE that are most frequently repaired/remanufactured today (information from participants of workshop organised as part of the AutoRess project):

- Engine, transmission, starter, steering gear, turbocharger, e-components (control units)
- Brake discs
- Fuel injectors
- Transmission and clutch
- Tyres for passenger cars

3.7.3 Legal framework

According to Article 2(6) of the ELV Directive, "reuse" means any operation by which components of end-of-life vehicles are used for the same purpose for which they were conceived. Re-use of components of end-of-life vehicles is therefore an operation that takes place when the vehicle reaches the waste stage. The same Directive does not introduce the terms 'refurbishment' or 'repair'.

On the other hand, the proposal for a regulation on end-of-life vehicles contains definitions for 'reuse', 'remanufacturing' and 'refurbishment'. According to the proposal:

- ‘reuse’ means any operation by which parts or components of end-of-life vehicles are used for the same purpose for which they were conceived;
- ‘remanufacturing’ (in German ‘Wiederaufarbeitung’) means an operation in which a new part or component is manufactured from parts and components that are either removed from vehicles or end-of-life vehicles and in which at least one change is made to the part or component that affects its safety, performance, purpose or type;
- ‘rufurbishment’ (in German ‘Überholung’) means actions carried out to prepare, clean, test and, where necessary, repair a part or component that is removed from vehicles or end-of-life vehicles in order to restore the performance or functionality of that part or component within the intended use and range of performance originally conceived at the design stage applicable at the time of its placing on the market.

In addition, the WFD defines ‘preparing for reuse’, which, in contrary to the term ‘reuse’ in the same Directive, applies to products or components of products that have become waste, and is included in the waste hierarchy defined in Article 4 of the WFD; however it does not appear in the ELV Directive.

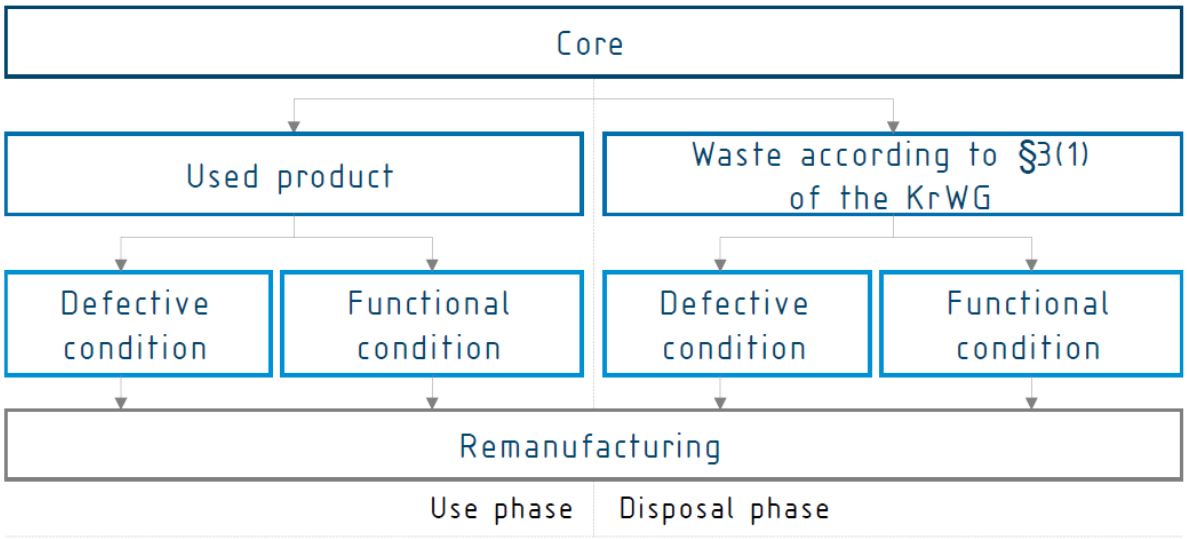
The above-mentioned definitions are legal terms, which in the case of the ELV Regulation is not yet in force. In literature, however, various definitions for these terms are used. For instance, (Lange 2017) outlines that the term ‘refurbishment’ is equated to the term ‘remanufacturing’. In contradiction to this statement stays (Nasr, Russel 2018) that additionally introduces term ‘direct reuse’ as ‘the using again of a product, object or substance that is not waste for the same purpose for which it was conceived without the necessity of repair or refurbishment.

(Gharfalkar et al. 2016) identifies in total five main levels of 'reuse': (i) reuse without any treatment (direct reuse), (ii) repair and reuse, (iii) recondition and reuse, (iii) refurbish and reuse and (v) remanufacture and reuse. (Gharfalkar et al. 2016) also stresses that in most of the studies reviewed, it is very difficult to understand whether the options discussed are part of direct reuse or other types of reuse.

In 2016, six global automotive remanufacturing associations reached an international agreement on a definition of remanufacturing specific to the automotive sector to enable support and raise awareness of remanufacturing. According to this agreement, 'remanufacturing is a standardized industrial process by which cores[18] are returned to same as new, or better, condition and performance (Bobba et al. 2021). The process is in line with specific technical specifications, including engineering, quality, and testing standards. The process yields fully warranted products. A core is a previously sold, worn or nonfunctional product or part, intended for the remanufacturing process. During reverse-logistics, a core is protected, handled and identified for remanufacturing to avoid damage and to preserve its value. A core is not waste or scrap and is not intended to be reused before remanufacturing.'

A detailed analysis of existing definitions of 'remanufacturing' was also done within the SMART Project (Bobba et al. 2021). Authors of this study outlined that the 'cores' are often classified as 'waste'. However, according to (Lange 2017) a core classification depends upon the application as a used product or as waste according to the German Waste Management Act (KrWG). This classification is independent of whether a product is in a functional or defective condition (seeFigure 75).

Figure 75: Classification of the term 'core'



Source: (Lange 2017)

The research to date shows that the definitions of the terms used are often imprecise or used interchangeably. Furthermore, in some studies, remanufacturing is not included in reuse; in others, remanufacturing is considered a specific type of reuse.

The preliminary analysis shows the complexity of the definitions of the terms, therefore, as agreed in the meeting with the UBA on 15 March 2024, the initial research fields of 'Repair' and 'Remanufacturing' have been merged into one research field called 'Repair and remanufacturing

[18] Used parts collected to be remanufactured are called 'cores' (Parker et al. 2015)

of parts and components from (end-of-life) vehicles'. Due to the follow-up works on the topic, the title of this chapter has been adjusted and is now ”Repair and remanufacturing of parts and components, excluding batteries”. We anticipate that the title may need to be adjusted in the light of new findings in the forthcoming research activities.

However, the newly proposed research area should investigate possible credits and burdens for activities that lead to the reuse of parts and components from vehicles (including end-of-life vehicles). The problem of the definition of ‘waste’ of dismantled parts and components (also in the context of their shipment) will be further investigated. This study will also look at possible measures to facilitate the re-use of parts and components from (end-of-life) vehicles. This issue has already been addressed in the proposed ELV Regulation (version from July 2023 (European Commission 2023a), which states that "parts and components removed from an end-of-life vehicle which are suitable for reuse, remanufacturing or refurbishment should not be considered as waste" (recital 58).

In addition, it was agreed with the UBA to treat end-of-life batteries as a separate area of research. The reasons for this decision are explained in the following chapter. This chapter therefore covers all parts and components of (end-of-life) vehicles, with the exception of batteries.

The results of different studies assessing the different treatment of parts and components removed from vehicles for reuse are outlined below. They show the variety of terminology used and the scope of the analysis carried out.

3.7.4 Foreseeable development trends

According to various stakeholders interviewed for the purpose of (Waugh, Ramjee 2021) project, the remanufacturing market is expected to grow at a slower rate than the overall aftermarket over the next decade, largely due to a business-as-usual approach. While some stakeholders believe remanufacturing growth will surpass the general aftermarket after 2025, many disagree, citing the decline in diesel powertrains as a significant factor. However, those optimistic about remanufacturing see sustainability as the key driver for future growth.

Table 32: Compound annual growth rate for the general and remanufacturing aftermarkets

	2020-2025	2025-2030
General aftermarket	4% to 5%	1% to 2%
Remanufacturing aftermarket	-3% to 0%	-1% to 0%

Source: (Waugh, Ramjee 2021)

Priority market trends

(Waugh, Ramjee 2021) investigated in their work five priority market trends that shall influence the trajectory of the automotive component remanufacturing industry between now and 2030:

- Consolidation
- Collaboration
- Rationalisation of product lines
- Digitalisation
- Transition to EV

Consolidation of the remanufacturing market through mergers and acquisition is set to continue. Acquisition allows a company to gain new markets, customer segments, and/or product lines more quickly than developing the capability internally.

It is also to expect increased strategic focus on **collaboration** through contracted remanufacturing activities. It includes interests of remanufacturers to look for opportunities to undertake contracted remanufacturing activities for OEMs, and OEMs and Tier 1[19] suppliers, respectively. This is driven by the increasing technical and economic challenges of remanufacturing highly digitised components without OEM support to access software and legacy components.

Rationalisation of product lines seems to be already partly driven by the transition to EV. The rationalisation is driven by declining markets, increased competition, or effort redirection to new opportunities. The JRC SMART report (Bobba et al. 2021) highlights that the remanufacturing market for certain components is in decline. Specifically, clutches have been declining since 2012, while alternators, constant-velocity driveshafts, pumps, and starters have been declining from 2018 to 2023. The most at-risk components are those made obsolete by technological advancements, such as the shift from manual to automatic transmissions, and those related to fossil-fuel powertrains. Remanufactured products face competition from both new original and new 'copy' products in terms of price and quality. The decision to discontinue some remanufacturing lines has been driven by increased competition, high labour costs in Europe, and the improved quality of imported 'copy' products, making remanufactured products less competitive.

Experts expects that transition to EV will have a less immediate impact on remanufacturing in comparison to the impact of **digitalisation**. Components are increasingly shifting from mechanical to electro-mechanical, and digitalization is adding complexity with more electronic parts. Additionally, business models are incorporating more digital elements, impacting remanufacturing practices and future prospects.

The transition to EV portfolio for remanufacturing industry in medium- to long-term will require investment and R&D into EV component remanufacturing. The effect of the electrification is expected to be minimal before 2030 in terms of remanufacturing operations and sales. The impact of the transition to electric vehicles can be broadly characterised in terms of three categories of products: 1) Traditional portfolio (powertrain specific) which are specific to the vehicle powertrain (e.g. petrol or diesel) and are related to the function of the combustion engine. Remanufacturing of these products will decline as EVs become more prevalent. Although petrol and diesel vehicles will still need maintenance, their numbers will decrease as internal combustion engine vehicles (ICEVs) are phased out. 2) Traditional portfolio (powertrain agnostic) which are used in ICEVs however are not connected with the combustion engine. Many components, such as brake components, will still be present in EVs, so remanufacturing is expected to continue. However, the transition to EVs may affect these components too, such as changes in brake caliper wear or a shift to brake drums. 3) EV portfolio where components are unique to EVs and represent a new opportunity for remanufacturers, like EV batteries (more about it in the following sub-chapter), electrical motors, inverters, 48-volt systems, e-axles, e-booster.

The transition to EVs will reduce powertrain complexity due to fewer components. However, this will make reverse engineering more complex, especially without standardized technology, increasing competition in remanufacturing. EV components are becoming more integrated and

[19] Component manufacturers that may also undertake remanufacturing.

sophisticated, likely shifting repairs from workshops to centralized remanufacturing due to the specialized skills and tools required. Although remanufacturing will become more complex and costly, the higher value of EV components presents a profitable opportunity for those who can enter the market successfully.

With the transition to electric vehicles, there are fewer powertrain components with moving parts that wear out, such as starters, alternators, and turbochargers. EV components are more likely to fail due to electrical faults rather than wear, leading to different remanufacturing processes and need for re-skilling of remanufacturing workforce. Additionally, regenerative braking technology reduces wear on brake components, potentially lowering remanufacturing volumes and increasing competition as these components last longer.

By reducing the number of moving parts and eliminating high-temperature combustion, many of the liquids associated with ICEVs (lubricants, fuel and engine coolant) are eliminated. This shift helps remanufacturing move towards a cleaner, high-tech image, reducing labor-intensive cleaning and hazardous waste. However, liquid coolants are still needed for battery packs.

3.7.4.1 Current activities to promote remanufacturing

The electrification contributes also to the implementation of new solutions that promote remanufacturing development. For instance, Renault subsidiary “The Future is Neutral”, has launched a remanufacturing service for electric motors, power electronics, and batteries for the company's electric vehicles. The initiative provides customers with an option that can be up to 30% cheaper than new original parts. Founded in 2022, the subsidiary aims to become the leading company in Europe for the circular economy in the motor vehicle sector by 2030. The electric motors will be available for reuse in models like the Zoe, Twingo E-Tech, Kangoo E-Tech, and Master E-Tech. Power electronics will be reusable for the Zoe and Kangoo E-Tech, while second-life batteries will be offered for the Zoe, Twingo E-Tech, and Megane E-Tech. At the French site in Flins in France, The Future is Neutral plans to achieve a production capacity of over 3,000 remanufactured components annually for electric vehicles starting from this year. In March 2024, the Renault Group has announced the establishment of an "industrial and collaborative system for circular economy solutions" that spans from Flins to Bursa in Turkey and Seville in Spain.

Alternative model represents Circular Car Concept from e.Volution . The Circular Economy Vehicle has been developed together with RWTH Aachen University and is designed to last for 50 years. A part of the Upgrade Re-Assembly Factory, which allows vehicles to be renewed and updated every five years. The adoption of the next generation vehicle construction concept requires a new approach to car modularity. Instead of a self-supporting body, a durable chassis will be used, along with interchangeable exterior and interior components with shorter lifespans. This modularity is made possible by the longer lifespan (4-5 times more) of electric motors compared to combustion engines. However, the success of this concept also relies on the establishment of further-reaching standards to enable the upgradeability of vehicles. To achieve this, the RWTH Aachen Campus has established OSCAR (Open Source Car Architecture Research), a platform that brings together communities, manufacturers, suppliers, and technology partners to define rolling standards. According to the RWTH Aachen University, the next-generation vehicle construction concept, with its focus on modularity, upgradeability, and standardization, has the potential to transform the automotive industry, leading to cheaper and more environmentally friendly electric vehicles.

3.7.4.2 Reuse of components/parts in EV

Components that will still be present in the future, in the remanufacturer's portfolio, are those that are deemed 'powertrain agnostic'; that is, are generally independent of the type of vehicle powertrain. These components may include, for example, brake components, air conditioning components and wiper motors, among others.

Parts/components from ICE that are most frequently repaired/remanufactured today (information from participants of workshop organised as part of the AutoRess project):

- Engine, transmission, starter, steering gear, turbocharger, e-components (control units)
- Brake discs
- Fuel injectors
- Transmission and clutch
- Tyres for passenger cars

According to the participants of workshop organised as part of the AutoRess project, the repaired/remanufactured parts/components from ICE that could also be reused in EVs are:

- Engine cooling system, gearbox
- Low-voltage electrical system
- Chassis: Wheels, load-bearing components not interchangeable (different weight distribution, brakes, suspension)
- Interior: occupant protection, seats, doors, windows
- Body and exterior: covers, insulation, structural parts (with modifications)
- Engines, wiper motors, bumpers and gearboxes are requested in larger quantities regardless of the vehicle)

Challenges in the reuse of repaired/remanufactured ICE components in EV are that:

- E-cars are often completely new models, therefore little overlap of components (rather interior could be reused)
- Electrification cause creation of a completely new market
- Differences between ICE models what limits the number of spare parts possible for reuse
- For instance, BMW offers all models with "all" drive types, however it is to expect that in the future there will be less BEV models which technology will overlap.

Potential of specific parts/components from EV for repair/remanufacturing:

- Technically vs. commercially viable: "All" mechanical components are suitable
- Batteries
- Electrics and control units are partially worthwhile

3.7.5 Fields of action and issues

There are possible various measures to promote repair and remanufacturing. They refer to technical, social, economic, and political & legal aspects. Selected, most frequently mentioned measures are:

Political & Legal:

- Obligation on car garages to provide customers with two options: repair using new components and repair using re-used/ remanufactured components. Legal French Circular Economy legislation (2018) introduced such law, aiming to increase the demand for the spare parts and promote a more sustainable repair process.
- More robust and comprehensive monitoring framework that would help to understand both the collection rates of parts/components (from end-of-life vehicles or from vehicles under repair/maintenance) and the specific amount (volume but also mass of materials) of remanufactured spare parts placed on the market (Bobba et al. 2021).
- Raise political awareness of remanufacturing. Educating political advocates about remanufacturing can raise the industry's profile and showcase its significant contribution to a circular economy (Waugh, Ramjee 2021).
- Mandatory corporate sustainability reports can increase awareness of benefits of remanufacturing since the aspect of sustainability (i.a. resource use and circular economy) is part of the reporting[20].

Economic:

- Introduction of economic incentives for vehicle owners that offer cost reduction for customers opting to repairs with the spare parts. An insurance company in France tackles sustainable car repair through reused components. They partner with qualified repair shops to dismantle specific vehicles (older than 8 years or total losses) and recover valuable parts (bodywork, lights). This approach not only benefits the environment but also offers potential cost reductions for customers opting for repairs with these reused parts. Their proactive policy has been a success, exceeding their target of 10% of repairs using reused components by 2020 (Tagesschau 2024).
- Tax initiatives that support remanufacturing. In 2016, Sweden reduced the Value Added Tax (VAT) on repair services for items like clothing, footwear, and household linen from 25% to 12% to encourage repairs over replacements. In 2022, the VAT was further reduced to 6%, but it was increased back to 12% in 2023 (The Guardian 2016).

Technical:

- Closer cooperation between stakeholders involved in the field of repair of vehicles and remanufacturing could increase number of remanufactured spare parts used to repair vehicles. This would require development of platforms to exchange information on demanded and available remanufactured spare parts.
    - In Germany, Allianz allows car repairs with used spare parts, which source will be vehicles that have been totally damaged and are often sold abroad for scrapping. Allianz wants to reuse parts such as doors, front and tailgates, as well as mirrors, headlights and

[20] Opinion comes from the participant of workshop organised as part of AutoRess project

rear lights. Safety-relevant parts such as steering systems, axle parts or wheels will not be used. The implementation of this activity has required a development of a database for the exchange between garages of existing remanufactured spare parts that can be used to repair vehicles insured by Allianz.

- Currently existing platforms to exchange information on spare parts: Stellantins B-Parts (Stellantis 2023).

- Design for remanufacturing (e.g. incentivising ease for disassembly, modularity of products) (Bobba et al. 2021).
- Develop and promote industry guidance on design for remanufacturing. Promoting industry guidance on design for remanufacturing by sharing best practices and business cases can encourage suppliers to adopt these methods. Additionally, independent remanufacturers can provide valuable feedback to OEMs on failure modes and ways to improve remanufacturability (Waugh, Ramjee 2021).
- Remanufacturing certification and labelling. Certification schemes for remanufacturing could help distinguish high-quality remanufacturers from those not adhering to accepted standards, thereby improving consumer confidence. These schemes, along with product labelling and potential regulatory support, could enhance trust and support circular practices. However, stakeholders have mixed views on their effectiveness and cost.
- 'Right-to-Repair'. An aftermarket initiative would require vehicle manufacturers to provide affordable access to software and spare parts for a set period after production ends, supporting legitimate remanufacturing activities (Waugh, Ramjee 2021).
- Access to sufficient information for garage on how to repair part/component. Additionally, should by accomplished with information on possible remanufacturing of part/component (statement from participants of workshop organised as part of AutoRess project).

Social:

- Raise awareness in society of the benefits of repaired/remanufactured spare parts in order to increase demand for such parts.

3.7.6 Modelling

The analysed variations depend on the proportion of materials from dismantled end-of-life parts/components for reuse/remanufacturing, with the proportion of BEV-Repair[21] in the stock, and with the prolonged lifetime of BEV-basis in stock. The three variants differed in the following ways:

- V1 – change in the share of materials from dismantled parts and components for reuse/remanufacturing as outlined in 3.11.6 (End-of-life Variation 1) and presented in Table 33, with no change in the lifetime of BEV vehicles comparing to the baseline.
- V2 – no change in the share of materials from dismantled parts and components for reuse/remanufacturing, however, there is an increase in the BEV-Repair share in the fleet comparing to the baseline. The prolonged lifetime corresponds to the Variant 2 of

[21] High repairability and reuse potential

reuse/repurpose EV batteries with the share of BEV with "High repairability and reuse potential" in the fleet (BEV-Repair) (more in 0 and Table 22).

- V3 – no change in the share of materials from dismantled parts and components for reuse/remanufacturing; however, an increase in the lifetime of BEV-Basis (corresponding to 100% of the fleet) within about 2 years,

Table 33 shows the values used in the model for the portions of reused/remanufactured materials. These are the same values used in the calculation of the end-of-life option in chapter 3.11.6.

Table 33: Share of reused/remanufactured material

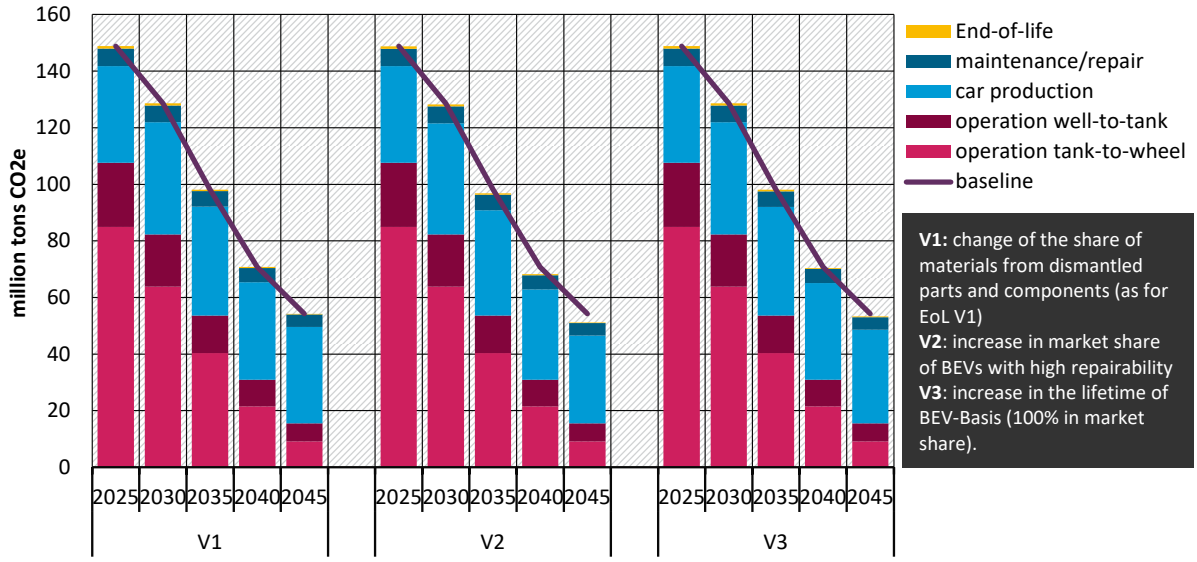
	Baseline	V1 2030	V1 2035	V1 2040	V1 2045	V1 2050
Flat steel	7%	7%	7%	7%	7%	7%
Long steel	7%	10%	15%	18%	20%	20%
Stainless steel	7%	10%	15%	18%	20%	20%
Cast iron	7%	10%	15%	18%	20%	20%
Wrought Aluminium	7%	10%	15%	18%	20%	20%
Cast Aluminium	7%	10%	15%	18%	20%	20%
Copper	7%	1%	2%	3%	4%	5%
Plastics	1%	5%	6%	7%	8%	10%
Glass	10%	5%	5%	5%	5%	5%

Source: own assumptions

3.7.7 Results

Repair and remanufacturing promote the concept of circular economy, reducing waste and extending the lifespan of products. Thanks to the reuse of parts and components from (end-of-life) vehicles, new component manufacturing can be avoided, which contributes to a reduction of CO_2 emissions and other environmental burdens in the production phase. The Figure 76 below illustrates potential GHG savings in comparison to the baseline.

Figure 76: GHG emissions for cars for the different variations (Repair and remanufacturing of parts and components, excluding batteries)



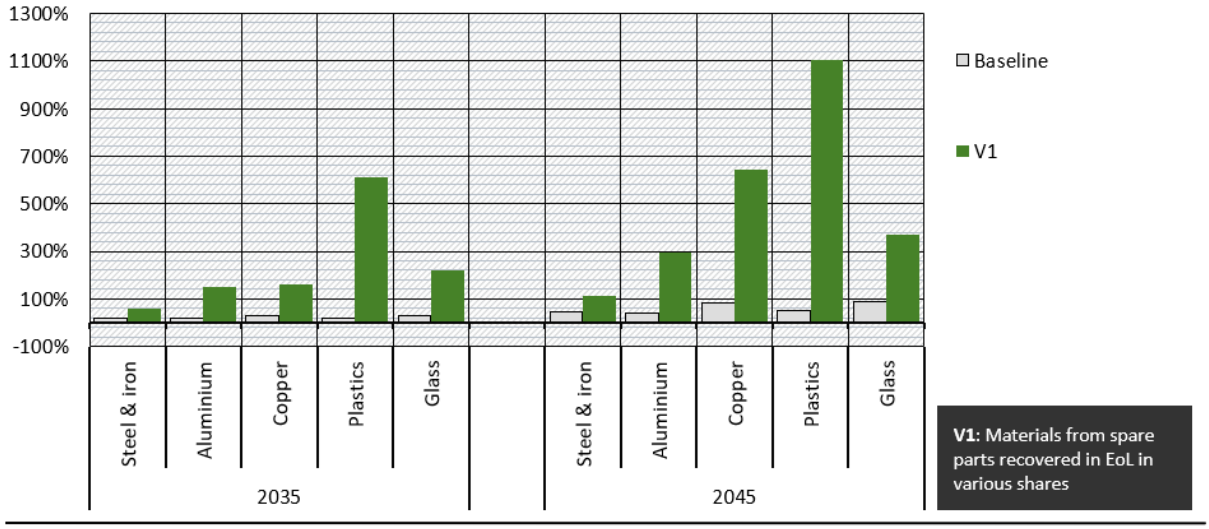
Source: own figure, ifeu/ Oeko Institut

An increase in the market share of BEV-Repair seems to bring the greatest savings in terms of greenhouse gas emissions. The BEV-Basis life extension option is also associated with a reduction in GHG emissions over the years, but at a lower level.

The chosen methodological approach to the model means that higher shares of materials from dismantled parts and components intended for reuse and remanufacturing have no direct impact on GHG (see Figure 76) since no credits are awarded for savings from primary material production. The reduction in greenhouse gas emissions is already accounted for in the baseline assumptions.

The existing model allows for the calculation of material amounts from spare parts for reuse and remanufacturing recovered in end-of-life. Figure 77 below shows the savings of new materials compared to 2025 (Reuse and remanufacturing).

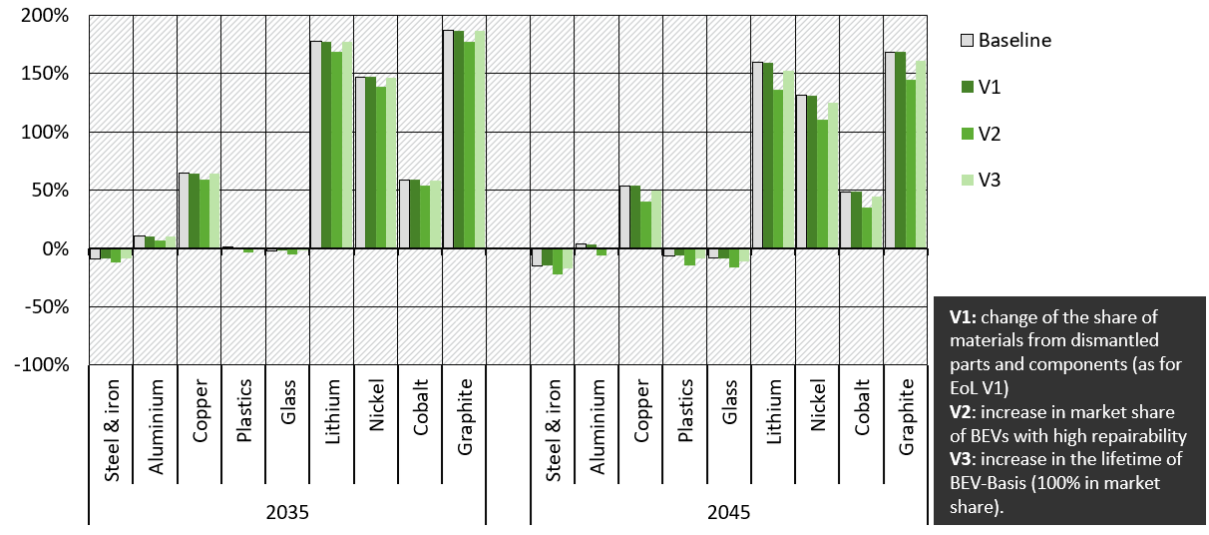
Figure 77: Material savings from spare parts recovered in EoL compared to 2025 (Reuse and remanufacturing of parts and components, excluding batteries)



Source: own figure, ifeu/ Oeko Institut

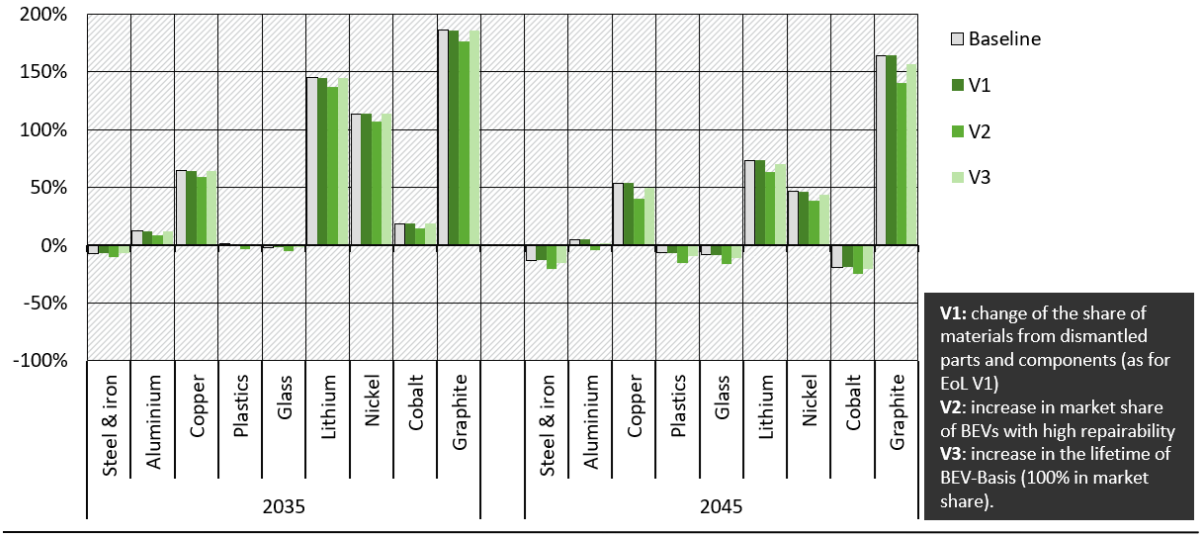
The long lifetime of BEVs with "High repairability and reuse potential" (V2) offers the most significant decrease in total and primary material demand in comparison to 2025. The V3 (increase in the lifetime of BEV-Basis) impacts both demand for total and primary materials, but to a lesser degree. Similar to GHG emissions, the baseline and V1 remain at the same level.

Figure 78: Changes in material demand (total) for cars for the different variations compared to 2025 (Repair and remanufacturing of parts and components, excluding batteries)



Source: own figure, ifeu/ Oeko Institut

Figure 79: Changes in material demand (primary) for cars for the different variations compared to 2025 (Repair and remanufacturing of parts and components, excluding batteries)



Source: own figure, ifeu/ Oeko Institut

3.8 Recycled content of battery materials

3.8.1 Background

The use of recyclates in preliminary products and/or in final production reduces the need for primary raw materials. Usually, less energy is required to produce the secondary material from recyclates compared to the primary material, which leads to considerable energy-related savings in greenhouse gas emissions. But is also requires energy input and can lead to considerable CO_2 emissions (Schmidt 2021). The energy savings from using secondary materials vary across different sectors. However, the effectiveness of recycling depends on material concentration, as lower concentrations in end-of-life products compared to natural ores can impede recycling efforts (Schmidt 2021).

In terms of battery systems, conventional materials such as iron, aluminium and plastics still dominate the list of materials in absolute terms. At cell level in particular, however, technology-strategic materials such as lithium, nickel and cobalt are coming to the fore. It is expected that their global production capacities will have to multiply considerably in order to supply the growing market for batteries for mobile and stationary applications (Maisel et al. 2023; McKinsey & Company 2023).

Currently, mostly primary materials are used in the production of traction batteries, especially for lithium, nickel and cobalt (Grohol, Veeh 2023). This is partly due to the high demands placed on battery materials and partly due to the lack of availability of secondary raw materials on the market. However, with the increasing market penetration of electromobility, the quantities of used batteries that are recycled in order to recover key raw materials will also increase.

The new EU Battery Regulation ((EU) 2023/1542) sets out key regulatory requirements along the entire battery life cycle, from production to disposal. In addition to requirements for recycling efficiency (Art. 71, Annex 12), explicit requirements are also made for secondary content in selected battery raw materials (Art. 8). The analyses of this topic area focus on the

effects on GHG emissions and the raw material requirements of vehicle traction batteries generated by an adapted use of recycled materials (EU Battery Regulation requirements).

3.8.2 Status quo

The analysis focuses on the battery materials lithium, cobalt and nickel (EU Battery Regulation). Copper is analysed in more detail in chapter 3.9. Graphite is also analysed, as the material is one of the EU's critical raw materials (Grohol, Veeh 2023) and is often the focus in terms of recycling research. The regulation does not yet specify any requirements for graphite as a anode material but reserves the right to add other materials that could be relevant in the future in a revision clause.

Cobalt

Cobalt is one of the most expensive materials in the active material of the battery cell. In recent years, the industry has pursued a strategy of continuously reducing the proportion of cobalt in lithium-ion batteries for mostly economic reasons. Lithium-ion technologies with a higher nickel content are currently being used. However, the high material price and the good recyclability of cobalt mean that recycling processes can be operated economically and become established. In its study on critical raw materials, the EU Commission assumes an End of Life Recycling Input Rate[22] (EoL-RIR) of 22% (Grohol, Veeh 2023). This figure initially appears very high and must be relativised to the extent that there may be higher quality requirements for battery materials and therefore a higher proportion of primary material is used in batteries. The Federal Institute for Geosciences and Natural Resources (BGR) assumes that cobalt recycling contributes around 10% to the total supply. The data here relates to the years 2017-2019. However, it is pointed out that although only small quantities are currently available to the market, the recycling sector will play a much greater role in the supply of cobalt and other battery metals in the long term (Schütte 2021).

According to the ecoinvent inventory database, however, the majority of recycling takes place downstream by reprocessing alloy scrap into new alloys or as an intermediate product in the cobalt chemical industry, where further refinement is required. Secondary production for "pure" cobalt is only considered to be of minor importance (less than 1% of the cobalt input) (ecoinvent 3.9). However, this data dates back to 2012 and must be categorised as outdated.

Nickel

Nickel is traditionally used for steel refinement and is also particularly important for numerous high-tech industries, among others. Stainless steel production and the production of alloys with a high nickel content accounted for around 86% of the primary applications of nickel in 2019 (Vasters et al. 2021). The use of nickel in batteries was still relatively low at around 5% of the nickel supply (Szurlies et al. 2021). However, this segment is expected to see by far the strongest increases in demand in the future, as the cathodes of lithium-ion batteries have recently evolved towards nickel-rich variants in order to increase cell capacity. By 2030, more than 25% of global nickel demand, which is estimated at around 4 million tonnes of nickel per year at that time, is expected to be used for battery production alone (Fraser et al. 2021). This corresponds to almost half of primary nickel production in 2019 (Vasters et al. 2021).

Nickel can be recycled without any loss of quality and used as a secondary raw material for many of its applications. Large quantities of secondary nickel are currently used to supplement newly mined ore. The economic value of nickel is an important incentive for recycling. In its study on critical raw materials, the EU Commission assumes an End of Life Recycling Input

[22] Percentage of total demand that can be covered by secondary raw materials.

Rate[23] (EoL-RIR) of 16% (Grohol, Veeh 2023). A considerable proportion of the secondary nickel collected for recycling is exported from the EU (Cristina et al. 2020). The largest proportion of secondary nickel goes into steel refining. Ecoinvent currently assumes <1% secondary content in the "nickel, class 1" process by treating metal parts from electronic scrap (Bourgault 2011).

Lithium

When looking at battery raw materials, lithium in particular is affected by very strong increases in demand. Estimated global demand in 2030 will exceed current supply by a factor of five (McKinsey & Company 2023). The projections for the EU show a tenfold increase in additional lithium consumption for batteries in electromobility alone compared to current lithium consumption in all applications in the EU (Bobba et al. 2020b).

Recycling is not yet a relevant factor in lithium production. On the one hand, the amount of lithium-containing material available for recycling is still relatively small, and on the other hand, recycling is relatively expensive and very process-intensive compared to mining (Drobe 2021). In the future, batteries could be the most important source of recycled lithium, but its recovery is still a challenge in 2021 due to the high energy consumption. Cobalt and nickel remain the two target metals and the most important sources of value in the recycling process. In its study on critical raw materials, the EU Commission assumes an End of Life Recycling Input Rate (EoL-RIR) of 0% and a 100% dependence on imports (Grohol, Veeh 2023).

It is expected that the recovery of lithium will become economically viable in the next decade due to the expansion of recycling plant capacity (Saatkamp 2023). The recovery of lithium compounds (Li2 CO3 and LiOH) as end products through hydrometallurgy is the most likely commercial recycling scenario (French Geological Survey 2023).

Graphite

Graphite is used in batteries as an active material in the anode. Natural graphite has been one of the EU's critical raw materials since 2020 due to its high country concentration in production (Grohol, Veeh 2023). The share of lithium-ion batteries as end consumers of graphite is now 8% in the EU. The main consumers, are refractory applications in steel production (54%) (French Geological Survey 2023). Global demand for battery-grade graphite is expected to triple by 2030 (European Commission 2021a). Graphite can also be produced synthetically, so there is no complete dependence on the primary material. Synthetic graphite and natural graphite compete in various applications. Both types are often mixed to achieve special material properties (French Geological Survey 2023). The choice of substitute is mainly determined by the relative price, carbon quality and particle size and shape. Both the processing of natural graphite and the production of synthetic graphite for the requirements of battery applications are very energy-intensive (Qizhong, Damm 2020).

In its study on critical raw materials, the EU Commission assumes an End of Life Recycling Input Rate (EoL-RIR) of 3% for graphite (Grohol, Veeh 2023). The recovery of graphite in battery recycling poses a challenge. In pyrometallurgical processes, graphite is burnt and lost. While the EU Battery Regulation does not establish material-specific efficiency target[24] for the recycling of graphite, given that the material constitutes a significant portion of the battery by mass (Kosenko et al. 2023), the recycling efficiency target in relation to the overall battery system can only be achieved if graphite is at least partially recovered. The use of hydrometallurgical

[23] Percentage of total demand that can be covered by secondary raw materials.

[24] By the end of 2025, the overall efficiency of lithium battery recycling must reach 65% by weight. After 2030, this efficiency will increase to 70% ((EU) 2023/1542).

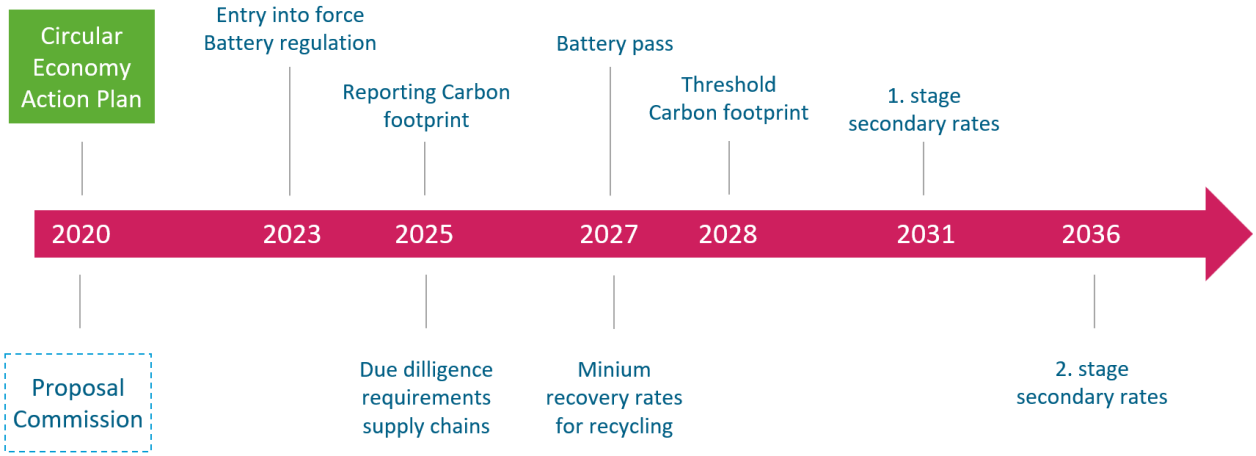
processes in combination with thermal treatment are promising recycling processes for this purpose (French Geological Survey 2023).

3.8.3 Legal framework

The specific handling of waste batteries is primarily economically motivated, but is also regulated by a number of laws, directives and standards for environmental and political reasons. The most important law is the new EU Battery Regulation, which was adopted in July 2023 (Regulation (EU) 2023/1542). This was one of the first initiatives to be launched under the New Circular Economy Action Plan, with the objective of achieving the goals set out in the European Green Deal.

The Regulation addresses the social, economic and environmental issues associated with all types of batteries. The regulation now creates a general legal framework that will be followed by a series of secondary regulations (delegated and implementing acts). These will regulate further technical and methodological details (e.g. calculation rules for efficiency rates and the CO_2 footprint) so that the Regulation can be fully implemented. Figure 80 summarizes the roadmap of the regulation with important annual figures for specific regulations.

Figure 80: Roadmap new EU battery regulation



Source: Adapted from (Neef et al. 2021).

The EU Battery Regulation covers the entire life cycle of batteries from production to disposal. In addition to a new differentiation of battery types (such as the special emphasis on traction batteries for electric vehicles), the law regulates binding requirements with regard to:

- Sustainability
- Safety and labelling
- Reuse of batteries: Definitions and role of economic operators
- Treatment of used batteries
- Due diligence obligations in the procurement of raw materials
- Regulations for the battery passport

The sustainability requirements in relation to the CO_2 footprint, recycled content, performance and service life will be gradually introduced from 2024 (see Table 34). In addition to specifying

the CO_2 footprint of the battery, a CO_2 upper limit will also be defined. Important technical data will be collected in the battery passport, which should simplify repair, reuse and recycling. A more comprehensive framework for extended producer responsibility (due diligence) will apply from mid-2025.

Waste batteries may not be disposed of or used for energy recovery (Art. 70), so that only reuse or recycling is an option. Annex 12 Part A specifies how waste batteries are to be treated, e.g. that the facilities must comply with the best available technology. By the end of 2025, the overall efficiency of lithium battery recycling must reach 65% by weight. After 2030, this efficiency will increase to 70%. The material-specific recycling targets for cobalt, nickel and copper are 90% (50% lithium) by 2027 and 95% (80% lithium) by 2031. In addition to recycling efficiency targets, the EU Battery Regulation also sets targets for recycled content of selected active materials in new batteries. These are also adjusted in a two-stage process (see Table 34).

Table 34: Specified secondary components in active materials of the battery according to EU Battery Regulation (EU) 2023/1542

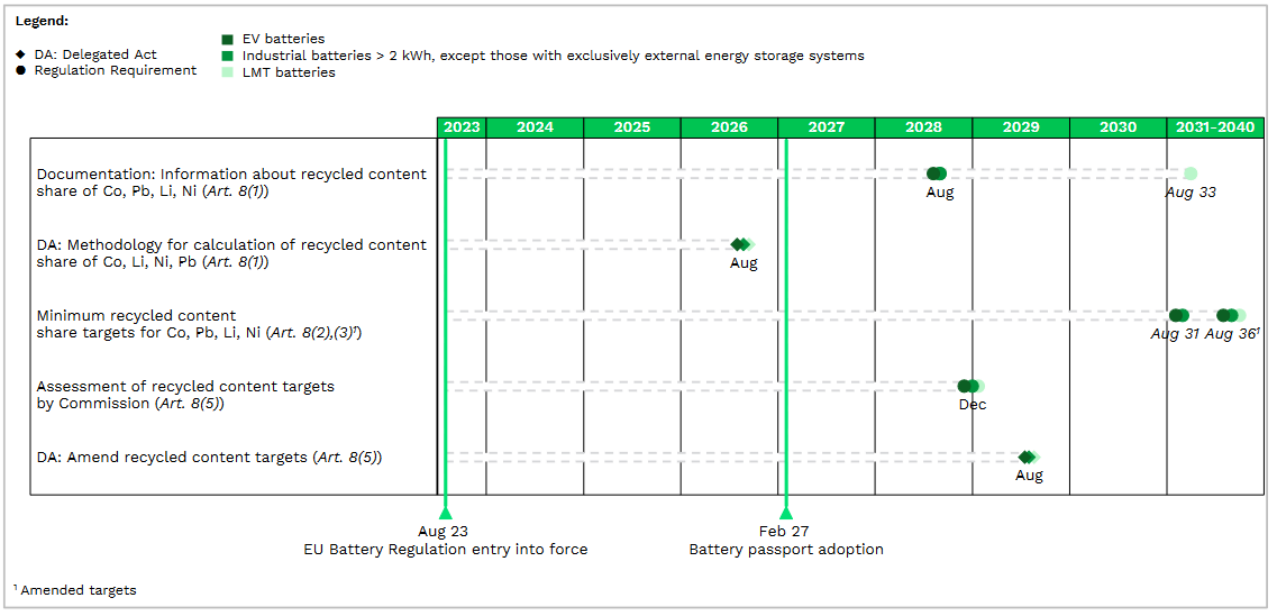
	Co	Ni	Li	Pb
First stage, 96 months after entry into force (2031)	16%	6%	6%	85%
Second stage, 156 months after entry into force (2036)	26%	15%	12%	85%

Source: own table Oeko-Institut / ifeu

The EU Battery Regulation focuses on cobalt, lithium, lead and nickel as relevant elements for the secondary content requirements. However, according to Article 8 (paragraph 6) of the regulation, other materials may be included in the scope of the regulation if market requirements or technical or scientific progress change. Therefore, the calculation method should be transferable to other materials if the secondary content for other materials is reported voluntarily or even becomes mandatory. This aspect is particularly interesting for graphite.

According to Art. 8 (para. 5), the regulation still reserves a revision clause regarding the selected battery materials with specifications on secondary content. By the end of 2028, the EU Commission will assess whether the raw material availability of the materials concerned is given and adjust the targets accordingly. Furthermore, the calculation method for the proportion of secondary material for the selected battery raw materials must still be described in a delegated act (by August 2026). Figure 81 provides an overview of the timetable for regulations and delegated acts relating to the secondary content in batteries.

Figure 81: Timetable for the recycled content requirements and the entry into force of the delegated acts



Source: (Battery Pass consortium 2023). Licence: CC BY-NC 4.0.

3.8.4 Foreseeable development trends

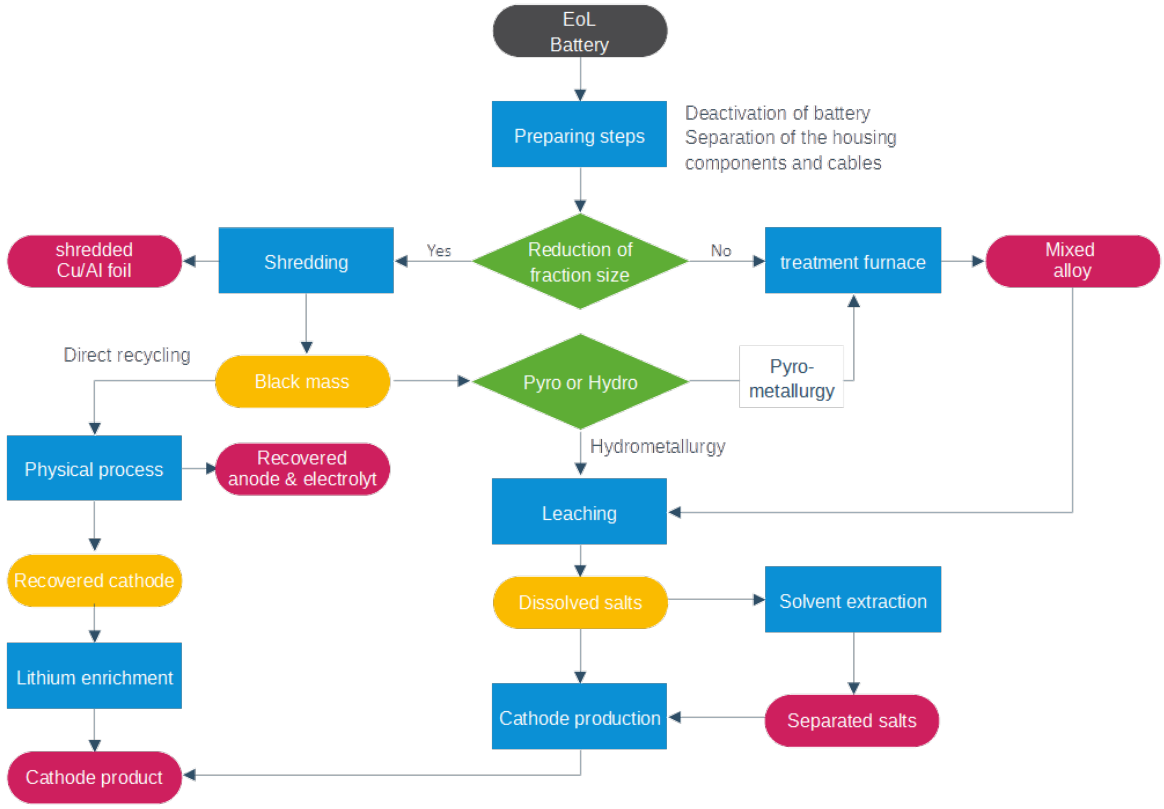
The most important development trend in increasing the use of recyclates in battery raw materials is the further development of battery recycling. Battery recycling is the most important secondary source of materials for lithium and cobalt in the future. Nickel has other potential secondary sources due to its broad field of application and established recycling systems for nickel steels. Graphite could also draw on other secondary sources, but quality requirements may limit this. A closed cycle of battery cell production and recycling is the most important strategy for increasing the use of recycled materials.

3.8.4.1 Battery recycling: process and state of the art

As soon as a battery has reached the end of its useful life and is no longer suitable for further use, it must be recycled in accordance with legal requirements. There are a variety of process steps that are now used in battery recycling, including pre-treatment such as deactivation of the battery. However, these can be summarised under three basic process types: Pyrometallurgy (smelting), hydrometallurgy (leaching) and direct recycling (physical/mechanical processes). Nowadays, a combination of process steps from different process types is predominantly used. However, the focus can often still be assigned to the process type (Wagner-Wenz et al. 2022).

Figure 82 shows the relationships between the process types. The individual process steps can be combined in different ways, depending on factors such as the quantity and properties of the available input material and the quantity and value of the materials to be utilised (Gaines 2018; Sommerville et al. 2021; Wagner-Wenz et al. 2022).

Figure 82: Flowchart of the recycling routes



Blue: process steps, green: decision for process type, yellow: intermediate product, pink: traded products
Black Mass: Pulverised active material (mixture).
Source: adapted from (Gaines 2018; Sommerville et al. 2021).

The first process step, which applies to all process routes, is the preparatory treatment. This includes deactivating the battery (discharging), separating the casing and, if necessary, decomposing the organic components by pyrolysis (Wagner-Wenz et al. 2022). It should be noted that the current input stream for battery recycling is still heavily characterised by smaller batteries from consumer electronics and batteries from micromobility (e.g. e-bikes, scooters). It is anticipated that in the near future, a greater quantity of batteries from electric vehicles will be introduced into the input stream, which will have an impact on the treatment steps that are currently in progress.

The next step is to decide whether the cells should follow the pyrometallurgical process route directly and be melted in the blast furnace. **Pyrometallurgy** utilises high temperatures to facilitate the oxidation and reduction reactions in which transition metals such as copper, cobalt and nickel are reduced from oxides to metals and recovered in a mixed metal alloy. The metals can then be separated hydrometallurgically and used to produce new cathode material. Other materials, such as aluminium, the graphite anode and the electrolyte, are oxidised in the melt and supply a large proportion of the process energy. The lithium oxides pass into the slag remaining from the combustion process and were not recovered further in the past for economic reasons. However, the slag was purchased by the construction industry as an aggregate. The specifications of the EU Battery Regulation require the recovery of lithium from the slag, which is possible in terms of process technology, but entails additional process costs.

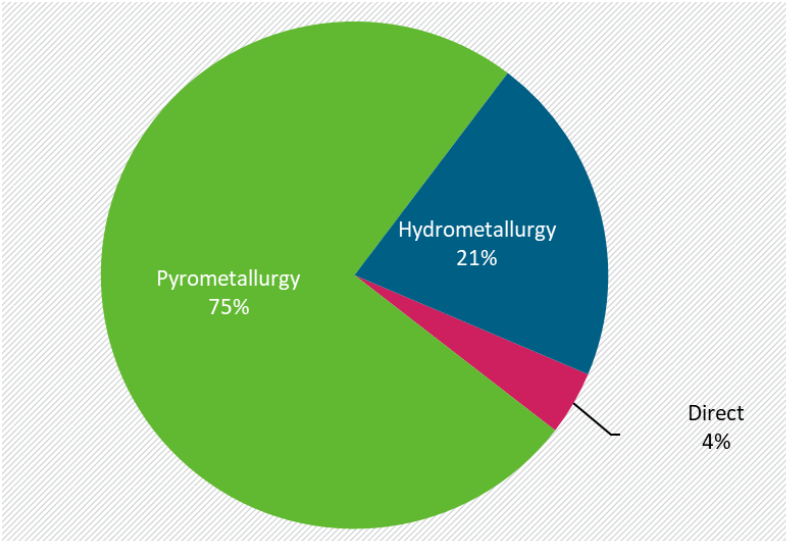
If a hydrometallurgical process route is to be selected after the preparatory treatment steps, the cells must first be shredded to reduce the fraction size. At this point, the copper and aluminium

foils are also recovered using mechanical processes. What remains is the black mass as pulverised active material. This is followed by treatment in **hydrometallurgy**. It uses acids to dissolve the valuable metals present in the black mass and thus produce a solution enriched with the valuable metals. These can be obtained by precipitation or solvent extraction and transferred with other recovered materials into a new cathode material.

Direct recovery separates the various components of the active material by physical processes (e.g. gravity separation). The separated materials can be recovered without chemical alteration, allowing direct recovery of cathode material with minimal treatment (Gaines 2018). Nevertheless, the current state of the art indicates that this process is still associated with a loss of quality, requiring at least one post-treatment step to improve quality (Zheng et al. 2018). The same applies to the recovery of the electrolyte and the anode. In addition, the cells would have to be recycled according to their chemical composition, which places further demands on the separation processes in the recycling process. Given that batteries remain in use for approximately 15 years before becoming available for recycling (Gaines 2018; Neef et al. 2021), it is possible that the types and composition of cathode materials for new applications may have undergone changes during this period. The currently very dynamic phase of technological development of rechargeable battery materials makes direct recovery of the active material unattractive. The viability of this recycling process will become more apparent in the future, once cell technology has reached a more stable phase of development and cell chemistries have been established for a longer period of time.

The main reason for the continued recycling of lithium-ion batteries after the cells have been shredded was previously the recovery of valuable raw materials (cobalt and nickel). In recent years, however, the cobalt content in the cells has decreased in order to save costs in production. In addition, regulatory pressure from the EU is now increasing due to the requirements of the EU Battery Regulation. As a result, there is now a need for action to recover further materials. Although the majority of battery materials can theoretically be recovered according to the current state of the art, not all recovery steps are economically or ecologically advantageous. In recent years, research initiatives have been launched at national and European level in particular (e.g. LithoRec, Libri, EcoBatRec) in order not to be left behind by the rapidly growing recycling market in East Asia. The Asian recycling market benefits from lower wage levels, making highly labour-intensive process routes such as the hydrometallurgical/direct process profitable.

Figure 83: Recycling routes by global capacity



Data basis: (Wagner-Wenz et al. 2022).

Despite the high energy input, the high loss rates and the special process requirements in waste gas aftertreatment during pyrometallurgy, this process is the most widely used and enables large capacities of individual plants. This is due to the high flexibility and the non-selective nature of the process (Baltac, Slater 2019; Zheng et al. 2018). This advantage is reflected in the global distribution of recycling routes by capacity. Figure 83 shows that around 75% is accounted for by the pyrometallurgical process, 21% by hydrometallurgy and only 4% by direct recycling routes (Wagner-Wenz et al. 2022). In recent years, however, hydrometallurgical recycling capacities have been increasingly established in Germany, although these are smaller in size than pyrometallurgical plants (expert interview UBA).

Higher efficiencies and a greater quantity of recovered materials can be achieved with hydrometallurgy. The challenge here is that, despite the lower energy input, the individual processes are more labour-intensive and efficiency is heavily dependent on the quality of the input material. In addition, large quantities of reagents are required for the chemical processes, which entails complex treatment of the process water. On the other hand, certain materials are not lost as process energy sources, such as graphite.

Many recycling companies are already moving away from pursuing an exclusively pyrometallurgical or hydrometallurgical path and instead developing individual hybrid processes (e.g. EcoBatRec process from Accurec (Buchert, Sutter 2016) or specialising only in certain sub-processes (expert interview in (Biemann et al. 2024)).

However, the recycling processes used to date are primarily designed for the recovery of expensive precious metals (mainly Co and Ni) from common cathode materials such as LCO, NMC and NCA. Lithium now also plays a role due to its legal requirement for recycling efficiency. The main process types described (pyrometallurgy and hydrometallurgy) have in common that they extract these materials in a highly pure elemental, oxidised or saline form. This is time-consuming and energy-intensive and is only economically viable if market prices are favourable. These processes are hardly suitable for cobalt- and nickel-free cathode materials, as the economic value of the individual elements they contain is too low to make the recycling process profitable. The lithium iron phosphate battery (LFP), which has recently gained popularity in both electric vehicles and stationary energy storage systems, falls into this category (Renier et al. 2023). Numerous Chinese car companies are already selling cars equipped with this type of

battery, although a large-scale recycling process has not yet been developed (Forte et al. 2021). Research has also focused primarily on the recovery of lithium. In order to improve the economic viability of LFP recycling, the recovery of other elements such as phosphorus is crucial in addition to the recycling of lithium (He et al. 2020). Various recycling approaches are being discussed in research, for example to use it as a secondary source of fertiliser (He et al. 2020; Yue et al. 2021) or to reprocess it as a cathode material via direct recycling (Renier et al. 2023).

3.8.4.2 Expansion of battery recycling in Germany and the EU

With the rapidly growing sales of electrified vehicles (cars, trucks, etc.) and stationary storage systems, a large input flow for the recycling of LIB is to be expected in the foreseeable future. The legal requirements stipulate recycling, including minimum standards for recycling efficiency. To date, the majority of LIB recycling capacities have been located in East Asia, particularly in China (Baum et al. 2022). Relevant capacities for LIB recycling are currently also being established in Europe.

Stephan (2025) analysed the recycling plants for lithium-ion batteries installed by the end of 2025 and those announced for the coming years in Europe, as well as their operators. The particularly high number of recycling plants in Central Europe is striking. This is often due to the proximity to battery material producers, battery cell manufacturers or car manufacturers. However, the analysis also shows cancelled projects which became increasingly frequent in mid-2024. Several major projects were affected such as Northvolt, Eramet and SungEel High Tech. Still in the forthcoming years, recycling capacity will significantly rise and countries such as Spain and the United Kingdom will diversifying the project situation in Europe. Several plants are planned from the outset in such a way that they can increase their capacity if required.

The recycling locations differ according to the degree of recycling depth, i.e. the input and output materials of the recycling process:

- systems to carry out the first steps of battery recycling: Discharging the old batteries, dismantling and mechanical processing into black mass.
- plants carry out the second stage of battery recycling: Further processing of the black mass using hydrometallurgical and/or pyrometallurgical processes so that valuable materials such as cobalt, nickel and lithium can be recovered.

Most recycling plants have published information on their recycling capacity. However, as not all plants have the same recycling depth, these capacities cannot simply be added together. In Europe, the plant types are distributed 50/50 according to the two defined recycling depths. The sum of the capacities of the plants in the first recycling stage makes it possible to estimate the total quantity of batteries that can theoretically be recycled. However, as individual recycling plants carry out both processing to black mass and further processing at the same site, the potential recycling volume tends to be underestimated. Based on the data collected by the BEMA2020 and BEMA On project (Fraunhofer ISI 2025), the capacity for the first stages of LIB recycling in the EU is expected to increase up to 420 kilotonnes per year by the end of 2026. Compared to 2023, this is more than a doubling of capacities (160,000 tonnes by the end of 2023). In 2025, the capacities for recycling black mass in hubs has increased significantly. By 2030, the announced total refining capacity (820 kilotonnes per year) will significantly exceed the return volume. This would correspond to a processing capacity of around 350 kilotonnes of black mass per year in 2030. Whether and to what extent the import of black mass as feedstock for material recovery will play a role is still unclear. (Stephan 2025). A comparison of the planned recycling capacities with the forecast return volumes of recycled batteries and

production waste shows that the planned capacities will exceed demand in the coming years (Saatkamp 2023; Stephan 2025).

3.8.4.3 Further trends in possible secondary sources for battery raw materials

In addition to the recycling of EoL batteries, the recycling of scrap materials from the planned gigafactories in Europe will be a relevant source of secondary material in battery raw materials. The report on the EU recycling market 2023 by PWC and RWTH Aachen assumes that the recyclate share of battery materials up to 2025 will still mainly consist of the recycling of metal scrap from cell production in the gigafactories (80%). From 2030, the first significant wave of electric vehicles will enter the recycling stream. Recycled cell material then already accounts for 40% in the scenario. In 2040, according to the study, the main driver for secondary material in batteries (90%) will be battery recycling itself (Neuhausen et al. 2023).

According to the current version of the EU Battery Regulation, there are no specifications for recycling efficiency and secondary content for graphite. The economic recovery of graphite in the recycling process is still a challenge. On a laboratory scale various methods have been developed to recover high-quality graphite, including pyrometallurgical and hydrometallurgical approaches. The recovery rates range between 40% to 95% with different levels of electrochemical performances (Rey et al. 2021). An interesting approach involves smelting under nitrogen atmosphere and ultrasonic separation which achieves over 77% graphite recovery with 99.5% purity (Yi et al. 2020). However, graphite recovery processes are still under development and face the challenge of being economically and even environmentally viable compared to primary extraction.

Theoretically, recycled graphite for anodes can also be obtained from other sources in addition to battery recycling. The recycling and processing of graphite-based refractory materials began more than thirty years ago in the EU. Recycled materials are used in some applications as full or partial substitutes for primary materials, e.g. in monolithic and moulded refractories (European Commission 2017). The extent to which secondary graphite from this field of application is suitable as an input material for the active material of the anode still needs to be investigated. In addition, cooking foam graphite is a potential additional secondary source of graphite that is produced during steel production. It forms on the free surface of the molten iron and grows in the form of lamellae. In steelworks, graphite flakes are produced in different quantities, sizes and purities. A technical and economic assessment was carried out for a process plant, which shows that the utilisation of this secondary resource could be economically feasible (Frost 2015). However, this has so far been categorised as an individual study.

Further trends for nickel recycling are describes in chapter 3.9.

3.8.5 Fields of action and issues

- Trade in recycled material or intermediate products

The focus on closed raw material cycles for batteries in Europe makes sense from an ecological and economic perspective. However, the battery and subsequent electric car manufacturing industry has a highly globalised supplier structure. Suppliers from other regions must also comply with the required recycled content for electric vehicles sold in Europe. In addition to being a strong location for battery cell production, East Asia has also developed an extensive cell recycling system. In addition to a strong demand for primary material for batteries, secondary material plays an important role. Defective batteries or electric vehicles may not be exported from the EU, but this does not apply to the intermediate recycling products. The extent to which

trade in these products is becoming more relevant and which volume flows are affected is an influencing factor that should be further analysed.

- Recycled materials are often not produced directly at the place of manufacture

Furthermore, the recycling materials are often not produced at the place where they were manufactured. New cars are exported globally and the used car trade also takes place across regions. Theoretically, an electric vehicle manufacturer has "extended producer responsibility" for the battery and is therefore responsible for legally compliant recycling. Within the EU, corresponding EoL logistics for electric vehicles should be accessible. In future, however, it will be necessary to reduce the hurdles to disposal by end consumers in order to prevent a shift to informal structures (trade in "defective" end-of-life vehicles).

The trade in used cars poses a further challenge for the transparent recycling of battery materials. According to foreign trade statistics and the Federal Environment Agency's estimate, around 340,000 used German cars and light commercial vehicles left the EU in 2019 (UBA and BMUV 2020). The figure is likely to be much higher if the used car cascade is continued by other EU countries such as Poland or Romania. As long as the electric vehicles remain in the EU, they are subject to the applicable legislation and are integrated into European recycling logistics. Exporting them to countries with a lack of regulation or lack of enforceability of the regulations makes it more difficult to recycle these materials. Due to the high value of EoL batteries, it can be assumed that there is at least an informal market that receives and processes some of the materials so that they can be fed back into the material flow as secondary material. An interesting data source for tracking the materials and ensuring the recycled content is the documentation of the battery data in the battery passport, as prescribed by the EU Battery Regulation. This documentation also provides stakeholders outside the EU with information about the composition and therefore suitable recycling routes. However, the conditions under which the processing then takes place and whether this is in line with the regulatory requirements remains questionable and would need to be analysed further.

- Activities of electric vehicle manufacturers with regard to material supply chains and investment in recycling facilities

Another measure for the transparent documentation of the sustainable use of raw materials is the commitment of electric car manufacturers to use established standards and pursue a supply chain strategy for batteries. A study shows that only a small proportion (one sixth) of the raw materials required by car manufacturers in the EU in 2030 will be secured via contracts. In terms of activity in sustainable procurement practices, German car manufacturers are considered to be leaders. But there is still room for improvement when it comes to integrating recycling facilities into their own raw material cycle. However, some efforts have already been made: Some major car manufacturers are either main operators (e.g. VW, Mercedes-Benz, Tesla, BYD) or shareholders of recycling plants (e.g. Renault, Stellantis) (Gimbert, J. 2023).

- Lithium-Ion technology replaces lead-acid battery as starter and on-board battery

Another aspect if recycled battery materials are considered is the role of lead-acid batteries in future cars. The lead-acid batteries supply the 12-volt power circuit in vehicles and are mainly used for on-board and security systems. Some electric vehicles removed the lead-acid batteries from the system and powered the low-voltage circuit with the traction battery and a converter (Gleich 2022). However, car manufactures preferred to keep the lead-acid batteries for the low-voltage circuit due to safety and cost aspects. It makes sense to power a low and high voltage power circuits from separate energy sources. Since the lead-acid batteries are cost-efficient and

established in the market. Electric vehicles currently have the system onboard besides the lithium-ion battery for traction (400-800 voltage). Recycling for lead-acid batteries are well established and recycling efficiency and recycled content is very high both >90% (Eurostat 2024; zvei 2022). However, as the price of lithium-ion batteries falls, it is becoming increasingly attractive to replace lead-acid batteries (Kowalyk 2021). The lead-acid battery is currently a very valuable system for which economically profitable recycling can be realised and a functioning deposit return system has been established. If the technology shifts for low-voltage circuits power sources to Li-Ion a large amount of lead is on the market without demand from a suitable end product. This would require a phase-out strategy for lead-acid, as the material is extremely hazardous to health and the environment. Further research and market analysis of this issue is needed.

- Delayed recycling volumes due to extended use or change of use

Many studies assume that the batteries installed in the first wave of electric car sales (2020) in Germany will have reached the end of their useful life around 10 years later (2030) and will be recycled (Neuhausen et al. 2023; Saatkamp 2023). Theoretically, it is possible that the recycling could be delayed even further, either because the vehicles continue to be operated with a shorter range or because the batteries are reused in other applications (second life, see chapter 3.7). An argument against this is that the technological development of batteries is currently very dynamic and batteries from 2020 will be considered obsolete in ten years' time and the cycle stability (calendar ageing) harbours an increased risk of defects. Furthermore, the economic viability of repurposing individual car batteries for other applications is considered very uncertain (Biemann et al. 2024). Primary data on this will not be available in Germany until 2030, but it will be possible to learn from some countries such as the USA or Norway, which started electrifying cars earlier.

3.8.6 Modelling

The baseline scenario gave the project the opportunity to review the requirements of recycled content by the EU Battery Regulation. The baseline considers a closed-loop recycling of battery materials. Recycling efficiency rates were taken from EU Battery Regulation as input parameters for the AutoRess model.

Table 35: Recycling efficiency rate requirements by EU Battery Regulation

Material	2025	2030	2035	2040	2045	2050
Lithium	50%	80%	80%	80%	80%	80%
Nickel	90%	95%	95%	95%	95%	95%
Cobalt	90%	95%	95%	95%	95%	95%
Graphite	8%	8%	8%	8%	8%	8%

Source: For Lithium, nickel and cobalt EU Battery Regulation Art. 8. For graphite (Cristina et al. 2020).

In addition to the recycling efficiency several parameters influence the general result. First, the return rate of materials into the same product (battery cells) is assessed. A high return rate indicates a closed recycling loop for a product. A low return rate indicates that the recycled material flows into other products, usually into products with lower economic value (downcycling). In general, for lithium, nickel and cobalt a possible return rate of 100% is assumed. The return rate of graphite is assumed to be 50% due to the specific material

requirements in structure and electrochemistry and lack of material specific requirements in the EU Battery Regulation. Besides the return values, export loss (-10%) and delayed return due to re-use (-10% in 2030 and -30% in 2035) have an influence on the result.

The first discussed result is therefore the baseline itself compared with the requirements from the EU Battery Regulation. Two other variations were integrated to assess a lower return rate of battery materials and a graphite recycling.

Table 36: Adjusted parameter "share high-quality recycling" for the variation "Lower return rates of battery materials"

Material	2030	2035	2040	2045	2050
Lithium	50%	50%	50%	50%	50%
Nickel	50%	50%	50%	50%	50%
Cobalt	50%	50%	50%	50%	50%
Graphite	25%	25%	25%	25%	25%

Source: own analysis

Table 36 summarizes the adjustments for the variation "Lower return rates of battery materials". It is assumed that only half of the material recovered in recycling is directly fed back into the production cycle. Various reasons can cause this effect such as specific quality requirements or obstacles in supply chains.

Table 37: Adjusted parameters for the variation "graphite recycling"

Parameter	Material	2030	2035	2040	2045	2050
Recycling efficiency	Graphite	60%	70%	80%	90%	90%
share high-quality recycling	Graphite	80%	80%	80%	80%	80%

Source: own analysis

Table 37 summarizes the adjustments for the variation "Graphite recycling". It is assumed that graphite recycling is established on an industrial scale. Recycling efficiency starts with 60% in 2030 and rises up to 90% in 2045. According to a meta-analysis by Rey et al. (2021) recycling efficiency varies from 40% to 95% depending on process. It is also assumed that graphite is recovered in high-quality which results in a higher share of direct closed-loop recycling (80%). The remaining 20% are assumed to be either primary natural graphite or synthetic graphite especially designed with certain product specifications.

3.8.7 Results

As previously outlined, the initial analysis entails a comparison between the baseline and the EU requirements for recycled content in battery materials. Table 38 presents a comparison between the baseline results and the EU requirements. As a consequence of the delayed legislative process pertaining to the EU Battery Regulation, the timeline for the required recycled content underwent a modification. Two-stage recycled content targets are required for the years 2031 and 2036. The AutoRess model presents the results in a five-year pattern, commencing in 2025.

It can be seen that the EU requirements for battery materials will not be fulfilled by 2030 if the EU target for 2031 is assumed. In the case of lithium, the percentage required by the EU Battery Regulation is 6%, which has to be achieved one year later. The figures for nickel (4%) and cobalt (7%) in 2030 are comparable. In the subsequent year, the requisite percentage for nickel is 6%, while the figure for cobalt is 16%. Nevertheless, at the conclusion of the initial recycled content requirement phase, the targets are met in 2035 (Li: 7%, Ni: 9%, Co: 15%). At this point, the targets of the second stage appear to be overly optimistic for 2036. However, in 2040, when a significant number of end-of-life BEVs are scrapped, the recycled content targets are more than fulfilled (Li: 20%, Ni: 23%, Co: 32%).

The primary reason for failing to achieve the EU targets within the model is the delayed availability of materials due the long service life of BEVs (10 years). Furthermore, the recycling of vehicles registered in 2020 and 2025 is only marginally represented in the recycling figures for 2030 and 2035. This is in contrast with the high demand for battery materials that will arise during the period of increased electrification in 2030. By 2040, a greater number of vehicles will be entering the recycling process, thereby facilitating the recovery of a larger quantity of resources for use in the production of secondary materials. It should be noted that this analysis focuses on closed-loop recycling. If other sources of recycling are considered, the target appears realistic for nickel, given that recycling is already established globally, although it is currently limited to meeting the specific requirements of the steel industry. Cobalt also has other sources of recycling, but the difference to the target is higher than for nickel. In the case of lithium, the recycling sources are restricted mainly to battery recycling, which presents a challenge for meeting the EU targets.

Table 38: Recycled content in battery material production, closed-loop

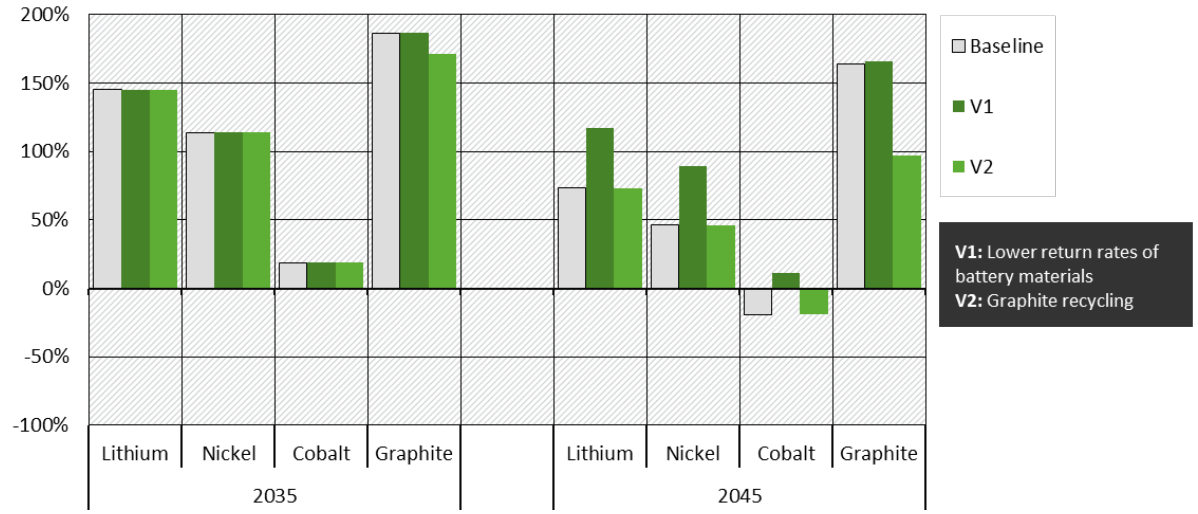
Material	2025	2030	2035	2040	2045
Lithium	0%	3% (6%, 2031)	7% (12%, 2036)	20%	33%
Nickel	1%	4% (6%, 2031)	9% (15%, 2036)	23%	40%
Cobalt	1%	7% (16%, 2031)	15% (26%, 2036)	32%	46%
Graphite	0%	0%	0%	1%	2%

Source: Baseline results, AutoRess model 2024. Numbers in brackets EU Battery Regulation Art. 8.

In addition to the examination of the baseline results, two variations were subjected to analysis. Given that the results have only a limited impact when the entire vehicle system is taken into account, the subsequent presentation will focus on the battery level outcomes and material demand only. Figure 84 illustrates the alterations in material demand (primary) for batteries across the two variations in comparison to the baseline scenario of 2025. By 2035, the changes in lower return rates (variation 1) won't show because minimum recycled content is assumed according to EU Battery regulation. Therefore, missing recyclate from closed-loop recycling will be stocked up by recyclate from other sectors (or from countries outside Europe), which could in turn lead to an increased use of primary materials in those sectors. In the case of the variation designated "graphite recycling," a reduction is observable in 2035 in comparison to the baseline scenario, amounting to a 15% decrease. This is due to the fact that the recycling of graphite is not a factor in the baseline scenario, and graphite constitutes a significant portion of the total weight of batteries. By 2045, the impact of these changes will be more evident, given the fact

that closed-loop secondary material will overfulfil the EU targets. Variation 1 demonstrates notable increases in the demand for lithium (+44% points), nickel (+43% points), and cobalt (+30% points) compared to the baseline scenario. The reason why changes are displayed for 2045 and not for 2035 is that the EU recycled content targets are exceeded by far and no recyclate from other sources is necessary to fill the gap. Variation 2 demonstrates a notable decline in primary graphite demand, with a reduction of 67% points. This is attributed to the assumption of 90% recycling efficiency by 2045.

Figure 84: Changes in material demand (primary) for batteries for the different variations compared to 2025 (Use of recycled battery materials)

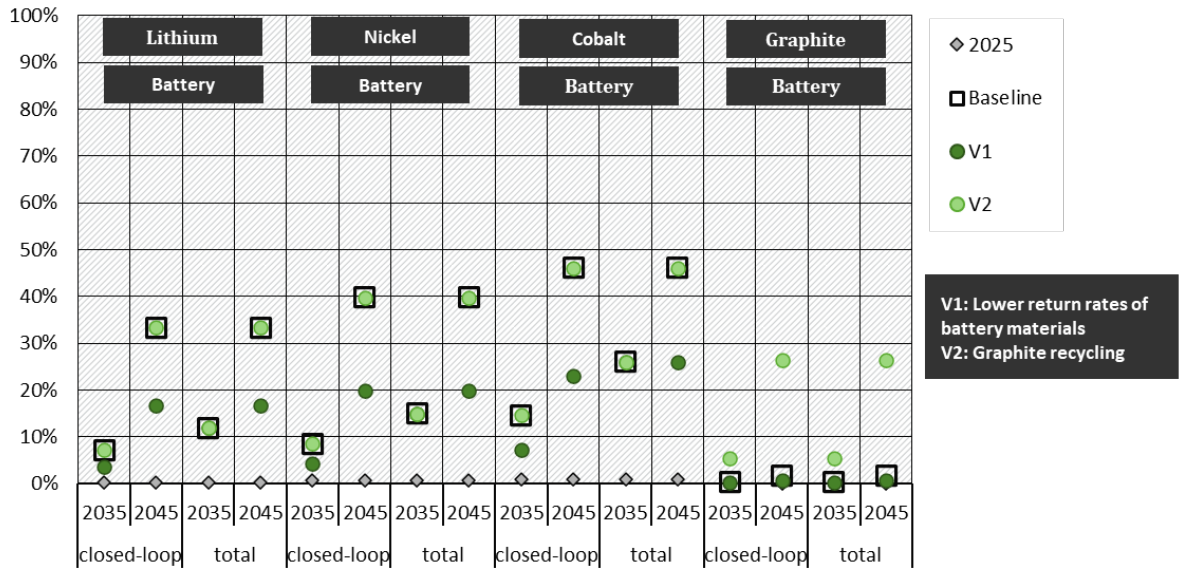


Source: AutoRess model 2024.

Figure 85 illustrates the alterations in recycled content for batteries for the different variations (Use of recycled battery materials) from closed-loop and open-loop perspective. As discussed in the previous chapter, differences for 2035 for variation 1 only show marginally because open-loop recycling is considered. However, with the focus on recycled content differentiated by closed/open-loop the following differences can be observed: lithium -3% points, nickel -5% points and cobalt -8% points. In 2045, the recycled content from closed-loop recycling of lithium only results in 17%, 20% (nickel) and 23% (cobalt). Cobalt would even miss the EU target for 2036 (26%) from the perspective of closed-loop recycling.

With regard to variation 2 (graphite recycling), the proportion of recycled content is estimated to reach 6% in 2035 and 27% in 2045. From the perspective of raw material demand, graphite recycling is a favourable option. Despite the ambitious assumptions made regarding the graphite recycling process, the recycled content remains below 30% in 2045. Further investigation is required to ascertain whether there is a case for accelerating support for graphite recycling. It is important to consider relevant restrictions, such as the additional GHG emissions and upper limits for recycled graphite in anode materials due to electrochemical performance.

Figure 85: Recycled content for batteries for the different variations (Use of recycled battery materials)



Source: AutoRess model 2024.

3.9 Recycled content of glider and powertrain (non-battery) metals

3.9.1 Background

The use of secondary raw materials is an important lever for reducing the use of primary materials in and outside Germany. The material utilization of end-of-life "waste" enables the substitution of primary raw materials.

For Germany, (Steger et al. 2019) quantified the contribution of the secondary raw materials industry to resource conservation. To this end, 30 materials, including various metals such as steel and cast iron, aluminium and copper, were examined for their recycling paths and use in Germany. It was shown that without the domestic recycling efforts of the materials analysed, Germany's domestic material input (DMI, excluding foreign upstream chains) would be 222 million tons, or 13% higher than without recycling. Per person, this would mean a domestic material input increase of around 2.6 tons. The recycling activities of steel and cast iron alone contribute to the fact that the DMI is not approx. 43 million tons (520 kg per person) higher. Copper recycling avoids an additional primary material requirement of around 21 million tons, while aluminium recycling substitutes around 8 million tons of primary material.

If indirect flows abroad are also taken into account, Germany's raw material input (RMI for short) is 18% higher, corresponding to around 490 million tons of additional primary material in absolute terms. Steel and cast iron recycling contribute to a substitution of almost 130 million tons of primary material and copper even almost 150 million tons (Steger et al. 2019).[25]

The use of secondary materials, especially secondary metals, therefore not only makes a significant contribution to reducing the extraction of primary materials and ores, but also generally leads to reduced energy consumption in processing, reduced GHG emissions and also has advantages over primary materials in terms of other environmental impacts. This has been

[25] The work of Steger et al. (2019) is currently being updated and the time series analysis is being continued. In addition, the analyses are expanded to include the avoidance of GHGs by the secondary raw materials industry.

analysed in various studies (Krall et al. 2024; Liesegang, Bookhagen 2023; Lutter et al. 2022; Prakash et al. 2023; Wolfram et al. 2021).

Vehicle manufacturing is one of the most resource-intensive industries in the EU. According to the EC, the European automotive industry accounts for around 19% of demand in the EU steel industry (over 7 million tons/year), 10% of total plastics consumption (6 million tons/year) and a significant share of demand for aluminium (42% for all vehicles, around 2 million tons/year), copper (6% for automotive parts), rubber (65% of general rubber goods production) and glass (1.5 million tons of flat glass from the EU) (European Commission 2023a)

In Germany in particular, the automotive industry is a key industrial sector in terms of raw material and, in particular metal requirements. The sector not only demands a substantial amount of raw materials but also provides a significant flow of secondary raw materials through EoL-vehicles. Depending on the material, however, downcycling is established (e.g. steel in construction steel) and secondary materials are not fed back into the same production process in a closed loop.

The aim of this priority subject area is therefore to analyse the contribution that the current and future use of secondary metals in passenger cars makes to conserving primary materials and avoiding GHG emissions. In contrast to subject area 7 (battery raw materials), the focus here is on the use of secondary metals in the non-drive part of the car, i.e. everything is considered except the battery. In consultation with UBA, the base metals iron and steel, aluminium, copper and nickel are placed in the focus of this subject area.

3.9.2 Status quo

3.9.2.1 Use of iron and steel, aluminium and copper in passenger cars (regardless of battery system)

The average material composition according to different drive types of a compact class car registered today was previously described in chapter 3.1.2.1 and is shown in Table 6. Iron, steel and aluminium clearly dominate the material composition with over 70%. Differentiated by structural components, these are largely located in the fuselage.

Steel is the material most frequently used in car bodies. It is easy to mold and has good fatigue strength against dents. Thanks to its stability and formability, it can absorb a high level of energy in the event of a crash. While conventional body construction steels have yield strengths of 290 N/mm^2, high-strength steels can achieve strengths of up to 1500 N/mm^2. In order to fulfil the current requirements for stability (crash behaviour), weight and appearance of the body, many new steel grades have been developed that are either very soft and easy to form (e.g. IF steel) or much stronger with acceptable forming properties (e.g. DP steel). On average, between 660 and 800 kg of iron and steel are installed in the vehicle body of today's compact classes, approx. 180-200 kg in the conventional drive, just under 50 kg in the electric drive and around 35 kg of iron and steel in the exhaust gas purification component.

Aluminium has also been used in body construction for a long time. With the Spaceframe, Audi has introduced the light metal to body construction on a larger scale (Deleker 2023). Depending on the drive type, between 52 and 63 kg of aluminium is used in the body of today's compact class cars. A further 50 - 58 kg in the powertrain of conventional cars.

Bodies made entirely from aluminium have already been mass-produced (for example the Panhard Dyna, Tesla Model S, Audi A2 and A8, Jaguar XJ, Mercedes-Benz SL and Opel Speedster). Individual vehicle parts are also made of aluminium in the mid-size class; for example, the

bonnets of the Citroën DS and the Subaru Legacy of the fourth series were made of aluminium, as was the tailgate of the Subaru (Deleker 2023).

After steel and aluminium, copper is the third most common metal in current car construction. Copper is used in automotive engineering primarily for electrical conduction purposes, for heat conduction purposes, but also in a variety of parts in the form of copper alloys (mainly with zinc, i.e. brass) and as an alloying element. Around 20 to 25 kg of copper are used in the fuselage and conventional drive or electric drive in an average compact class. The largest copper-containing component is the main wiring harness. In addition to the wiring harness, other copper-containing components include various electric motors, e.g. for pumps, window regulators, fans and air conditioning, plug-in springs and contact springs (Hook 2008).

3.9.2.2 Status quo secondary shares for non-drive metals

Relevant literature on the status quo of secondary metal use in cars is scarce. For this reason, the status quo for Germany (and comparatively for the EU and globally) is first analysed to determine which secondary metal use rates are cited in the literature for the four base metals for the economy as a whole.

Steel

According to the German Scrap, E-Scrap and Automotive Recycling Association (bvse), steel scrap will account for approx. 45.8% of German crude steel production of approx. 36.8 million tons in 2022 (bvse 2023). The contribution of steel scrap to production has remained more or less constant at around 44% since 2016 (Liesegang, Bookhagen 2023; Wirtschaftsvereinigung Stahl 2022).

Important companies in Germany with regard to the use of recycled raw materials are THYSSENKRUPP STEEL EUROPE AG (Duisburg), ArcelorMittal Germany Holding GmbH (Hamburg) and Salzgitter AG (Salzgitter) (Liesegang, Bookhagen 2023).

The proportion of scrap is higher in the production of cast iron. Around 90% of cast iron is produced from scrap and only 10% is primary pig iron (Steger et al. 2019). In 2021, around 3.9 million tons of cast iron were produced by German foundries (BDGuss 2024).

The European Commission calculates an EoL recycling rate of approx. 31% for iron in 2020 as part of the Material System Analyses (MSA) (JRC 2023c). Globally, the share of steel scrap in crude steel production is approx. 35.5% (EuRIC 2020).

The EoL recycling rate in the EU is around 75%; with regard to product-related recycling rates, the rate varies from 70-80% for standard stainless steels and over 90% for stainless steel products and alloy steel scrap (Liesegang, Bookhagen 2023).

Nowadays, however, secondary steel from post-consumer scrap is mainly used in lower-value applications, particularly in the construction steel sector. In vehicle production, secondary steel from post-consumer scrap has so far only been used for long products. For flat products, e.g. sheet metal, no recycled steel from post-consumer scrap is used in current production processes, only primary steel. In addition to pig iron, post-industrial scrap is also used for cooling in the converter in primary steel production. Contamination with copper is a key problem for the use of post-consumer scrap in primary steel production.

The majority of steel utilized in automotive manufacturing continues to be primary steel. However, recent data indicate a gradual increase in the incorporation of recycled steel across several major manufacturers. In 2022, BMW and Volvo Cars reported recycled steel shares of 25% and 15%, respectively. The Renault Group estimated that the recycled steel content in its vehicles ranged from 17% for flat steel to over 90% for steel bars and cast-iron components.

Similarly, Stellantis indicated that, on average, up to 30% of the steel it uses—comprising both pre- and post-consumer scrap—is recycled, according to supplier data. Other manufacturers have sourced steel with even higher recycled content from specific suppliers; for instance, Mercedes-Benz reported that the sheet steel procured from Steel Dynamics for its Tuscaloosa, Alabama, facility contains at least 70% recycled steel.

Advancements in scrap sorting and processing technologies have enabled certain steel producers to achieve particularly high recycled content in their products. For example, Nucor has attained a 60% recycled content in its automotive-grade flat steel. Likewise, in 2023, a subsidiary of the Swiss Steel Group achieved a recycled steel share of 77% —including both pre- and post-consumer scrap— in its stainless-steel grades. These developments highlight the growing technical feasibility and industry commitment to increasing recycled steel use in vehicle production (Negri, Bleker 2025).

Copper

Total global copper production (refined) was around 609,000 tons in 2022. Of this, 245,000 tons were from secondary material, which corresponds to a recycling input rate of 40% (excluding new scrap) (Liesegang, Bookhagen 2023). Across the EU (according to EU RMIS), the EoL-RIR is currently 33% (JRC 2023b). The overall EoL recycling rate for copper is 80%, while the sector-specific recycling rate in construction and transport is only 50%.

Important companies in Germany with regard to the use of recycled raw materials are AURUBIS AG (Hamburg/Lünen); Wieland Recycling (Ulm) and KME Germany GmbH & Co. (Liesegang, Bookhagen 2023).

Germany had an import surplus of copper scrap in 2022. Only around 9% of the copper produced in Germany goes into the manufacture of cars and accessories (Liesegang, Bookhagen 2023).

Two general recycling routes can be distinguished (Bookhagen and Mählitz 2023). High-quality scrap from new scrap, cable scrap or cleanly separated alloy scrap can be used in the manufacture of semi-finished products and remelted directly into new products. This recycling route is very energy and cost-effective and has a low environmental impact, although the possibilities for purification are limited. More heavily contaminated scrap goes through several steps of refining and electrolysis as required, allowing copper to be recovered in the quality of primary metal. Depending on the quality of the scrap used, this route is correspondingly more energy intensive.

According to (Schwimmer and Haberling 2017) there are functioning circuits for brass alloys, which are separated from the copper cycle. (Bookhagen and Mählitz 2023) describe and list a variety of barriers and options for copper recycling.

Aluminium

In Germany, 58% of refined aluminium production (approx. 813,000 tons in 2022) is recycled (i.e. around 473 kt in 2022). The majority of the total of almost 3 million tons of recycled aluminium production comes mainly from the remelting of new scrap (Liesegang, Bookhagen 2023). In an average stamping process, for example, 30 to 40% of an aluminium strip becomes scrap that can be directly remelted (Zinser 2023).

In Germany, around 44% of the aluminium produced in 2019 was used to manufacture vehicles. Secondary aluminium is mainly used to produce rolled products and cast parts for the automotive industry.

Important companies in Germany with regard to the use of recycled raw materials are Aluminium Norf GmbH (Neuss), TRIMET Aluminium SE (Essen), and Novelis Deutschland GmbH (Nachterstedt) (Liesegang, Bookhagen 2023).

According to EU-RMIS, the proportion of EoL aluminium scrap is only 20% (EoL-RIR) (JRC 2023d). However, due to different system boundaries and definitions, no direct comparison is possible here with the 58% secondary share of refined aluminium, for example.

The aluminium recycling rate in the automotive and construction sectors is 90% (EU-wide). Even higher RR rates are achieved in the German packaging sector (approx. 95%) and for beverage cans (approx. 99%). Overall, the EoL recycling rate of 69% in the EU (no data available for DE) (Liesegang, Bookhagen 2023).

The production of secondary aluminium requires 90-95% less energy compared to primary aluminium. For durable products such as cars or buildings, the demand for secondary aluminium currently significantly exceeds the supply. This makes circular economy approaches more difficult. In the long term, there is too much low-quality scrap (Krall et al. 2024).

End-of-life vehicles are mainly shredded and metals are sorted. This results in significant impurities in the aluminium, particularly due to iron and copper. Yet, in recent years, improved sensor sorting techniques have been developed with which complex scrap can be processed according to material quality (alloy types) using modern detection methods. These approaches are, however, not yet broadly used (Raatz et al. 2022).

For this reason, and due to the (still) high demand for casting alloys, it has so far been more profitable to "dilute" aluminium and downcycle it into casting alloys. These serve as a sink for foreign elements and impurities (Krall et al. 2024). An important application (to date) for cast aluminium alloys, which contain higher levels of alloying elements overall, are engine blocks in vehicle construction (Bookhagen and Mählitz 2023).

Nickel

For nickel, the proportion of recycled raw materials in production is around 16% (EU value). The EoL recycling rate in Germany is 70% and around 50% for stainless steels.

Important companies in Germany with regard to the use of recycled raw materials are NICKELHÜTTE AUE GMBH (Aue), Siegfried Jacob Metallwerke GmbH & Co. KG (Ennepetal) and VDM Metals GmbH, (Unna) (Liesegang, Bookhagen 2023).

Secondary raw materials in vehicles

The previously reported proportions of recycled metals in production refer to the economy as a whole. For further analysis, it is necessary to validate the extent to which these values can be transferred to automotive production, in particular to glider and drive train production of vehicles.

A bottom-up analysis of individual parts and the recycled content of vehicle components is out of the scope of this project, given the high number of components (approx. 7,000-9,000 components per car). Studies that analyse recycled content specifically for the automotive industry are rare, but there is some literature.

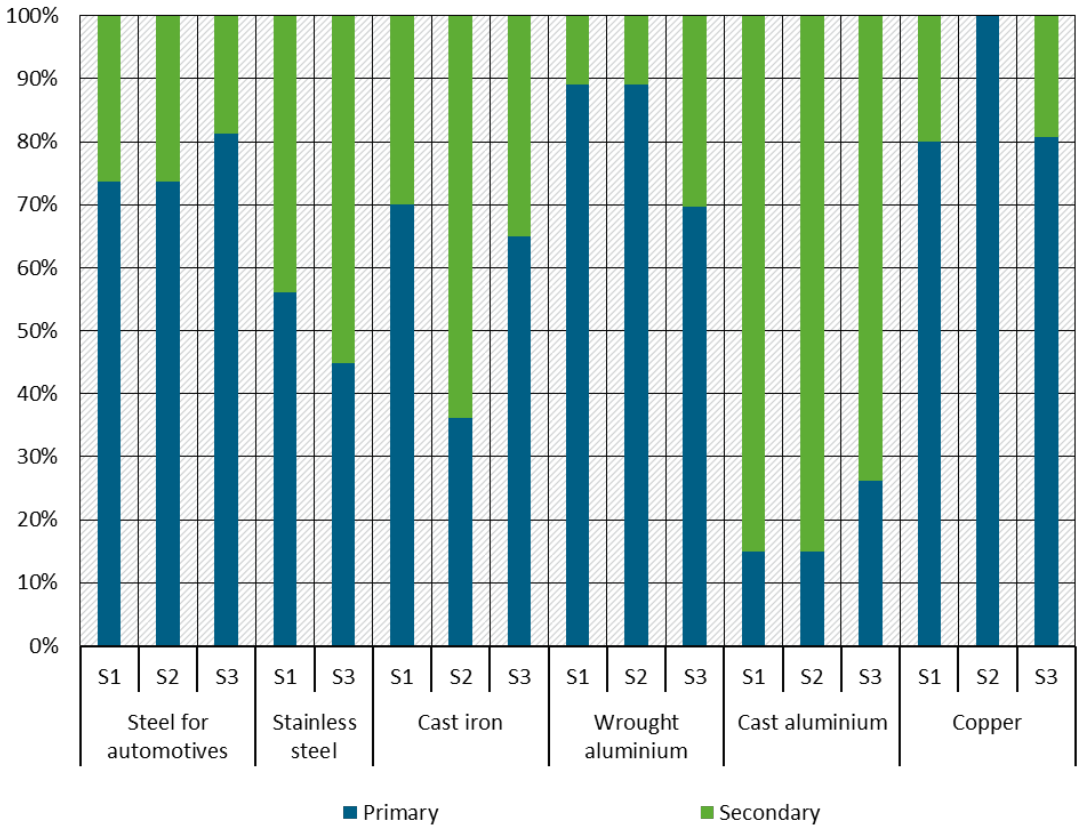
For instance, (Wolfram et al. 2021) investigate various approaches to increase the material efficiency of passenger cars to reduce greenhouse gas emissions of the sector. For their modelling, the authors indicate recycled content for steel (for the automobile), cast iron, stainless steel, copper, wrought and cast aluminium and plastics for passenger cars.

(Aguilar Esteva et al. 2021) analyse the automotive circular economy in the U.S. using amongst others metrics of recycled materials, however for the U.S.

Third, the (sector-unspecific) metalworking processes in the ecoinvent database (version 3.8) provide a further source with regard to recycled content in various metals Figure 86 shows the primary and secondary metal content shares of the three sources (Wernet et al. 2016). The recycled content values from ecoinvent database (S3) indicate the secondary metal input for selected processes (globally) and selected reference products (for details on processes see Table 88 in appendix).

The comparison of the three sources show that the proportion of recycled material are more or less in the same magnitude, with the exception of cast iron; (Aguilar Esteva et al. 2021) report a recycled content of around 64% compared to 30 to 35% in (Wolfram et al. 2021) and ecoinvent. (Wernet et al. 2016).

Figure 86: Secondary metal content in cars for various metals



Source: own figure Oeko-Institut / ifeu, based on S1 (Wolfram et al. 2021); S2 (Aguilar Esteva et al. 2021) and S3 (Wernet et al. 2016). Note S1: Figures for secondary share of metals used are based on literature analysis (automotive steel and aluminium), expert assessments (stainless steel) or non-sector-specific and older estimates (cast iron and copper) (from the supporting information). Note S3: Ecoinvent, version 3.8, allocation at cut off. The following Ecoinvent processes were selected as representative: steel production, converter, low-alloyed; steel production, electric, chromium steel 18/8; cast iron production; market for aluminium, wrought alloy; market for aluminium, cast alloy; market for copper, cathode.

For the modelling it was decided to use the reported recycled content values from the ecoinvent database. These are in line with values in literature (see (Wolfram et al. 2021)). Another benefit of using this dataset is that the ecoinvent database displays GHG emissions related to the specific processes, as described in chapter 3.1.2.2.

A screening of German OEMs and their sustainability reports shows that qualitative information is provided, but no quantitative values with regard to recycled metal content are published:

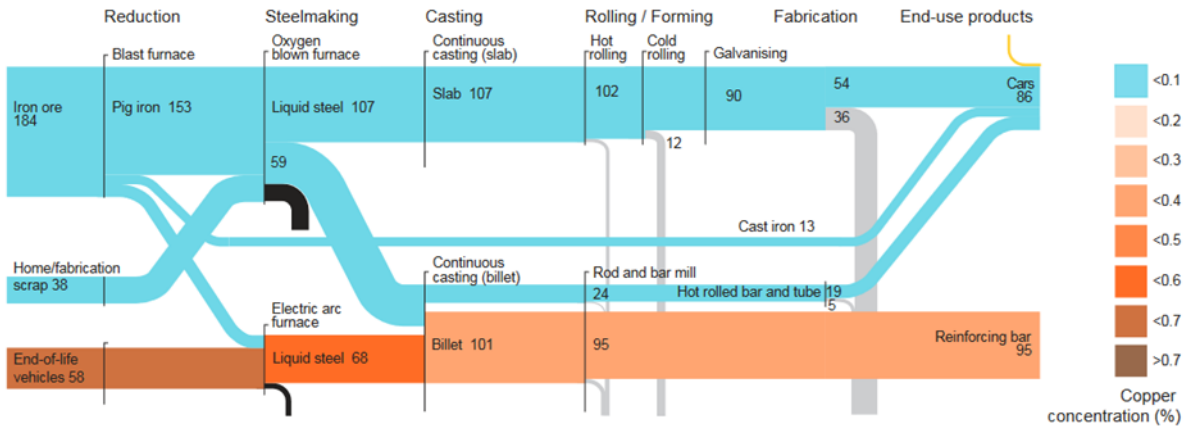
- Daimler: "We will consistently reduce the use of primary raw materials in purchased parts in order to conserve valuable resources. Here, too, we will start with certain focus components and continue to increase the specifications for recycled content in consultation with suppliers." [...] "For example, we want to recycle aluminium scrap in order to return the material to our vehicles via the material cycle. This not only conserves valuable resources, but also reduces CO_2 emissions, as a lot of energy is required to smelt aluminium." (Daimler 2021)
- Volkswagen Group: "For many components, the use of recycled materials is prioritised if they meet the same quality requirements as primary materials and are available in sufficient quantities over their lifetime.(Volkswagen Group 2023)"
- BMW Group: "Already today, a certain proportion of BMW Group vehicles are made from recycled and reused materials. Following the "Secondary First" approach, we want to maximize the use of secondary materials in the future, taking into account technical feasibility and availability. To this end, we will priorities secondary materials for our future vehicles within the framework of selected product, material and supplier requirements. Our BMW i Vision Circular symbolizes our ambitions - only recycled or renewable raw materials are used in this vision vehicle." (BMW Group 2022)

"The BMW i Vision Circular deliberately dispenses with a paint finish on the exterior. Instead, the vehicle body was anodized in light gold from secondary aluminium. [...] This shows how surfaces could be refined in the future using innovative processes without having to use paint." (BMW Group 2021)

The BMW Group continues: "Currently, BMW Group vehicles are manufactured from an average of just under 30% recycled and reused materials." (BMW Group 2022)This rate is in line with the initial research, considering that steel in particular (with a secondary use of 26%) dominates the material composition of passenger cars (see Figure 87).

The recycled content shares do not yet indicate what proportion of scrap comes from the automotive industry and what proportion comes from other industries. In (Allwood 2016) steel material flows are presented for the UK. It can be deduced from the information that the automotive industry only purchases primary iron. All steel scrap from EoL-vehicles is further processed into structural steel (reinforcing steel). The reason given is the copper concentrations in the EoL scrap, which do not allow it to be reused in the automotive sector.

Figure 87: Iron and steel material flows in the UK



Source: (Allwood 2016) courtesy of the University of Cambridge

Other important metals such as nickel, chromium and molybdenum, which are used in significant proportions in automotive steels, are not recovered and end up in reinforcing bars. (Allwood 2016)

The insufficient quality of recycled metals in relation to the high-quality demands of the automotive industry leads to almost non-existing closed-loop recycling structure. In the ELV assessment of the European Commission estimates for the share of closed-loop recycling are given. For iron and steel 2%, for aluminium 1% and for copper 5% of recycled metals have a sufficient quality to be used for the production of new vehicles again (see also chapter 3.1.2.1 and Table 6).

A more circular use of automotive steel depends on recovering high-quality steel from end-of-life vehicles, using it to produce new vehicles, and connecting recycled steel flows between the automotive industry and other sectors. As stated before, automotive steel flows are defined by stringent quality requirements at the vehicle manufacturing stage, particularly a copper concentration below 0.1%. In contrast, steel scrap recovered from end-of-life vehicles typically exhibits poor quality due to contamination, most notably from copper wiring, resulting in scrap copper contents reaching up to 0.7%. This contamination leads to downcycling, whereby recycled steel is unsuitable for automotive applications without significant dilution with primary steel and is instead diverted to sectors with lower quality demands, such as construction. With each recycling cycle, copper content accumulates, eventually rendering the scrap unfit even for high tolerance uses and leading to its disposal. Consequently, the automotive industry's demand for high-quality steel is predominantly met by primary steel production, which is almost exclusively reliant on the greenhouse gas-intensive blast furnace–basic oxygen furnace (BF-BOF) process, resulting in an emissions intensity for automotive steel that exceeds the industry average (Negri, Bleker 2025).

3.9.3 Legal framework

In June 2023, the European Parliament and the European Council adopted a proposal for a regulation on requirements for the circular design of vehicles and on the disposal of end-of-life vehicles. This proposal is intended to repeal the previous Regulations 2018/858 and 2019/2020 as well as Directives 2000/53/EC and 2005/64/EC. The proposed regulation will repeal the 3R Type Approval Directive and the End-of-Life Vehicles Directive and replace them with a single legal instrument. (European Commission 2023a)

The EU Commission's new draft of the End-of-Life Vehicles Regulation specifies a requirement for the use of recyclates for plastics (6.25% closed loop from end-of-life vehicles, 25% in total), as well as an export ban on used vehicles (see chapter 3.10.1) (European Commission 2023a)

According to the draft, the European steel industry has so far rejected a target for the proportion of recycled steel in new vehicles.

With regard to steel, however, this option authorises the EU Commission to set a target for the recycled content of steel (from consumer waste/EoL) in newly registered vehicles within three years of the Regulation entering into force on the basis of a feasibility study. The option to set targets for the recycled content of other materials such as aluminium (and critical raw materials) will be reviewed in the future based on changes in vehicle design and the availability of recycling capacity.

The feasibility study should take the following aspects into account:

a) the current and forecasted availability of steel recycled from post-consumer sources of steel waste;

b) the current share of post-consumer waste in various steel semi-products and intermediates used in vehicles;

c) the potential uptake of post-consumer recycled steel by manufacturers in vehicles to be type-approved in the future;

d) the relative demand of the automotive sector in comparison to the demand for post-consumer steel waste of other sectors;

e) economic viability, technical and scientific progress, including changes in the availability of recycling technologies concerning steel recycling rates;

f) the contribution of a minimum share of recycled content of steel in vehicles to the Union's open strategic autonomy, climate and environmental objectives;

g) the need to prevent disproportionate negative impacts on the affordability of vehicles; and

h) the influence on the overall costs and competitiveness of the automotive sector.

The Commission may adopt an implementing act laying down the methodology for the calculation and verification of the content of recycled steel from consumer waste contained and installed in types of vehicles. (European Commission 2023a)

Also interesting to note is that steel is the first intermediate product for which a proposal for a product-specific regulation is currently being drafted as part of the new European Ecodesign for Sustainable Products Regulation (ESPR) (European Commission 2024a; UBA 2024). The aim of the ESPR is to create a broad legal framework for a wide range of products (including textiles, mattresses and aluminium) in order to make products sold on the EU market more sustainable. The ecodesign requirements for products include the criteria of recycled content, durability, reusability, upgradability and reparability, but also the creation of a CO_2 and environmental footprint, as well as making extensive product information available in the form of a digital product passport. (European Commission 2024b). Product-specific requirements for the individual criteria are adopted as part of separate delegated acts. (UBA 2024).

For steel, ecological and technical-economic aspects of iron and steel products are currently being examined as part of a preparatory study. The study provides a basis for the future legal act for iron and steel products and is intended to identify corresponding measures for optimization potential. (European Commission 2024a). The workplan on steel started in June 2024 and

should be completed by June 2025. The requirements for a digital product passport also include the development of a label. According to the Commission, this includes "*an easily accessible label on products that provides immediate access to information on the sustainability of the product. It will be useful not only for consumers, but also for customs and market surveillance authorities*." (European Commission 2024b)

3.9.4 Foreseeable development trends

To date, there have been no foreseeable developments in the use of recycled iron and steel, copper, aluminium and nickel in vehicles. This is mainly due to the fact that there are currently no legal requirements (target corridors) for the use of metallic secondary raw materials in vehicle construction.

Recycling input rates (if they are determined) are therefore currently a result of the available secondary metal and the proportion of scrap metal used for vehicle construction in relation to the total metal requirements of vehicle construction.

Against this background, it is currently only possible to describe qualitatively which developments will influence the secondary metal utilization rate. Generally, all developments that influence the total metal demand of (German) vehicle manufacturing affect the recycling input rate. By reducing the total metal demand (denominator), the ratio increases even if the use of recycled materials remains the same.

An important driver that will influence the current use of recycled materials in vehicle construction is the switch to electric cars. The automotive industry is currently the largest consumer of secondary casting alloys. The switch from combustion engines to electromobility is expected to significantly reduce this demand. One example is that the combustion engine block will disappear as a sink for secondary aluminium (as discussed above). Instead, the demand for wrought aluminium will increase.

Electric cars tend to have a higher demand for aluminium and copper than combustion engines. Copper is particularly important for the batteries in electric vehicles, so the switch to electric cars will significantly increase the forecast demand within the automotive industry in the future (IDTechEx 2022). If the copper requirement of the battery (approx. 57 kg in the compact class) is excluded, electric cars require around 5 kg more than petrol and diesel (compact class cars).

Another factor is the availability of EoL scrap: The availability of secondary copper from EoL products will be limited in the foreseeable future, as copper is mainly used in long-life products, with an average lifespan of 35 years (Bookhagen and Mählitz 2023). The quality of the EoL scrap is even more crucial (Pauliuk et al. 2013; Seidel et al. 2022). The quality of the scrap is an important factor in whether the recyclate is suitable for open/closed-loop recycling and thus contributes to maintaining high-quality.

Important drivers for future developments

Future developments that will influence the recycling input rate in passenger cars are improvements in the disposal of end-of-life vehicles and the recycling of end-of-life vehicles, which will increase the availability of high-quality scrap from the automotive sector for the automotive sector. The study by (Allwood 2016) for example, shows ways to improve the separation and recycling of steel and copper from end-of-life vehicles. The study by (Krall et al. 2024) shows that high-quality wrought aluminium alloys can also be produced from unsorted end-of-life vehicle aluminium scrap. Other aluminium recycling options in automotive manufacturing will also become important in the future, which do not require downcycling, e.g. closed loop (see Figure 88).

Figure 88: Schematic representation of aluminium closed-loop in the automotive industry



Source: (Zinser 2023)

Developments outside end-of-life vehicle recycling in other sectors that contribute to the availability of more high-quality post-consumer secondary metals without interfering elements and fewer secondary metals being lost (e.g. through illegal disposal) or less loss in the recycling process are also factors that can influence the use of recyclates in passenger cars (see chapter 3.11) (Seidel et al. 2022).

Technological innovations in vehicle construction also influence the use of secondary metals, specifically depending on whether they offer better or worse opportunities using secondary metals. One foreseeable development is the Tesla Giga casting trend in car body production. (Fuchslocher 2022; Schwarzer 2024) The new aluminium die casting process entails that key body structures can be cast as a single part. This means that around 70 components can be replaced. Tesla has already implemented the process in the Model Y, Toyota will do so from 2026, Volvo, Hyundai, Ford and perhaps the rest of the car industry are involved or will follow. Fraunhofer IWS is conducting research on this (Fraunhofer IFAM 2024). In this context, the question of the ratio of primary and secondary metals that can be used in these production processes is essential. The impact of giga casting is not modelled in this option but considered within the option lightweight, see chapter 3.4.

3.9.5 Fields of action and issues

All ten priority subject areas considered in this project influence the level of the resulting recycling input rate. This is because in all options, the total metal demand (denominator) of vehicle construction will vary due to different parameter changes and thus (with the absolute secondary metal input remaining constant) the recycling input rate. The quantity of secondary metal available from the disposal of end-of-life vehicles will also vary, for example due to different decommissioning of cars.

Relevant factors influencing the material quantity are described in 3.1. Thanks to the modelling approach, it is possible to derive recycling input rates for each of the ten options. Further, it can be differentiated if the recycled material comes from within the sector (closed-loop) or from other sectors (open-loop), depending on the availability of high-quality recycling material.

Other aspects

This subject area touches on the question of whether a mandatory (and yet to be determined) recycling input rate for vehicle construction is expedient. A thought experiment illustrates possible challenges: For now, closed loop recycling has only played a subordinate role in the automotive industry (European Commission 2023a). Setting an ambitious recycling input rate for metals in vehicle construction can have two effects:

1. Manufacturers have an incentive to improve the quality of recyclates from end-of-life vehicle recycling to ensure closed-loop secondary materials.
2. Manufacturers source secondary metals of sufficient quality from other industries or increase imports.

From a global perspective, the latter variant in particular leads to a shift in secondary metals: what is now used in vehicle construction may be lacking elsewhere and must be replaced by primary materials. It is not possible to analyse this global displacement effect within the scope of this project.

The extent of these "shifts" can be reduced by improving closed loop recycling efforts within the automotive sector to reduce overall material losses during recycling and quality losses and to ensure the high quality of secondary metals. A (potential) mandatory recycling input rate should therefore differentiate and take into account closed-loop and open-loop secondary metals. It is particularly important to ensure that the recycling input rate does not apply to new scrap, as this could create a false incentive for excessive scrap production in stamping or milling processes, for example, in order to generate the necessary quantities of new scrap to meet the target. This must be prevented for reasons of material efficiency and resource conservation.

In the study Sutter et al. (2025), this aspect is specifically addressed. To assess how to increase scrap-based steel use in the automotive industry under the proposed End-of-Life Vehicles (ELV) regulation, Oeko-Institut conducted a dedicated feasibility study on recycled steel targets. The study examines potential pathways and policy measures for boosting the share of recycled steel in car manufacturing, evaluating both the technical feasibility and the environmental benefits of increasing scrap-based steel use.

At an expert workshop held on June 27, 2024, as part of this project, various issues relating to recycling input rate were discussed with experts and stakeholders from the industry. The issue of mandatory recycling content targets was subject of a controversial debate. On the one hand, the view was expressed that there is not a demand problem but rather a supply problem when it comes to secondary materials and that targets are therefore not necessary in order to increase the use of recycled materials. Further, targets which are set too low are not effective, targets set too high are not reachable. Therefore, it would be crucial to set targets at exactly the right level, which is difficult to incorporate in top-down regulation. On the other hand, a mandatory target was also seen as an incentive to recycle components whose recycling is currently not yet profitable for cost reasons and thus to increase the supply of secondary materials.

In general recycling rates for end-of-life vehicles are high, but the return of the material is low; there is currently no practicable alternative solution for downcycling steel (and copper) in the construction sector.

3.9.6 Modelling

Compared to the baseline (see chapter 3.1.2.2) several parameters were adjusted to model the option of recycled content of non-battery metals. The following table gives an overview of the adjusted parameters. The first parameter that was adjusted is “Increase in recycled content for

cars with-out battery (glider + powertrain)". For different material groups recycled content targets were defined (see Table 40 and Table 41). Second, "the share of high-quality material" was set, indicating the share of closed loop material that is used for the production of new cars, and thus substituting secondary material demand from other sectors.

In order to get an understanding of the impact of selecting and adjusting parameters on the results, four different variations were implemented (see Table 39).

The first two variation V1 and V2 set a target only for the recycled content, but not for the high-quality materials that can be used for closed-loop recycling. These two variations indicate, the impact of secondary material that is needed from other sectors and thus create a possible shortage in these sectors that might be substituted with primary materials. The two variations differentiate in terms of ambition: variation V1 is the less ambitions variation that sets recycled content targets being accomplished in 2045. V2 is more ambitious as the same recycled content targets are already being accomplished in 2035 and the held constant.

The two remaining variations V3 and V4 represent pathways in which in addition to recycled content targets, also targets for closed loop recycling are set in place. Such targets were suggested for plastics by the EC (see chapter 3.10.2.1). These two variations thus indicate to which extent the automobile sector can decrease demand for high quality secondary materials from secondary materials by developing closed-loop recycling infrastructure. Again, the V3 and V4 differentiate by the level of ambition with regard to accomplishing the targets: In V3 recycled content and closed loop recycling targets are set and accomplished in 2045; in V4 the targets are accomplished ten years before in 2035 and held constant then.

Table 39: Overview of adjusted parameters for the variations and results

Parameters / Variation	V1	V2	V3	V4
Increase in recycled content for cars without battery (body + powertrain)	**X**	**X**	**X**	**X**
Share of high-quality material (closed loop)	-	-	**X** Body and drive (no battery)	**X** Body and drive (no battery)

Source: own table Oeko-Institut / ifeu

The underlying assumptions and targets made in the four variations are shown in Table 40 to Table 43. Here, only targets for the four metals under consideration were set, values for plastics and glass are left at baseline levels.

In variation V1 it was assumed that an overall recycling input rate of 30% for steel (flat and long steel) is in place in 2045. This assumption is consistent, yet below the ambition levels, of the findings of Sutter et al. (2025), who demonstrate that achieving a recycled content of 30% in steel is feasible. Their research indicates that establishing recycled steel content targets specifically, 30% by 2030 and 40% by 2035—as well as implementing quality requirements for recycled steel, are both technically and economically viable. The share of flat and long steel in cars is assumed constant at around 79% and 21% respectively. For flat steel in the baseline there is no input of post-consumer scrap, but only new scrap. However, in 2021, the project REDER by ThyssenKrupp and TSR developed an advanced shredder technology, producing a steel fraction ready to be used in flat steel production. In the meantime, the new TSR shredder plant in Duisburg is operative. Based on the technology achievement it is assumed that also for flat steel an increase of secondary metal is feasible in the option scenario. The new steel recycling process from TSR achieves Cu content below < 0.1%, recycling material can be used in

the blast furnace (10-15%) and in the converter (25-30%), achieving an overall recycling share of 32-40% for flat steel. For V1 the lower range of 30% is being set as a target in 2045. For long steel the same target is set, yet starting from an already high recycled content share, for instance ArcelorMittal Europe uses 32% post-consumer scrap.

The recycled content target of 30% in 2045 for steel compares to the suggestion made by the EC in the proposal of "Requirements for the circular design of vehicles and for the disposal of end-of-life vehicles" stating: "M10c – Recycled content for steel 30% for type-approved vehicles, of that 15% from closed loop production". However, this suggestion was not prioritized.

For Stainless steel the recycled content is held constant as there was no literature indicating an increase in secondary material share. For cast iron it is assumed that the share of secondary material is increased to 65% based on (Aguilar Esteva et al. 2021). For Nickel it was assumed that the European average recycling input rate of 16% is also being achieved in the automobile industry, closing the gap to the sector average (JRC 2023e).

For copper and aluminium, target levels for the input of secondary material were taken from the project REFINE by the German Federal Environment Agency (Dittrich et al. 2025). In this project, economy-wide recycling input rates (RIR) were calculated for ten different metals in separate in-depth studies. The RIRs were determined for different scenarios, representing differently ambitioned transformation pathways, up until the year 2050. The studies on secondary input shares are based on an estimation of the future total demand for the respective metal and the quantity of secondary material that will be available after the utilization phase of different metal-containing products. For copper, an RIR of 59% and 66% for aluminium was assumed. For the variations, the economy-wide RIR-values of the ambitious transformation scenario (GreenSupreme) were employed for RIR within the automotive sector. For variation V1 these targets were assumed for 2050, in accordance with the REFINE scenario. In the more ambitious variation V2, the target RIR was assumed to be achieved in 2040. For 2020 the RIR of the baseline scenario was assumed and values for base years up to the respective target year were linearly approximated.

According to (Ducker 2022), in 2022, the average passenger vehicle's aluminium consists of around 60% cast alloys and 40% wrought alloys. Since the RIR of cast aluminium is already on a high level, improvements in the usage of secondary material must be achieved especially within wrought aluminium production, where RIRs are significantly lower (see chapter 3.9.2). In order to approach the target of an overall aluminium-RIR of 66% in 2050, the RIR of wrought aluminium must exceed 50%. This represents an increase of 20 percentage points. (Krall et al. 2024) demonstrate unrealized potential within the use of certain wrought aluminium alloys produced from EoL-scrap, which are currently outside the scope of automotive production. Another way of improving the RIR of wrought aluminium is the improvement of high-quality closed-loop recycling within the automotive industry. There are a variety of projects and initiatives focusing on the latter, e.g. (Alumobility 2021; Audi AG 2022; World Economic Forum 2020).

For copper, in order to reach the REFINE target RIR in 2050, a strong increase of 40 percentage points is necessary. According to the European Copper Institute (European Copper Institute 2023), potential for improved ELV copper recycling lies especially in reducing the number of illegal imports and vehicles dismantled in illegal sites (about 363.000 vehicles dismantled in illegal sites and 73.000 exported illegally in 2018 in Germany (Zimmermann et al. 2022)) and improving the quality of dismantling and the recovery of material. Options for achieving the latter include improvements in dismantling and sorting staff and equipment, as well as a Design-for-Sustainability approach, which includes a concept for dismantling from the beginning.

Table 40: Overview of targets set in Variation V1

Parameter	Material	2030	2035	2040	2045	2050
RIR	Flat steel	15%	20%	25%	30%	30%
RIR	Long steel	27%	28%	29%	30%	30%
RIR	Stainless steel	55%	55%	55%	55%	55%
RIR	Cast iron	40%	45%	55%	65%	65%
RIR	Wrought aluminium	34%	38%	42%	46%	50%
RIR	Cast aluminium	74%	74%	74%	74%	74%
RIR	Copper	27%	35%	43%	51%	59%
RIR	Nickel	4%	8%	12%	16%	16%
Share of closed loop material High quality material	No changes compared to baseline					

Source: own table Oeko-Institut / ifeu, assumptions based on several sources

In variation V2 Table 41 the same recycling targets are set for secondary material input, but they are accomplished ten years earlier compared to V1. With respect to steel, this remains within the range of recycled content that has been identified as technically feasible by Sutter et al. (2025).

Table 41: Overview of targets set in Variation V2

Parameter	Material	2030	2035	2040	2045	2050
RIR	Flat steel	15%	30%	30%	30%	30%
RIR	Long steel	28%	30%	30%	30%	30%
RIR	Stainless steel	55%	55%	55%	55%	55%
RIR	Cast iron	55%	65%	65%	65%	65%
RIR	Wrought aluminium	37%	43%	50%	50%	50%
RIR	Cast aluminium	74%	74%	74%	74%	74%
RIR	Copper	33%	46%	59%	59%	59%
RIR	Nickel	8%	16%	16%	16%	16%
Share of closed loop material High quality material	No changes compared to baseline					

Source: own table Oeko-Institut / ifeu, assumptions based on several sources

In V3 (Table 42) the same targets for the recycling input rates are set as in V1 In addition, in this variation a higher share of higher quality materials from recycling is assumed, and thus closed-loop recycling is increased accordingly. Reference for the selected higher quality material share is the "Study to support the impact assessment for the review of Directive 2000/53/EC on end-of-life vehicles"(Baron et al. 2023). For several materials, routes of treatment were considered

under the various scenarios. For this variation the ambitious assumptions from scenario 4 were selected and considered for 2045.

In scenario 4, amongst others, a higher share of dismantled steel is sent to the recycler directly (skipping the shredding process) in contrary to other scenarios. High dismantling is assumed in order to see how the environmental benefits could change when it is required to dismantle more components prior to shredding or when Cu-content threshold is put on steel scrap in order to obtain outputs from shredder/PST facilities in sufficient quality. For further details on the scenario assumption and technological improvements, see the respective study (Baron et al. 2023).

With respect to steel, the targets established for Variation 3 and Variation 4 remain within the range identified by a subsequent study published after the modelling was conducted. This study finds that the quantities of recycled steel recoverable from end-of-life vehicles (ELVs) within the EU would, in principle, be sufficient to achieve a recycled content target of 30% from post-consumer scrap in the automotive sector by 2035, assuming a closed-loop recycling system (Sutter et al. 2025). Also, Negri and Bieker (2025) find that if all end-of-life vehicles scrapped in the European Union were processed using methods that enable the complete recovery and recycling of steel from vehicle bodies and chassis, the resulting recovered steel could support a closed-loop recycled steel share of up to 30% in new car production.[26]

Table 42: Overview of targets set in Variation V3

Parameter	Material	2030	2035	2040	2045	2050
RIR	all	Same as in V1				
Share closed loop material	Steel /iron	9%	15%	17%	18%	18%
Share closed loop material	Aluminium	6%	11%	16%	22%	22%
Share closed loop material	Copper	15%	25%	35%	46%	46%
Share closed loop material	Nickel	9%	15%	17%	18%	18%

Source: own table Oeko-Institut / ifeu, assumptions based on (Baron et al. 2023)

In the last variation V4 the same targets are set as in V2, however the closed loop rates are accomplished ten years earlier in 2035 (see Table 43).

[26] Both referenced studies were published subsequent to the completion of the modelling phase in this project.

Table 43: Overview of targets set in Variation V4

Parameter	Material	2030	2035	2040	2045	2050
RIR	all	Same as in V2				
Share closed loop material	Steel/iron	10%	18%	18%	18%	18%
Share closed loop material	Aluminium	12%	22%	22%	22%	22%
Share closed loop material	Copper	12%	22%	22%	22%	22%
Share closed loop material	Nickel	10%	18%	18%	18%	18%

Note: Steel/iron comprises: flat steel, long steel, stainless steel and cast iron; aluminium comprises wrought and cast aluminium. Source: own table Oeko-Institut / ifeu, assumptions based on (Baron et al. 2023)

The four variations and their general characteristics can be summarized as follows:

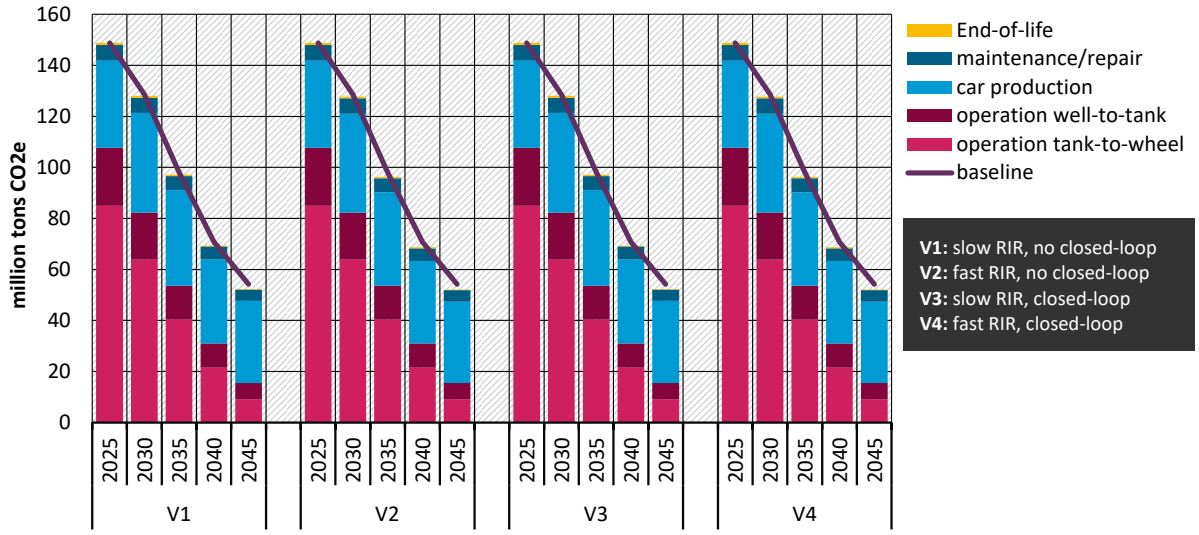
- V1: slow RIR, no closed loop: recycled content targets are set, but are only met in 2045, no closed loop recycling input targets are set;
- V2: fast RIR, no closed loop: recycled content targets are set, and are met in 2035, then kept constant, no closed loop recycling input targets are set;
- V3: slow RIR, closed loop: recycled content targets are set, but are only met in 2045, more ambitious closed loop recycling targets (compared to baseline) are set;
- V4: fast RIR, closed loop: recycled content targets are set, and are met in 2035, then kept constant, more ambitious closed loop recycling targets (compared to baseline) are set.

3.9.7 Results

The variations of recycled content of body and drive train metals described in the previous chapter (chapter 3.9.6) result in low impacts with regard to total GHG emission reductions along the whole life cycle. Figure 89 shows the GHG emissions for the variation 1 to 4. It appears that none of the four variations has significant impacts on the GHG emissions in the considered time period compared to the baseline.

The targets for recycled content for steel & iron, copper, aluminium and nickel for the body and powertrain impact the GHG emission of the car production phase. No further phase of the life cycle is influenced by this option. Therefore, total GHG emissions do only decrease slightly due to higher use of secondary materials with lower GHG intensity per kg metal. V1 and V3 show the same results. This is because the GHG intensity of secondary materials is considered equal for open loop and closed loop secondary materials. The same picture is drawn for V2 and V4. Since the difference in variation is the share of closed loop recycling, the GHG emissions are equal.

Figure 89: GHG emissions for cars for the different variations (recycled content of non-battery / glider and powertrain metals)

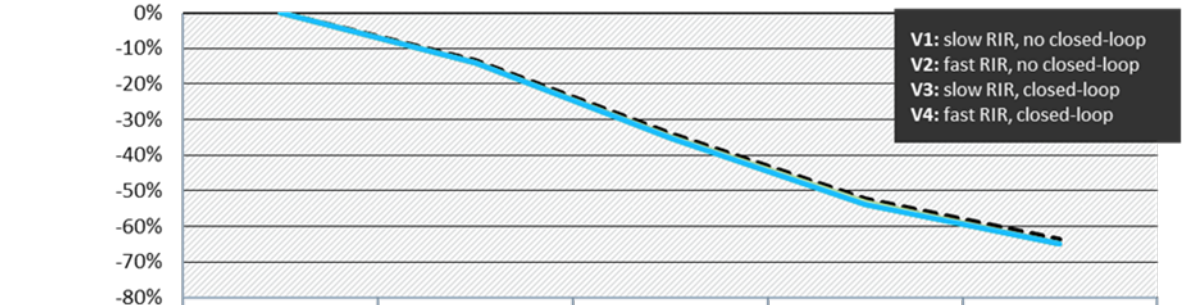


Source: own figure Oeko-Institut / ifeu

V2 and V4 show slightly higher GHG reductions compared to V1 and V3. This is because in V2 and V4 recycled content targets are assumed to be met in 2035; in V1 and V3 the same targets are met ten years later in 2045.

Compared to the development of total GHG emissions in the baseline, the four variations in this option lead to a minimal increase of reductions, yet the effects remain below 1.5% for all variations in the considered years (see Figure 90).

Figure 90: Change in GHG emissions for cars for the different variations compared to 2025 (recycled content of non-battery / glider and powertrain metals)



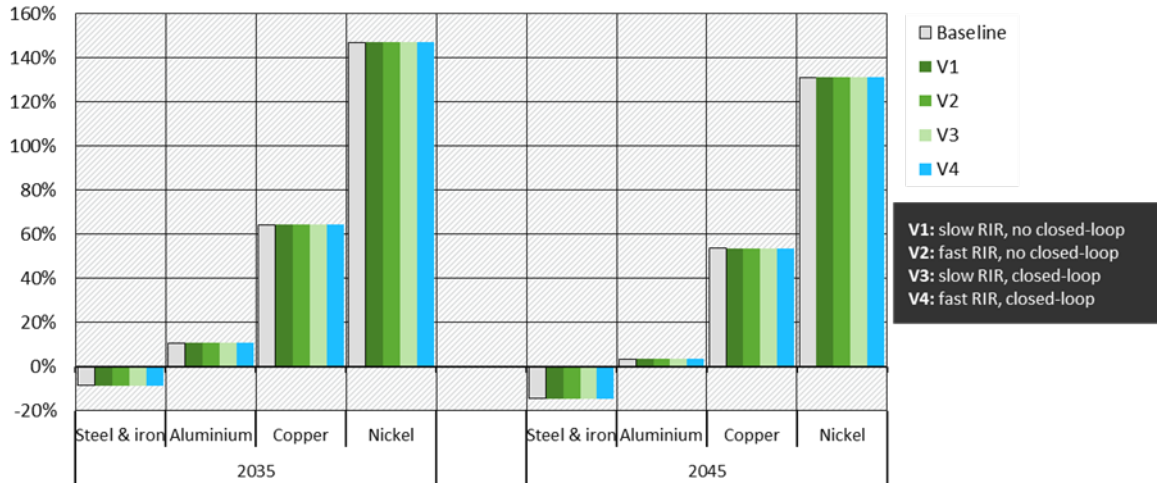
	2025	2030	2035	2040	2045
Baseline	0.0%	-13.6%	-34.1%	-52.5%	-63.6%
V1	0.0%	-14.0%	-34.8%	-53.4%	-64.9%
V2	0.0%	-14.2%	-35.3%	-53.9%	-65.0%
V3	0.0%	-14.0%	-34.8%	-53.4%	-64.9%
V4	0.0%	-14.2%	-35.3%	-53.9%	-65.0%

Source: own figure Oeko-Institut / ifeu

The results for GHG emissions indicate that the recycled content of materials only has a marginal effect on total GHG emissions, given that only emissions of car production are affected. To increase the effect of this option it is essential to set recycled content targets as early as possible and as ambitious as possible.

With regard to total material demand, none of the variations modelled in this option impact total material demand. This is because this option does change the share of primary and secondary material composition in the car, but not the demand per car. Consequently, the total material demand remains constant in the four variations considered (see Figure 91).

Figure 91: Changes in material demand (total) for cars for the different variations compared to 2025 (recycled content of non-battery / glider and powertrain metals)



Source: own figure Oeko-Institut / ifeu

More interesting are the results with regard to the primary material demand.

The results illustrated in Figure 92 show the change in primary raw material demand compared to the baseline year 2025. As before the results for V1 and V3 as well as V2 and V4 are identical, since the variations only differ in the origin of the primary raw material (closed-/open loop) but not the specific amount. The primary raw material demand for steel & iron decreased in all variations compared to the baseline, between -15% (V1 and V3) and -24% (V2 and V4) in 2035. In 2045 all variations reach the same recycled content target, therefore the reductions compared to the baseline year are identical at almost 30% in all variations.

According to the development of material demand in the baseline (see Chapter 3.1.2.2), the primary material demand for aluminium, copper and nickel increase in 2035 compared to 2025. Given the increased share of secondary raw materials in the variations V1-4 the primary raw material demand is below the baseline demand in 2035 and 2045.

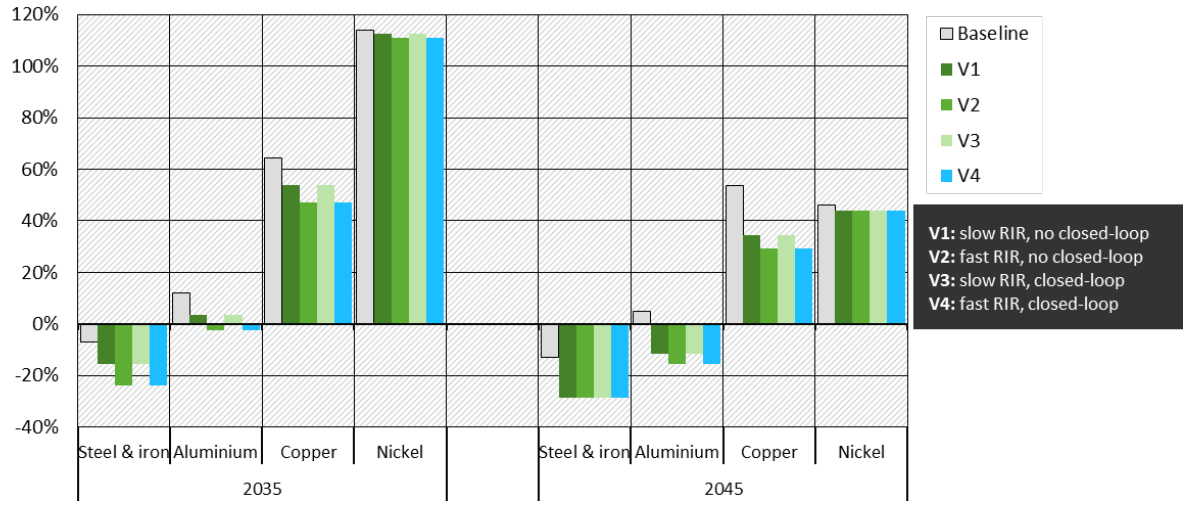
For copper the primary material demand in 2035 increases by 54% (V1 and V3) and 47% (V2 and V4) compared to 2025, while the baseline demand increases by 64%. In 2045, the demand for primary copper increases by 34% (V1 and V3) and 29% (V2 and V4) compared to 2025, while the baseline demand increases by 54%.

For aluminium the primary material demand in 2035 increases slightly by 3% (V1 and V3) and decreases slightly by -2% in the variations V2 and V4, compared to 2025. At the same time the baseline demand for primary aluminium increases by 12%. In 2045, the demand for primary aluminium decreases in all variations: -11% (V1 and V3) and -16% (V2 and V4) compared to 2025. At the same time, the baseline demand increases by 5%.

For nickel, the primary material demand in 2035 in all variations increases significantly, compared to 2025: 112% (V1 and V3) and 111% (V2 and V4). However, these increases only marginally deviate from the baseline, which sees an increase of 114%. In 2045, due to the

recycled content target reached in all variations, the demand for primary nickel increases equally by 44%. This is slightly below the increase of the baseline with 46%.

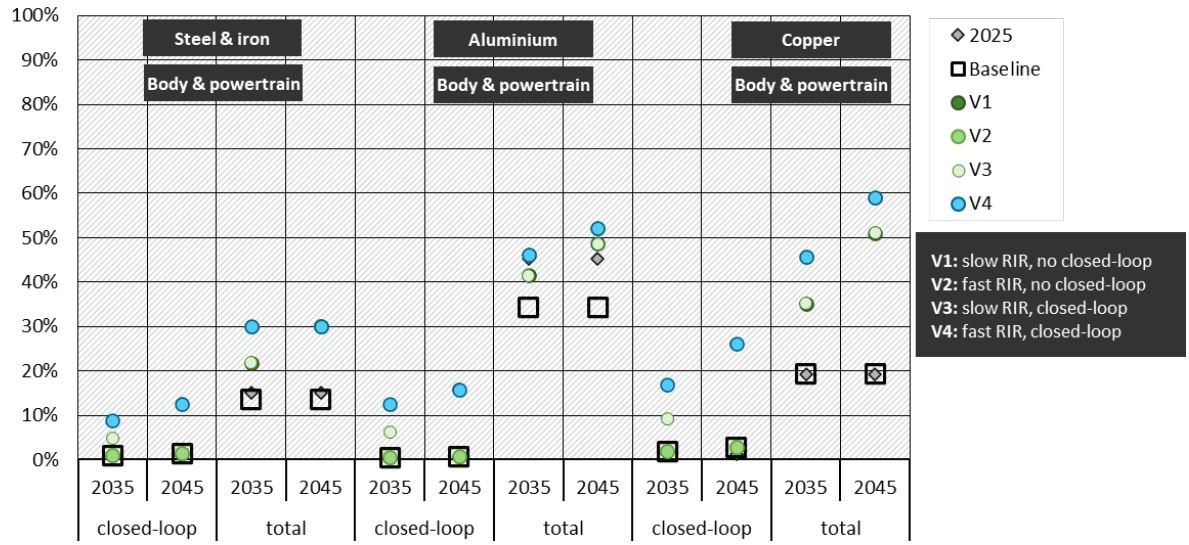
Figure 92: Changes in material demand (primary) for cars for the different variations compared to 2025 (recycled content of non-battery / glider and powertrain metals)



Source: own figure Oeko-Institut / ifeu

The recycled content for cars for the different variations are a result of the set recycled content targets summarized in Figure 93. It can be seen that only in V3 and V4 closed loop targets are increased compared to the baseline. In V1 and V2, thus, closed loop shares remain identical with the baseline assumptions. Therefore, these two variations indicate the amount of secondary material that needs to be sourced from other sectors for pathways that foresee higher recycled content rates (as in the baseline) but do not accomplish or plan to increase closed loop recycling infrastructure.

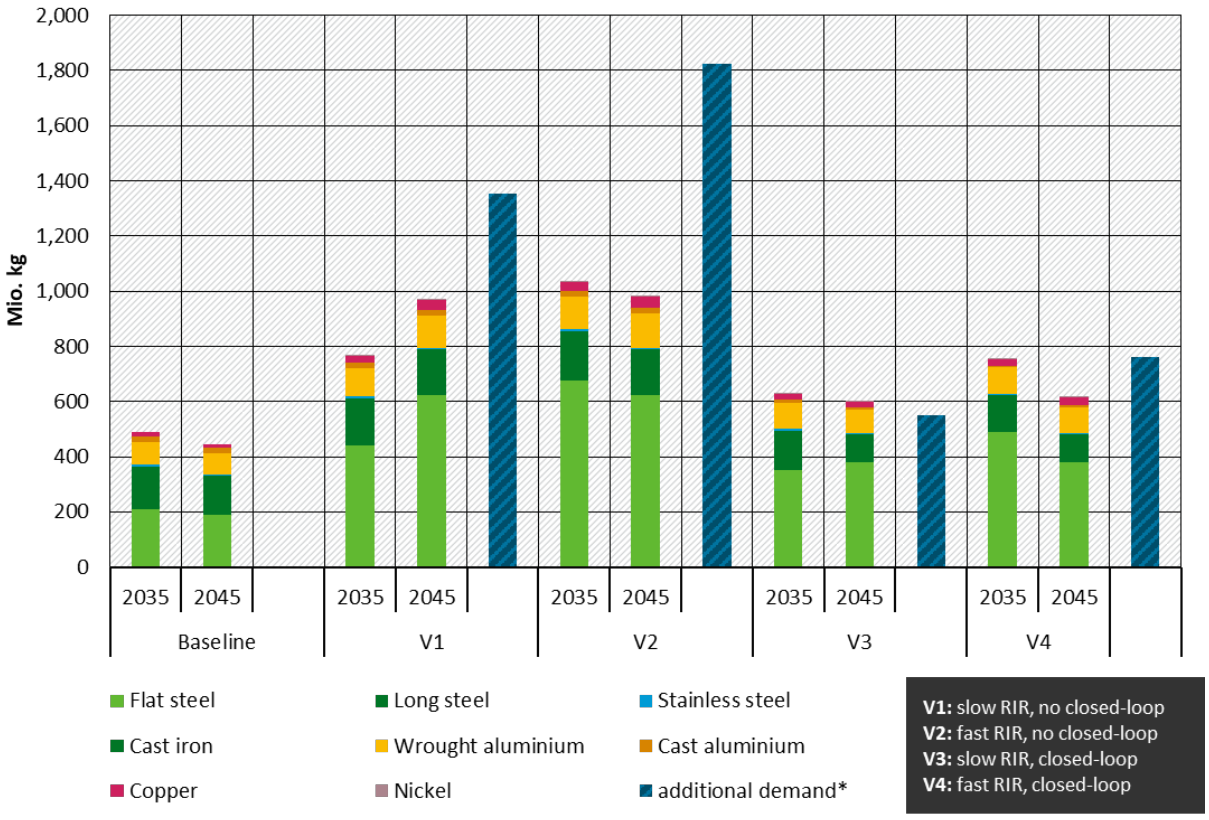
Figure 93: Recycled content for cars for the different variations (recycled content of non-battery / glider and powertrain metals)



Source: own figure Oeko-Institut / ifeu

The effects of recycled content targets on the demand of secondary material that is sourced from other sectors is illustrated in Figure 94. In general, higher recycled content targets in V1-4 lead to higher demand of secondary materials from other sectors. Further, it can clearly be seen that more secondary material needs to be sourced from other sectors in V1 and V2 where recycled content targets are set, but no increase of closed loop recycling is set in place. In V1 the additional demand of secondary material from other sectors for the years 2030, 3035, 2040 and 2045 add up to 1.35 Mio tons. In V2 even 1.82 Mio. tons of secondary material must be sourced from outside the automobile sector. It must be considered that these amounts are then not available in these sectors and might be substituted by primary raw materials. This indicates the importance of setting closed loop targets for the automobile sector (V3 and V4). In case of improved closed-loop recycling and the availability of high-quality secondary material, the automobile sector is able to satisfy a significantly higher share of its demand by its own secondary material. Nevertheless, in both V3 and V4 there is still an additional demand for secondary materials (0.55 million tons in V3 and 0.76 million tons in V4), which must be sourced from other sectors. Secondary material demand consists mostly of flat and long steel and to a lesser extent wrought aluminium.

Figure 94: Demand of secondary material from other sectors for different materials (recycled content of non-battery / glider and powertrain metals)



Source: own figure Oeko-Institut / ifeu; note * additional cumulated demand for secondary material from other sectors compared to baseline for years 2030, 2035, 2040 and 2045

These results indicate on the one hand, that recycled content targets must go along with closed loop recycling targets to avoid the gap that is provoked in other sectors when sourcing significant amounts of secondary materials from other sectors. Secondly, the results imply that

the closed loop targets assumed (see Table 42 and Table 43) are not yet ambitious enough to ensure that the automobile sector can secure its secondary material demand internally.

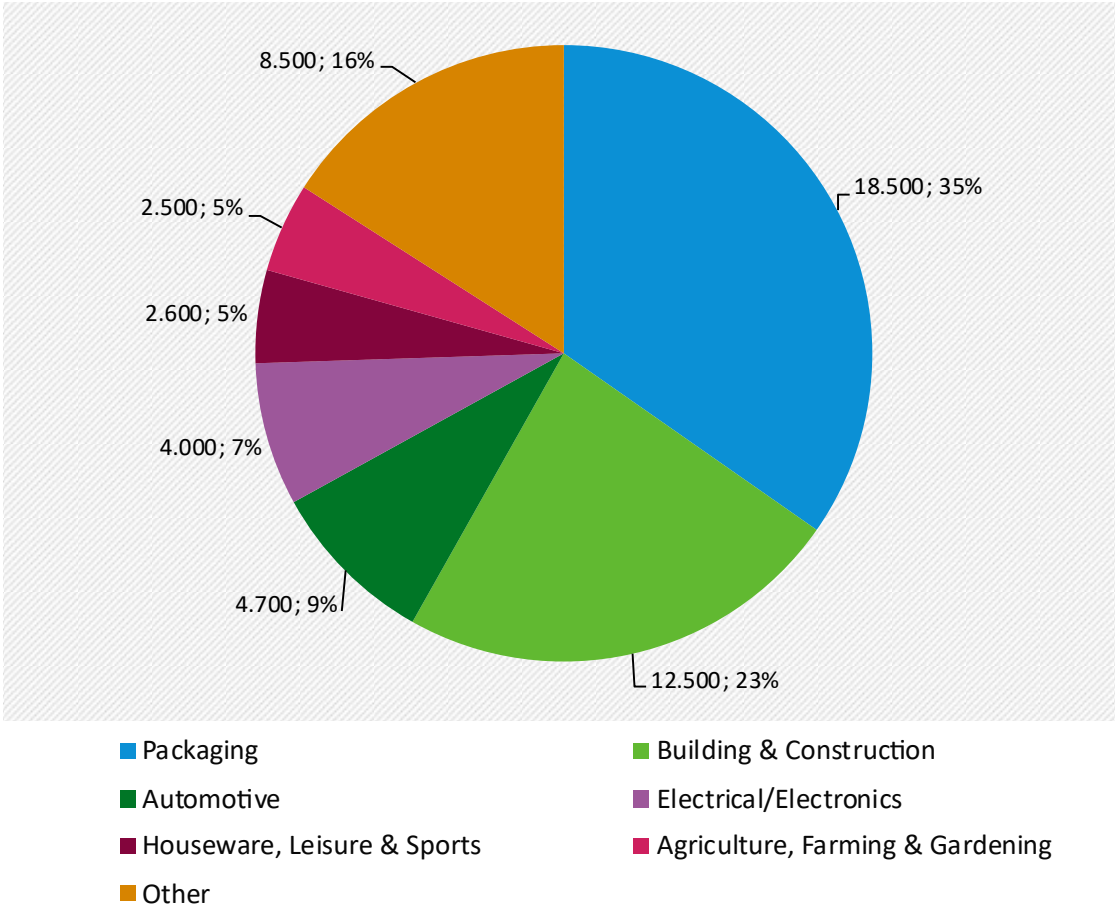
The results therefore suggest measures that combine recycled content targets (incl. closed-loop targets) with options that decrease the total material demand, e.g. smaller specific material demand per car constructed (see chapter 3.3).

3.10 Plastics cycles

3.10.1 Background

In the year 2021, the EU27+Norway, Switzerland and United Kingdom produced a total of 57.2 million tons of plastics, including fossil-based and recycled plastics as well as plastics from biomass (Plastics Europe 2023) For automotive construction, plastics can help to reduce the weight of vehicles and therefore improve fuel efficiency. Due to their characteristics such as flexibility and durability on one hand and resistance to impacts on the other hand, they have long been favoured in many components. Hence the automotive industry is the third largest sector regarding the usage of plastics after construction and packaging with 10% of the overall shares in the EU+3. (Figure 95)

Figure 95: Plastics consumption per sector in the EU27+3 in kt

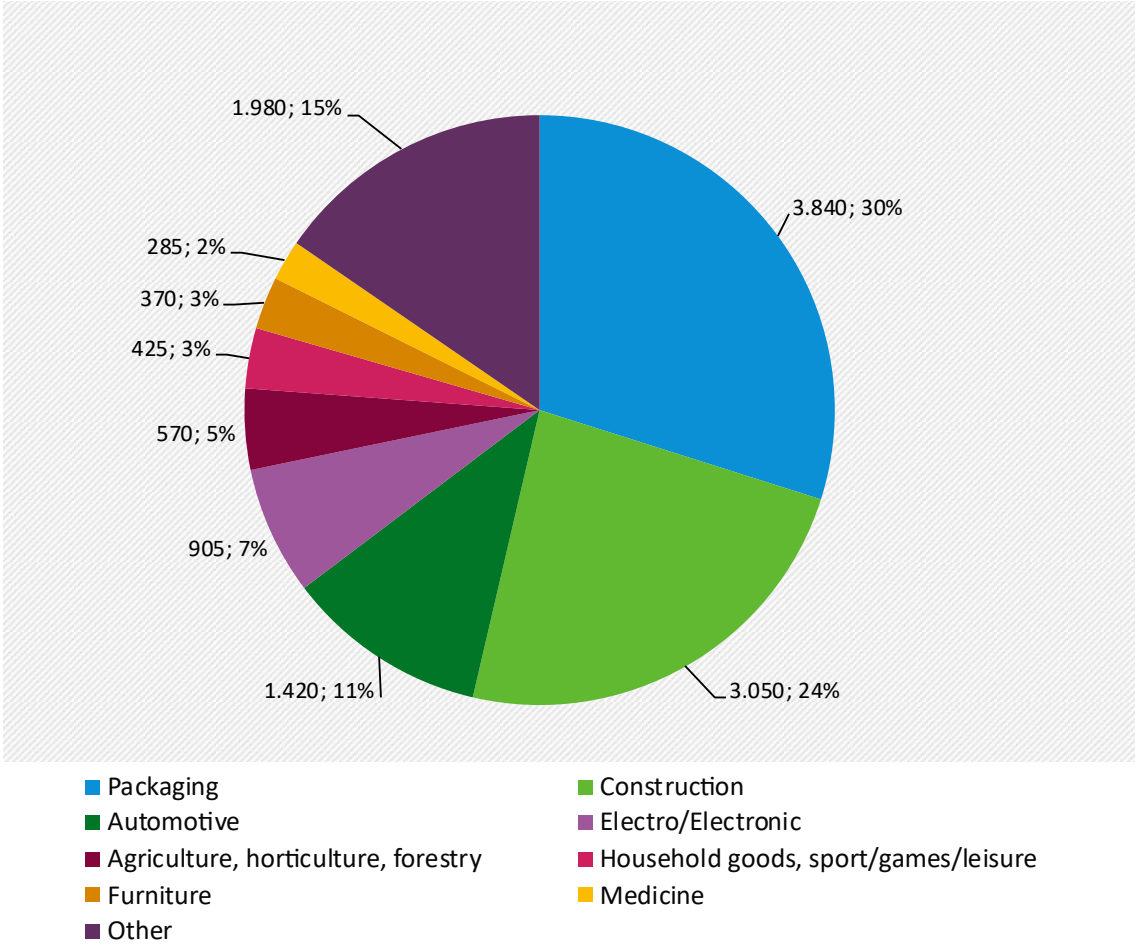


Amounts calculated by given shares and the total amount of 53.3 Mio.t
Source: Own figure Oeko-Institut / ifeu, data from (Plastics Europe 2024)

In the year 2023 in Germany, 1.420 kt plastic were used in the production of automobiles. Thereof, 92.3% were based on fossil fuels and only 7.7% (110 kt) were based on recyclates and

byproducts (Lindner et al. 2024)). Regarding all the relevant sectors, a total of 11% of plastics is therefore processed in the German automotive sector, but from the recyclates and by-products used for production across all sectors, only 4.5% amount to the automotive sector. (Lindner et al. 2024). The main reasons are the high quality requirements of the automotive sector, the missing plastic recycling of ELVs and large variety of (technical) polymers needed for a car, which are not found in sectors such as packaging or construction.

Figure 96: Plastics consumption (primary and recyclates) per sector in Germany in kt; %



Source: Own figure Oeko-Institut / ifeu, data by (Lindner et al. 2024)

Hence there is a large potential on one hand to recycle plastic waste from end-of-life vehicles and on the other hand to increase the amount of recyclates in the construction of new vehicles. Both of which will save primary resources and lower the carbon footprint of the automotive sector.

For an average car, the areas in which plastics are used can be categorized into the following applications: Over half of the plastics processed are found in the interior e.g., in dashboards and paneling (54%). Other key components are applications in the exterior (18%), "under the hood" e.g., engine linings, encapsulation and fuel tanks (16%), as well as in electrics/lighting (13%) (Lindner et al. 2020).

A great diversity of polymer types is used in a wide range of automotive applications. The types with the largest proportion and their applications are described in Table 44 (Maury et al. 2023).

Table 44: Main polymer types in vehicles

Polymer type	Application
Polypropylen (PP)	Front/rear bumpers, interior panels, dashboard, cable insulation
Polyurethane (PUR)	Flexible foam seating, foam insulation panels, elastomeric wheels and tires, suspension bushings, cushions, electrical potting compounds, hard plastic parts
Polyamide (PA)	Gears, bushes, cams, bearings, weatherproof coatings, carpet fibers
Polyethylene (PE-HD/MD)	Fuel tank, car bodies, electrical insulation
Acrylonitrile butadiene styrene (ABS)	Body parts, dashboards, wheel covers
Polyethylene terephthalate (PET)	Wiper arm, gear housings, headlamp retainer, engine cover, connector housings
Other	Door handles, bumpers, interior and exterior trims, instrument panels, buttons,

Source: (Maury et al. 2023)

Apart from the polymers listed in the table, other components include various thermoplastics such as polyoxymethylene (POM), polycarbonate (PC), polybutylene terephthalate (PBT) and numerous blends, which are made up of two or more polymer types. Some of their applications include the rear bumper, door handles, interior and exterior paneling, and headlight glass (Maury et al. 2023).

The proportion of plastics in the total weight of vehicles heavily depends on the type of drive, vehicle model and manufacturer. Between today and two decades ago, the proportion of plastic in new cars has increased, leading to a large difference in amount of plastics between ELVs and new cars. Currently the plastic share in a passenger car ranges from 14 to 18%. In absolute figures, the proportion by weight is between 190 and 360 kg per car in the commercial sector(Maury et al. 2023). End-of-life vehicles currently being processed for recyclates in the EU are on average 20 years old[27]. Hence, they have a lower weight than cars being produced today and their overall share of plastics is only 12%. According to the JRC report, this results in an estimated 132 kg of plastic waste per deregistered vehicle today. (Maury et al. 2023)

[27] A distinction must be made between deregistration and treatment, as a certain proportion is still travelling outside the EU and is therefore not recycled in the EU. This leads to an lower average age of cars deregistered in the EU compared to their processing for recyclates.

Table 45: Amount and type of plastics in ELVs in the EU

	Current ELV sent to ATFs	Future ICE-equivalent ELV sent to ATFs	Future BE-ELV sent to ATFs
Total weight of the vehicle (kg)	1100	1300	1600
Total plastic composition	12%	16%	13%
PP	37%	37%	40%
PUR	15%	15%	10%
PA	12%	12%	8%
PE	8%	8%	15%
ABS/SAN	7%	7%	5%
PET	5%	8%	10%
Others	16%	13%	12%

Source: (Maury et al. 2023)

The transition to BEVs includes vast changes in the design of cars which may lead to changes in the average polymer composition in cars. PP is expected to remain the most used polymer in cars, with potential growth due to its suitability for applications with lower thermal constraints and fewer needs for high-density PE for fuel tanks. Some forecasts predict that the use of PVC will decline due to the complexity of recycling. ABS consumption is also expected to decrease, as improved polystyrene and PP composites increasingly replace ABS in interior decorative parts, except in high-end cars. In contrast, polycarbonate consumption is anticipated to rise, driven by its use in automotive glazing applications and the growing demand for lightweight materials. Additionally, the increasing connectivity in future cars will likely boost demand for PC in sensors and optical devices, however not leading to a higher total share of plastics in a car (Maury et al. 2023).

3.10.2 Status quo and future trends

According to the European Union's Waste Framework Directive, two main waste categories can be specified: Post-industrial material and post-consumer material. The former refers to materials left over in production. To be considered as post-industrial recyclate the material scraps must be declared as waste first and then be sold to recyclers. Otherwise, they are referred to simply as by-products. Post-consumer waste stems mostly from repair workshops or end-of-life vehicle waste.

As mentioned above, 110 kt (7.7%) of the plastic processed in the automotive sector was recycled material. For 2019, Conversio states the proportion of post-industrial recyclates (PIR) at 55% and post-consumer recyclates (PCR) at 45%. (Lindner et al. 2020) PCR does not only come from ELVs, but from other sectors like the packaging sector (e.g. PET from single-use plastic bottles used, which can be used for textiles in a new car).

End-of-life vehicles are recycled in several stages. In a first depollution step, hazardous components such as batteries, fuels, lubricating oils, coolant and brake fluids are removed from the vehicle. After that, the dismantling of selective parts takes place. Components containing plastic, which may be dismantled, include bumpers, dashboards, fluid containers, etc. in practice, all plastics are rather shredded so far than dismantled due to labor costs.(Maury et al. 2023).

After dismantling, the hulks are baled and then transferred to authorized shredder plants where they are shredded in a mixture with other waste streams such as WEEE. The generated automotive shredder residue (ASR) can be separated into a light fraction including plastics, textiles, rubber, metal, wires and others as opposed to a heavy fraction containing metal fines, rubber, glass and soil.

According to several experts, shredder technology is a necessary and economical method for shredding end-of-life vehicles and separating them into secondary material streams. However, it is questioned whether the shredder light fraction is at all suitable for high-quality reprocessing; in fact, the stream of dismantled materials is much more in demand. In general, further investment should be made in the investigation of post-shredder technologies in order to optimise the quality of the output fractions. Furthermore, the importance of design for recycling is emphasised, which includes the fact that components can be removed mechanically and that the step is also economically worthwhile.

3.10.2.1 Recycled content targets in legislation

The EU's Directive on end-of-life vehiclesis currently being revised. The new proposal for a Regulation sets out new rules on the use of recyclates in new cars. According to this, the proportion of recyclates from post-consumer recycling should be 25%, starting in 2030. Converted to the consumption of 1,420 kt in the automotive industry in Germany, this corresponds to an absolute value of around 355 kt of required recyclates. It is also specified that 25% of this (i.e. 6.25% of the total volume) must come from closed-loop recycling. This means that a proportion of around 89 kt must be obtained from end-of-life vehicles and processed for use in new vehicles. The remaining share may come from open-loop recycling, i.e. from other sectors such as electrical and electronic waste or packaging.

In 2019, 233 kt of post-consumer waste was recovered from end-of-life vehicles in Germany. Of this, 26%, i.e. 61 kt, was recycled, 72% was thermally recovered and 2% was sent to landfill. In 2021, the waste totalled only 200 kt, which raises the question of the extent to which the set target can realistically be achieved by 2030. (Lindner et al. 2020)

In interviews, various experts from the automotive industry as well as recycling plants and disposal companies have estimated that it is unrealistic to expect this target to be achieved by 2030. Basically, all sides say that the necessary quantities of waste are simply not available at the moment, as the return rate of vehicles is too low. As vehicles only represent a proportion of shredders, the proportion of closed-loop components in shredder residue cannot be clearly determined. This would be a further reason for dismantling and separate treatment of plastic parts from vehicles. With regard to achievability by 2030, car manufacturers noted that the production time for new models is 5-7 years, but that no clear information on the availability of recyclates could be provided at present.

Another obstacle are the high quality requirements for certain components, which are difficult to achieve with recycled materials. In this context, there were calls for OEMs to lower their own requirements and move away from complex composites. Ideally, use should be limited to a few polymers and recycling should be made easier, for example, by avoiding back-moulding with other materials. In this context, according to an expert in the recycling industry, the expectation of a lower price level for recyclates should be changed if they fulfil the quality requirements, as sustainability should be the focus for manufacturers and not the reduction of production costs.

Nevertheless, many experts have emphasised that recycled content targets per se are very important in order to exert a certain amount of pressure on car manufacturers and at the same time create a level playing field between first movers and the rest. On the one hand, this is

necessary as there is no interest in recycling plastics from vehicles for economic reasons. On the other hand, this prevents major fluctuations in demand depending on prices for primary raw materials, thus ensuring stable sales and investment security for collectors and recyclers.

3.10.2.2 Chemical recycling

Chemical recycling refers to various processes that transform polymeric waste by altering its chemical structure, converting it to its constituents (e.g. monomers, oligomers) and other hydrocarbons and chemical agents. This can be achieved by different processes using a combination of heat and pressure in an oxygen deprived environment which are referred to as depolymerisation, pyrolysis and gasification.

Depolymerization encompasses processes that break down polymers into monomers or oligomers, which can then be used to produce new polymers. Also known as 'solvolysis' or 'chemolysis', these processes are identified by the chemical agents used, such as glycolysis, hydrolysis, and aminolysis. Depolymerization requires a homogeneous input stream and is suitable for specific polymers like PET, polyamide, and polyurethane. Not all types of plastic can be recycled with depolymerization. And in addition, materials such as PET, PS and PC are better suited for mechanical recycling anyways. Its greatest potential therefore lies in the recycling of polyester fibres, PUR and PA.

Pyrolysis is a thermal treatment method that converts plastic waste into primarily liquid hydrocarbons using heat in the absence of oxygen. It can process mixed plastic waste, but high polyolefin content (PE and PP) is more favourable, while high PVC and PET content is less ideal. The resulting pyrolysis oil consists of various hydrocarbon products and requires further purification before it can be used as feedstock for polymer production.

Gasification is a thermal treatment method similar to pyrolysis but operates at higher temperatures to produce primarily gaseous 'syngas,' a mixture of carbon monoxide and hydrogen. Syngas can be used as feedstock for the chemical industry or as a fuel.

According to expert interviews, due to the demands on the purity of the end product, it is currently only possible to achieve a recycling efficiency rate of 50% of the input. This is not economically viable and must be increased to 80% through better pre-sorting of the input material. Once again, it is becoming apparent that dismantling and mechanical recycling are favoured for certain plastics. Pre-sorting is also a top priority in order to achieve a homogeneous input stream and to be able to utilise chemical recycling methods.

3.10.2.3 Plastics produced from biomass

Plastics made from biomass feedstock are known as 'biobased plastics'. The term 'bioplastic' can refer to two different characteristics: the biobased origin of the input materials or the plastic's biodegradability at the end of its life. The use of the term 'bioplastics' is often inconsistent, leading to confusion. Similarly, 'biopolymer' refers to polymers synthesized by living organisms, such as polysaccharides, proteins, and lignin, which can be used industrially after extraction, purification, and sometimes chemical modification. However, biobased plastics do not have to come from biopolymers. For instance, the biobased plastic PLA (polylactic acid) is made from the biobased monomer lactic acid. Common biomass sources for producing biobased plastics include sugarcane, rice, tapioca, cassava, potato, corn, bamboo, betel leaf, areca nut palm leaf, and mixed agricultural waste.

Plastics made from biomass feedstock only serve a very niche market. Reasons for this are mostly the higher price and lacking incentive. According to interviews with OEMs, this will not

change, and the share compared to fossil-based plastics will not increase if there is no legal obligation or other form of encouragement.

3.10.2.4 Plastics made from captured carbon

Carbon Capture and Utilization (CCU) refers to methods that capture CO_2 from industrial sources or the atmosphere (the latter is called direct air capture, DAC) and convert it into useful carbon-based substances. This captured CO_2 can be used to produce chemicals, fuels, or other products like carbonic acid. CCU is seen as a potential strategy for achieving net-zero greenhouse gas emissions, especially in industries where CO_2 emissions are unavoidable, such as cement production. The effectiveness of CCU in reducing greenhouse gas emissions depends on the energy required for the process and how the captured carbon is used and re-emitted. While converting CO_2 into fuel results in quick re-emission, using it in durable products can provide temporary sequestration. Additionally, CCU can produce energy carriers (e-fuels) and organic chemicals without relying on fossil fuels or agricultural products, potentially filling a future gap in raw material supply without increasing the demand for agricultural resources. However, the process is energy intensive and not without other challenges (British Geological Survey 2025).

The processes to produce plastics from CO_2 are still under development and do not yet have been applied in the car sector in the EU. Similar to plastics made from biomass feedstock, this will not change as long as there is no regulation to support this.

3.10.3 Fields of action and issues

This option is the only one considering a change for the treatment of plastics in ELVs and the amount of recycled content of plastics in new cars placed on the market in the EU. However, other factors will influence the availability of recyclates and the amount of closed loop recycling. This option therefore focuses on the change of input of plastics by assuming recycled content targets set by the EU (V1) and in a second variation, assuming that all levers proposed by the plastics industry (Plastics Europe 2023) are used to reduce the carbon footprint to zero by 2050 (V2). The levers, additionally to mechanically recycled content, are:

- Chemically recycled plastics
- Plastics produced from biomass
- Plastics produced from captured carbon
- Avoidance of incineration
- Maximising energy efficiency
- De-fossilisation of energy production and transport
- Electrifying plastic production

3.10.4 Modelling

To compare the options with the baseline, two variations were modelled:

- Variation 1: Recycled content
- Variation 2: GHG neutrality of the plastic sector by 2050

Compared to the baseline (see chapter 3.1.2.2) several parameters were adjusted to model the option of recycled content of plastics. The following table gives an overview of the adjusted

parameters. In the baseline, there is no improvement of recycled content, recycling of plastics, use of recycled materials from the automotive sector (closed loop recycling) or anything else, which could be seen as an improvement for plastics in the automotive sector. This is a conservative approach, however, the conducted interviews all pointed in the same direction that the recycled content targets are not yet finalized (September 2025), are still heavily debated and, additionally, that without incentive, there will not be a significant change.

Table 46: Overview of adjusted parameters for the variations and results (plastic recycling)

Parameters / Variation	Baseline	V1	V2
Recycled content (RC) of plastics in new cars	2.5%	Increases to 25% in 2030 and from there to 40% in 2045	Increases to 25% in 2030 and from there to 40% in 2045
Share of reuse and recycling of plastic from ELVs	18%	Increases to 30% in 2030 and from there steadily to 45% in 2045	Increases to 30% in 2030 and from there steadily to 45% in 2045
Share of plastics recycled closed loop compared to open loop	20%	Increases to 45% in 2030 and from there steadily to 60% in 2045 due to RC regulation	Increases to 45% in 2030 and from there steadily to 60% in 2045 due to RC regulation
Decrease of GHG emissions of plastics in cars	-	Calculated by the share of recycled content	GHG neutrality of the plastic sector by 2050 (down to 20% by 2045) by using all levers and the scenario by Plastics Europe (Plastics Europe 2023)

Source: Own assumptions

All parameters are applied for plastics in the whole car (body, powertrain and battery). As in the baseline, the amount of plastic used in new cars does not change over the years.

For the recycled content, it is assumed that a target of 25% is introduced, similar to the one planned so far in the ELV Regulation. Also, the 30% mandatory recycling rate planned in the ELV regulation is introduced and raised steadily to 45% by 2045. The GHG savings resulting from this are calculated by the amount of GHG of recycled plastics. An amount of 1.4 kg CO_2e /kg of recycled plastics was used (Wolfram et al. 2021), while the GHG footprint of primary plastics from the model assumed an amount of about 5.2 kg CO_2e /kg. The latter value is higher than the average carbon footprint usually given for the general plastic production in the EU. The reason is the high amount of so-called technical polymers used in the automotive sector, which are more complex to produce and result in higher GHG emissions.

Furthermore, similar to the plans of the EU, in 2030, at least 25% of the mandatory 25% recycled content for plastics has to come from ELVs. This leads to a closed loop recycled content share of at least 6.25%. Due to this, the share of plastics recycled from cars and used in new cars (closed loop) compared to using recycled plastics is assumed to increase from 20% to 45% by 2030 as there is a strong market for it. This leads to a closed loop recycled content share of at 6.6% and thus only slightly above the necessary 6.25%. As plastics recycling is connected to high losses, it is assumed that the share of plastics recycled closed loop compared to open loop only increases to 60% by 2045.

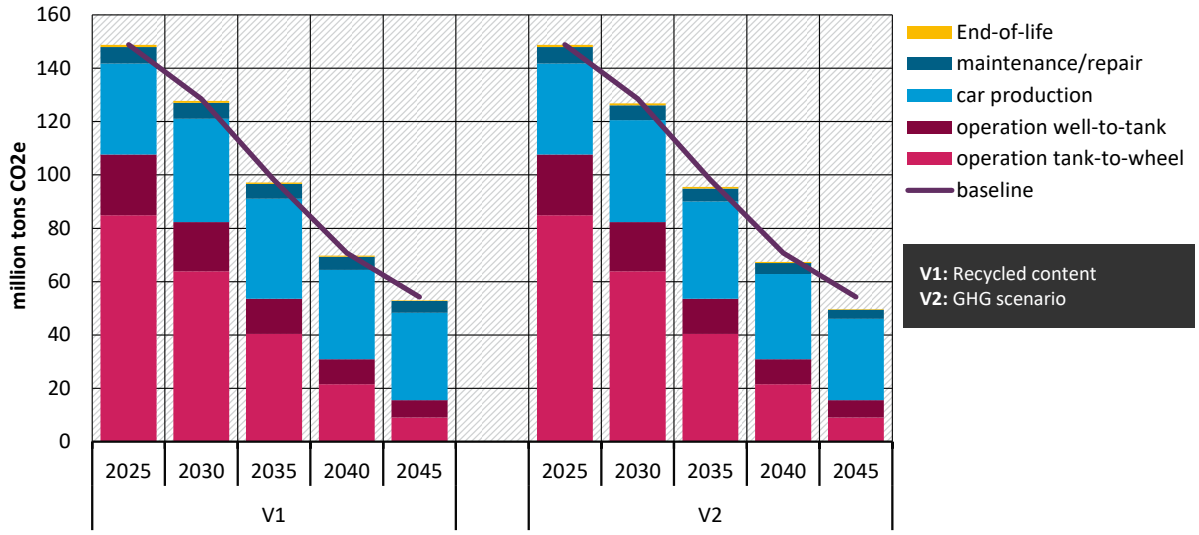
In comparison to alternative options and materials, the greenhouse gas (GHG) emissions of plastics in the model are mitigated not only by the utilisation of secondary materials, but also by

the alteration of input and other levers outlined in the preceding chapter. As the modelling of chemical recycling, biomass, CCU and so on exceeds the scope of the project, a scenario of Plastics Europe was used (Plastics Europe 2023). This scenario demonstrates a path how the plastics industry plans to reduce their carbon emission to zero by 2050 in the EU. For this, every of the named levers is necessary and combined. The resulting decrease in GHG emissions is taken from the scenario and put into the model to demonstrate the impact of this on the whole GHG footprint of the automotive sector.

3.10.5 Results

The two variations depicted in the previous chapter do not have a large effect on the total GHG emissions for cars over their whole life cycle as they only influence the car production. The introduction of recycled content targets (V1) of 25% for plastics reduce the GHG emissions for the car production in Germany in 2030 by 2%, based on the assumptions described before. The increase to 40% plastic recycled content by 2045 doubles these savings, which are, however difficult to detect in the following depiction.

Figure 97: GHG emissions for cars for the different variations (plastics cycles)

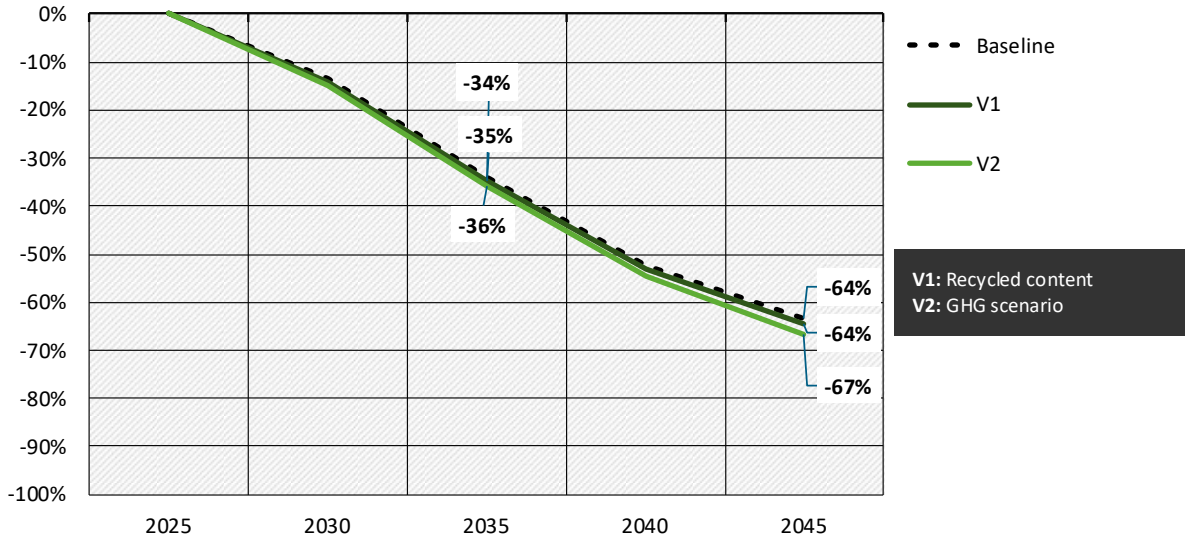


Source: Own figure Oeko-Institut / ifeu

For the second variation (V2), the scenario of the plastics industry to reduce the total GHG emissions by 2050, a reduction in GHG emissions of 3% for the car production can be seen for 2030. They even increase to 10% by 2045. Maintenance/repair is also reduced by 23%, as in this scenario, emissions from plastic production are reduced by 80% in 2045 compared to 2025.

These reductions can decrease the total GHG emissions over the whole life cycle by 3 percentage points, as can be seen in the following graph.

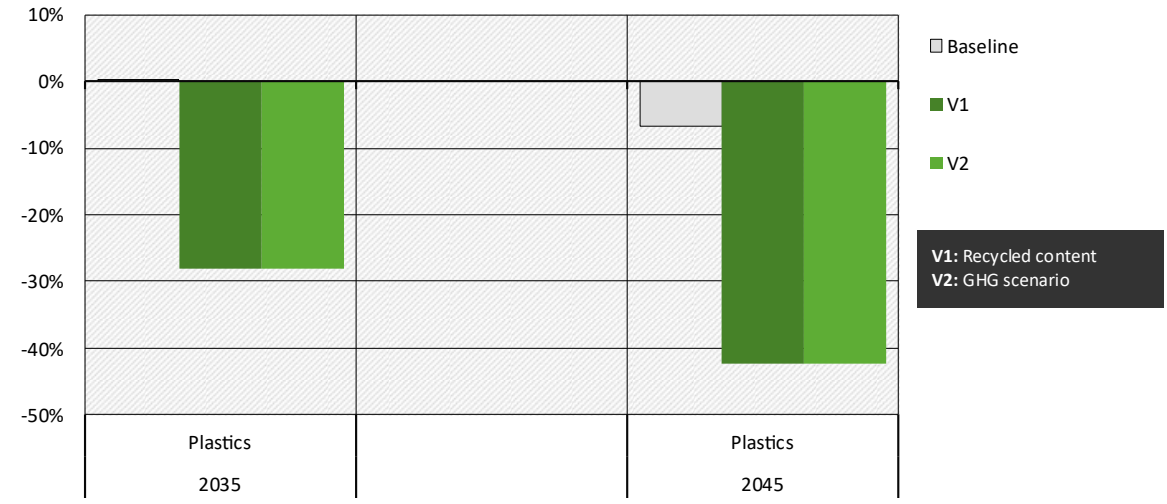
Figure 98: GHG emissions for cars for the different variations (plastics cycles)



Source: Own figure Oeko-Institut / ifeu

The following graph gives a depiction of the primary material demand of plastics for cars in the different variations compared to 2025. The baseline does not have any significant change in total plastic consumption from 2025 to 2035, as the reduction of plastics in the body and the drive train is balanced out by the additional plastic in the battery. As the recycled content does not change in the base line (apart from 2045), there is no change in primary plastic consumption in 2035. In 2045, mainly due to the assumption of fewer new cars on the road, the primary plastic consumption in the baseline is reduced by 7%. For V1 and V2, recycled content measures lead to a reduced primary plastic consumption of 28% in 2035 and 42% in 2045 compared to 2025.

Figure 99: Changes in primary plastic material demand for cars for the different variations compared to 2025 (plastics cycles)

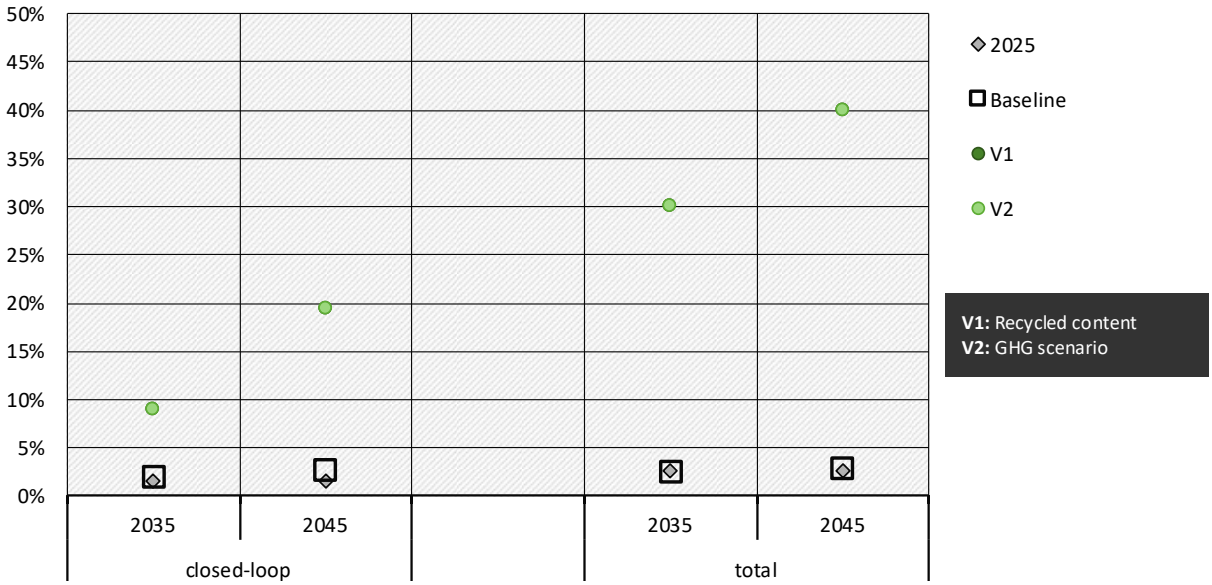


Source: Own figure Oeko-Institut / ifeu

The actual recycled content for the whole car is depicted in the following figure. As described before, the recycled content does not change in the baseline apart from 2045, where a larger amount of ELVs and fewer new cars enable a slight increase from 2.5% to 2.8% of (closed loop) plastic recycled content. For V1 and V2, the closed loop recycled content rises to 9% in 2035 and 19% in 2045 due to a higher recycling rates (reuse and recycling combined) of 35% in 2035 and

45% in 2045 together with a higher closed loop recycling rate of 50% for 2035 and 60% in 2045 (meaning that 50% and 60% of material recycled from ELVs could be used directly in new cars again, respectively). In this scenario, the total recycled content target for 2035 and 2045 of 30% and 40%, respectively, can only be reached by additional recycled material from other sectors, like the packaging or the EEE sectors. As these sectors also have to fulfill their own targets, this means that the automotive sector has to increase their own recycling rates even further and use the resulting material to be able to close their own material cycle as fast as possible and not having to rely too much on biomass and CCU as their alternative.

Figure 100: Recycled content of plastics for cars (including body and battery) for the different variations (plastics cycles)



Source: Own figure Oeko-Institut / ifeu

3.11 End of life

3.11.1 Background

In the case of disposal of end-of-life vehicles, the prescribed overall recycling rate, material-specific recycling rates and their qualities as well as the fate of vehicles that do not go into regular disposal channels are particularly relevant for a possible reduction in greenhouse gases and raw material requirements.

3.11.2 Status quo

End-of-life vehicles are depolluted and treated in authorised treatment facilities (ATFs) and then shredded in shredder facilities. According to the annual report on ELV recovery rates in Germany in 2022 in accordance with Article 7(2) of the ELV Directive 2000/53/EC (European Parliament, Council of the European Union 2000) a total of 296,422 ELVs were treated in the ATFs in Germany in 2022 (2021: 400,277; 2020: 409,903), of which 292,877 were generated in Germany (2021: 396,773; 2020: 406,044) and 3,545 were delivered from abroad (2021: 3,504; 2020: 3,859). According to the Federal Statistical Office, 991 authorised treatment facilities and 47 shredder and other facilities accepted end-of-life vehicles for treatment in 2022.

The majority of authorised treatment facilities are very small: more than half of the dismantling facilities treated 250 or fewer ELVs per year in 2021, while the largest 2% of facilities treated 29% of ELVs.

Table 47 shows the quantities of materials that were generated and treated during the shredding of end-of-life vehicles in Germany in 2022 (in tonnes per year)

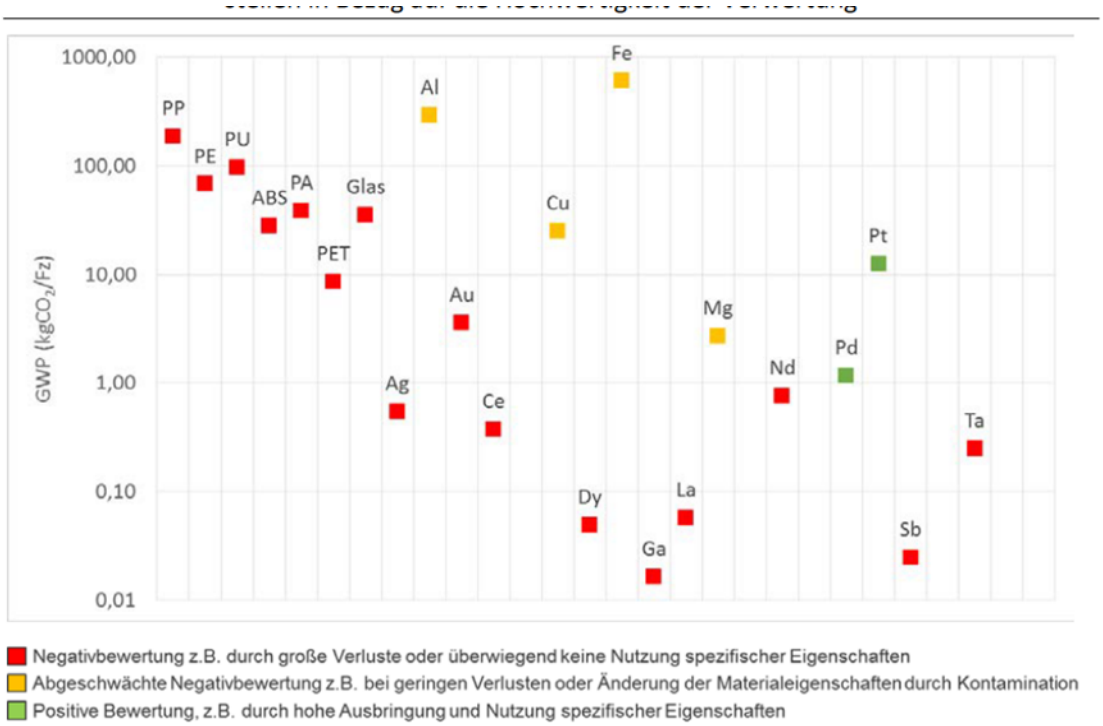
Table 47: Material flows from shredding of ELVs in Germany 2021

Material	Recycling	Energy recovery	Total recovery	Disposal
	in t	in t	in t	in t
Ferrous scrap (steel)	141,356	0	141,356	0
Non-ferrous materials (aluminium, copper, zinc, lead, etc.)	26,685	0	26,685	0
Shredder light fraction (SLF)	17,198	18,766	35,963	6,178
Other	0	0	0	0
Total	185,238	18,766	204,004	6,178

Source: (UBA, BMUV 2022)

Even if the recovery targets are being met, the key challenge in improving end-of-life vehicle recycling lies in the qualitative problems of the recycling routes (downcycling). While platinum and palladium are already recycled to a high quality and in high proportions for economic reasons, steel is recycled to a lower quality due to contamination with impurities and alloying elements in the scrap, and the higher-quality wrought alloys are often not separated in the case of aluminium. Instead, they are combined with the lower-quality cast alloys, copper is discharged into other fractions and for many other materials, little or no recycling takes place as the materials are not separated but are discharged from the shredder via the various output streams. Glass is not recycled into glass material. Plastic is mainly used for energy recovery instead of being recycled as a material. Figure 101 shows GWP values for the production of various materials per vehicle and a color-coded assessment of possible weak points in relation to the high quality of recycling.

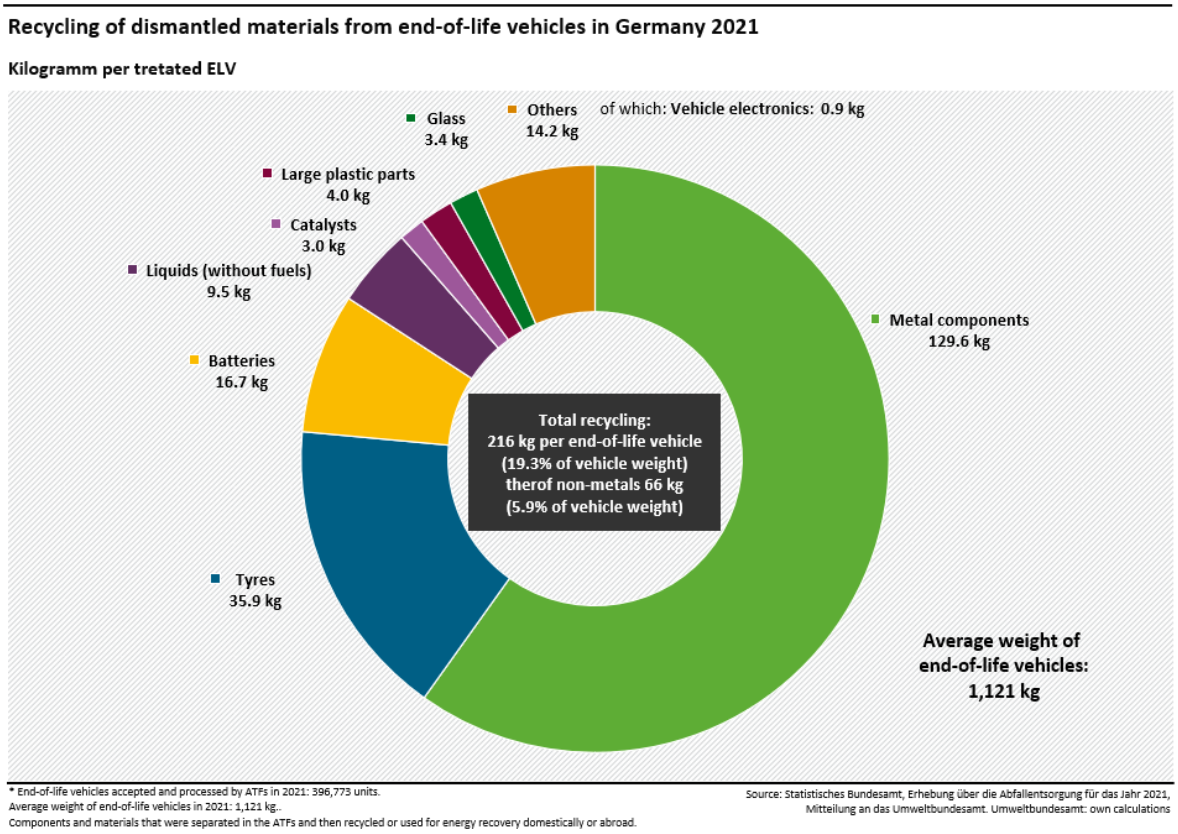
Figure 101: GWP of different materials per car and assessment of possible weak points in relation to the high value of recycling



Source: Sander et al. (2020)

One way to achieve higher-quality recycling routes is to increase the dismantling of materials and components before shredding. Figure 102 shows the quantities of materials that were generated in 2021 during the dismantling of end-of-life vehicles in Germany in 2021 (in tonnes per year)

Figure 102: Recycling of dismantled materials from end-of-life vehicles in Germany 2021



Source: (UBA 2023b)

Sander et al. (2020, p. 86-87) reported some key aspects of current output streams and future expectations by surveying ATFs and shredding companies:

Dismantling at ATFs:

- Glass and large plastic parts were predominantly not dismantled. because many authorised dismantling facilities have an exemption from the general dismantling obligation of the German ELV ordinance granted by the authorities.
- Some electronic components were dismantled. Offers for economic treatment and recycling of the separated components were available and were utilized. Servomotors were not dismantled. More extensive dismantling failed due to the lack of economic viability. In 2023, only 0.6 kg electronic components per German ELV were dismantled, according to statistical data. (Destatis 2023)
- The differentiated sale of metals was estimated to be declining. The disassembly of the powertrain is technically easy to implement and was economically viable in the past. Due to the fall in scrap prices, it was no longer economically viable. In addition, shredder operators prefered to accept complete body shells and are also pushing this through financial incentives.
- The sale of spare parts was declining. There are four reasons for this:
  - The number of remanufacturing companies was declining.

- The quality of the vehicles had increased and the number of saled components failed at the same time.
- The complexity of the engine in particular had increased immensely and replacement was no longer feasible for repair workshops with low equipment level.
- Buyer behavior has deteriorated as a result of online trading in that the number of unfounded returns has risen massively.

Shredding:

- Most of the glass goes into the shredding process and cannot be recovered as a glass fraction due to the sorting technology, but is disposed of as part of the mineral fraction. For example, it is used for backfilling of mines.
- Further differentiated sorting of the steel fraction has not not yet been comprehensively implemented. Developments in the field of aluminium treatment and sorting have been perceived positively and are selled to aluminium recyclers.
- The metal content of residual body shells without engines and gearboxes is estimated to be declining.
- Circuit boards and printed circuit boards from body shells are also recorded separately as an output fraction in some of the large shredders. Differentiated collection is currently economical there.
- The larger servomotors are separated manually.

3.11.3 Legal framework

The European End-of-Life Vehicles Directive was adopted in 2000. It contains provisions on the collection of end-of-life vehicles, the depollution and dismantling before shredding, limits the use of hazardous substances in new vehicles and sets targets for reuse, recycling and recovery.

According to this EU End-of-Life Vehicles Directive and the German End-of-Life Vehicle Ordinance (AltfahrzeugV, Bundesministeriums der Justiz 2020) authorised dismantling facilities shall remove batteries and steer them into proper treatment according to the batteries legislation, remove liquid gas tanks and treat them properly according to the manufacturer's specifications, and have pyrotechnic components either dismantled by trained specialist personnel according to the manufacturer's specifications and disposed of in authorised facilities or rendered harmless by triggering them when installed.

Operating fluids and components must be removed by the dismantling companies and collected separately (depllution).

Furthermore, dismantling facilities must remove several components, substances and materials before shredding and prioritise their reuse or recycling, e. g. aluminium rims, front, rear and side windows as well as glass roofs, large plastic components such as bumpers, hubcaps and radiator grilles if the relevant materials are not separated during or after shredding in such a way that they can be recycled,

Metal components containing copper, aluminium and magnesium if the corresponding metals are not separated during or after shredding.

The following targets apply to the entire waste management chain in relation to the average empty vehicle weight of all end-of-life vehicles handed over per year from 1 January 2015:

- Reuse and recovery at least 95 per cent by weight,
- Reuse and recycling at least 85 per cent by weight.

On 13 July 2023, the European Commission presented a proposal for a regulation on requirements for the circular design of vehicles and the disposal of end-of-life vehicles. (European Commission 2023a)This regulation is intended to merge the content of the previous Directives 2000/53/EC (End-of-Life Vehicles Directive) from 2000 (European Parliament, Council of the European Union 2000) and 2005/64/EC (3R Type Approval Directive) (European Parliament, Council of the European Union 2005a) update them and add further aspects.

For the collection and treatment of end-of-life vehicles, in addition to obligations on the recycled content of plastics (see the key topic recycling of plastics in chapter 3.10), requirements for dismantling, for the overall targets of reuse, recycling and recovery and additional information obligations are proposed. On the topic of recycled content targets for metals a feasibility study is foreseen (see the key topic recycled content of glider and powertrain metals in chapter 3.9). According to the draft, manufacturers should bear the costs of collection, treatment and recovery, less the revenues for spare parts and materials.

The proposal includes the following measures with relevance for circularity and resource efficiency:

- In the short term, vehicle manufacturers should be obliged to provide detailed and user-friendly dismantling and recycling information, including on the use and fate of critical raw materials in vehicles and the proportion of recycled materials in new vehicles.
- A stricter definition of "recycling" should be established to ensure more efficient treatment. The landfilling of shredder residues from end-of-life vehicles is to be prohibited. Furthermore, the list of components to be removed during dismantling before shredding is to be expanded.
- In order to tackle unknown whereabouts, a clearer allocation of responsibility for certificates of destruction, binding criteria for distinguishing between used vehicles and end-of-life vehicles and new enforcement provisions are to be introduced. The export of used vehicles that are no longer roadworthy under EU law is to be prohibited.
- Financial and organisational incentives through the definition of extended producer responsibility obligations should help to tackle unknown whereabouts and offset the costs of improved treatment quality.

Some of the provisions of the regulation are to be gradually extended to other vehicle types. To this end, manufacturers of vehicles in the classes L3e to L7e (two- and three-wheeled vehicles) as well as lorries, buses and trailers will be obliged to provide information on the composition of their vehicles. Furthermore, minimum requirements for the disposal of these end-of-life vehicles are to be introduced.

Recycling, recovery and disposal of batteries are regulated in a separate regulation (European Parliament, Council of the European Union 2023). The EU Battery Regulation (EU) 2023/1542 sets targets for the recycling efficiency of overall batteries and targets for the recovery of individual materials (Art. 71, Annex 12).

Table 48 shows recycling efficiency targets for different battery types, which are to be achieved by 31 December 2025 and by 31 December 2030, respectively.

Table 48: Recycling efficiency targets for batteries to be achieved by year

Year	Lead acid batteries	Lithium ion batteries
2025	75% wt	65% wt
2030	80% wt	70% wt

Source: EU Battery Regulation (EU) 2023/1542

Table 49 shows recovery targets for specific materials, which are to be achieved by 31 December 2027 and 31 December 2031 respectively.

Table 49: Material recovery targets to be achieved by year

Year	Co/Cu/Ni/Pb	Li
2027	90% wt	50% wt
2031	90% wt	80% wt

Source: EU Battery Regulation (EU) 2023/1542

For discussion of the use of recycled battery materials, see chapter 3.8.

3.11.4 Foreseeable development trends

A key change in the area of end-of-life vehicle disposal is the switch to electromobility. More and more cars with electric motors and HV batteries will be recycled, but even after the de facto EU-wide ban on placing cars with combustion engines on the market from 2035, large numbers of vehicles with petrol and diesel engines will continue to enter the recycling routes.

End-of-life vehicles will become heavier, they will contain more electronics and the proportion of plastics is likely to increase (Potrykus et al. 2023).

Large vehicle recycling factories may emerge in which manual dismantling is replaced by automation (e.g. in conjunction with the vehicle passport) (IN4climate.RR 2023).

It is not yet possible to predict when post-shredder technologies (PST), which can be used to separate plastics and metals, for example, will be established to the extent that they will become part of the standard route.

3.11.5 Fields of action and issues

The key questions for instruments in the focus topic were:

- What impact would higher recycling rates for specific materials have on resource consumption?
- What impact would higher quality recycling requirements have, especially for metals (steel, aluminium) and glass? (For high quality plastic recycling see 3.10)
- What would be the impact of material-specific targets for high-quality recycling?
- Where does dismantling before shredding make more sense, and where is better post-shredder technology needed?

3.11.6 Modelling

The variation contains three measures:

- Higher shares of dismantled materials (metals, plastics, glass) before shredding.
  - Dismantled components may be reused or remanufactured (see chapter 3.7). Table 50 shows the values used in the modelling for the shares of reused/repurposed materials.
  - Other materials that are dismantled before shredding can be recycled to a higher quality as they are not contaminated with other impurities in the shredding process.
- Higher share of material recycling of glass. Backfilling is not considered as recycling, but only the material recycling of glass into new glass products, usually packaging glass or even flat glass. Table 51 shows the values used in the modelling for the share of material recovery of glass.
- Higher share of high-quality recycling of specific materials. The materials are sorted and treated and recycled to such a high quality that closed-loop approaches are possible in the vehicle sector. Table 52 shows the values used in the modelling for the shares of high-quality recycling of materials.

Table 50: Share of reused/repurposed material

	Baseline	V1 2030	V1 2035	V1 2040	V1 2045	V1 2050
Flat steel	7%	7%	7%	7%	7%	7%
Long steel	7%	10%	15%	18%	20%	20%
Stainless steel	7%	10%	15%	18%	20%	20%
Cast iron	7%	10%	15%	18%	20%	20%
Wrought Aluminium	7%	10%	15%	18%	20%	20%
Cast Aluminium	7%	10%	15%	18%	20%	20%
Copper	7%	1%	2%	3%	4%	5%
Plastics	1%	5%	6%	7%	8%	10%
Nickel	4%	10%	10%	10%	10%	10%
Glass	10%	5%	5%	5%	5%	5%

Source: own assumptions; based on European Commission (2023c)

Table 51: Share of glass recycling

	Baseline	V1 2030	V1 2035	V1 2040	V1 2045	V1 2050
Glass	0%	10%	25%	60%	70%	80%

Source: own assumptions; based on European Commission (2023c)

Table 52: Share of high-quality recycling per material

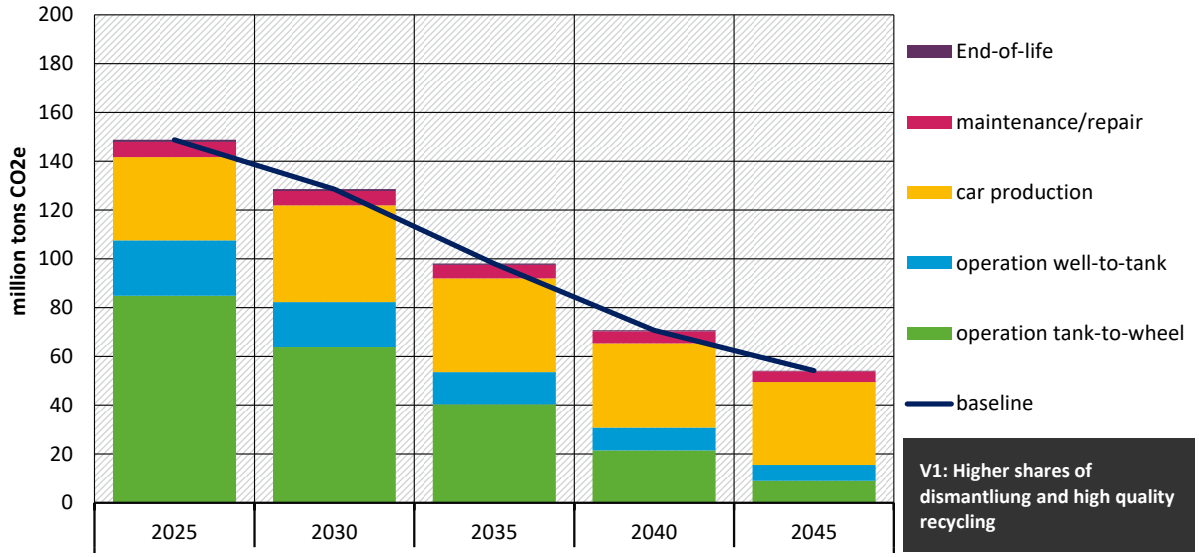
	Baseline	V1 2030	V1 2035	V1 2040	V1 2045	V1 2050
Flat steel	2%	2%	5%	10%	15%	20%
Long steel	2%	5%	10%	15%	20%	20%
Stainless steel	2%	5%	10%	15%	20%	20%
Cast iron	2%	2%	5%	10%	15%	20%
Wrought Aluminium	1%	5%	10%	15%	20%	20%
Cast Aluminium	1%	5%	10%	15%	20%	20%
Copper	5%	10%	15%	20%	25%	30%
Plastics	20%	20%	20%	20%	20%	20%
Nickel	2%	2%	2%	2%	2%	2%
Glass	0%	5%	20%	50%	60%	70%

Source: own assumptions; based on European Commission (2023c)

3.11.7 Results

In the chosen methodological cut-off approach in the model, higher recycling rates at the end of life have no direct impact on the emission of greenhouse gases (see Figure 103), as no credits are awarded for saved primary production of materials. The reduction in greenhouse gas emissions already results from the baseline assumptions. Additional savings of the emission of greenhouse gases would be possible in a closed-loop recycling. In the model, however, instead of specific closed-loop approaches, recycled content targets are set. The material cycles are closed alternatively by purchasing recycled material from other sources if no material from the end-of-life vehicles is available.

Figure 103: GHG emissions for cars for the variation of end-of-life (higher shares of dismantling and high quality recycling)



Source: own analysis

For this reason, the material flows are considered below. Table 53 shows the proportion of specific material from closed-loop recycling that would be possible with variation 1. The results include material from reused components and high-quality recycling. If more recycled material from the end of life is available for vehicle production, less recycling material from other applications is required to achieve the specified recycled content target (see chapter 3.9).

Table 53: Achievable share of recycled content from closed loop per material

	Baseline	V1: 2025	V1: 2030	V1: 2035	V1: 2040	V1: 2045
Flat steel	1%	1%	1%	2%	6%	10%
Long steel	1%	1%	2%	5%	8%	12%
Stainless steel	0%	0%	0%	2%	5%	11%
Wrought Aluminium	0%	0%	1%	3%	6%	11%
Cast Aluminium	1%	1%	4%	22%	26%	29%
Copper	1%	1%	3%	5%	9%	14%
Plastics	2%	2%	2%	2%	2%	3%
Nickel	0%	0%	0%	0%	0%	1%
Glass	0%	0%	0%	3%	20%	34%

Source: own assumptions

Particularly in the case of glass and cast aluminium, higher rates for reused materials and high-quality recycling can achieve relevant shares of recycled content from closed loop recycling. For other materials such as flat steel, long steel or copper, the achievable percentages are lower.

These high shares of material recycling of glass can only be achieved if the glass from the windows is dismantled before shredding.

In order to achieve high-quality steel recycling, the copper contamination in steel scrap must be reduced to well below 0.1%. This requires the removal of copper-containing components before shredding (e.g. the main wire harness) and further processing steps after the shredding process. In order to achieve high-quality aluminum recycling, aluminum scrap must be processed so that different alloys can be recycled.

In the variants assumed here only low recycled content targets for plastics from closed-loop recycling can be achieved. For specific variants to achieve higher recycled content targets for plastics, see subchapter 3.10.

3.12 Comparison of GHG and material impacts for the analysed options

3.12.1 GHG impacts

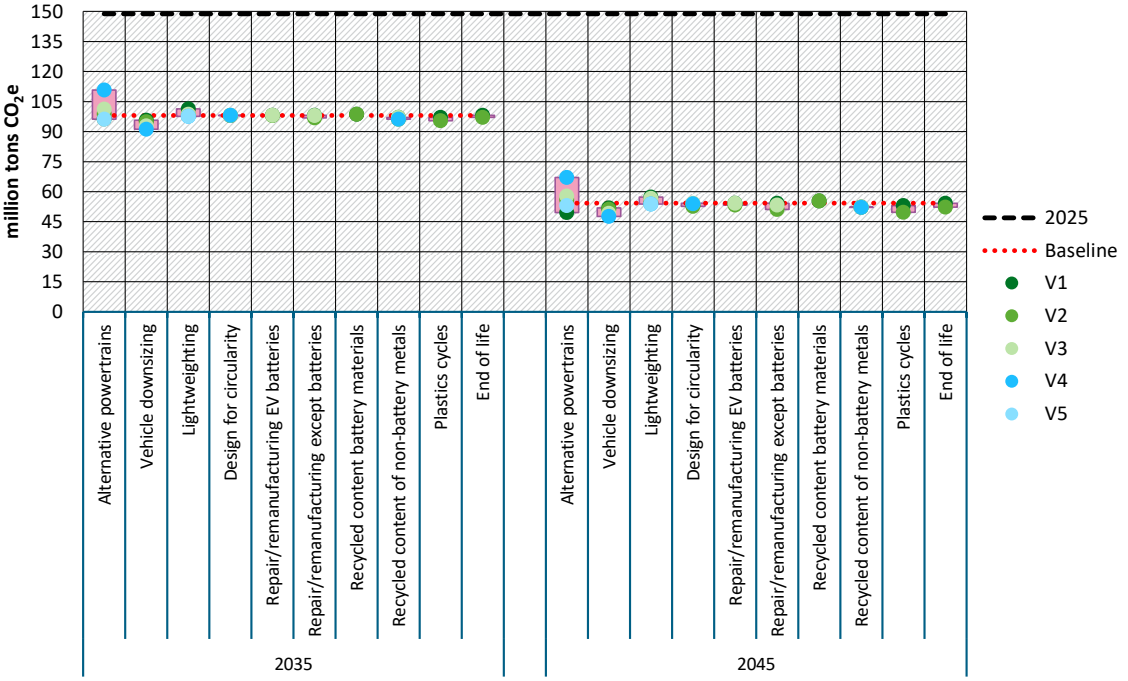
Figure 104 shows the GHG emissions from passenger car traffic in Germany for the base year 2025 (black dashed line), for the years 2035 and 2045 in the trend development (red dashed lines) and for the 10 options examined (columns and dots). The total emissions include the emissions from the production of all newly registered cars in the scenario year, emissions from the energy required for vehicle use and emissions from car maintenance and disposal in the respective scenario year. As already shown for the GHG baseline development, the annual emissions are mainly determined by energy consumption during the use phase and vehicle production.

In the trend development, GHG emissions from car transport in Germany decrease significantly, with emissions falling by around a third by 2035 and by two thirds by 2045 compared to 2025. The reductions are predominantly the result of the increasing energy efficiency and decarbonisation of energy supply in vehicle usage – due to the shift to electromobility with a simultaneous energy transition in the power sector – and additionally of the decarbonisation of car production processes in Europe. Any additional GHG emission savings from a possible long-term defossilisation of global material supply chains are not considered in the model (see model development in chapter 3.1.2).

The additional GHG impact of each individual option is generally low compared to the trend development. Depending on the individual approaches, additional GHG savings can be achieved compared to the trend development, but emission savings can also be weakened compared to the trend development. Additional GHG emissions were mainly derived from the options „alternative powertrains“ (which compares impacts of different battery technologies and sizes) and „lightweighting. The main reasons for this are:

- Not only reduction potentials were examined, but also the general effects of alternative development paths. One example is the assumption of battery capacities increasing beyond the trend, which causes corresponding additional emissions in battery production and, due to heavier vehicles, also in vehicle operation.
- The targeted saving of selected critical battery materials such as lithium and cobalt, e. g. through the use of sodium-ion batteries, can lead to increased vehicle weights and thus additional GHG emissions during vehicle use.
- Lightweighting reduces GHG emissions in vehicle operation. However, aluminium lightweighting leads to an increase in emissions during car production, which more than compensates for the emission savings in the vehicle operation. In contrast, the constructive lightweighting approach for battery housings investigated slightly reduces emissions in both the production and vehicle operation.

Figure 104: GHG emissions of car transport in Germany 2035 and 2045 (all vehicle life stages) with individual options compared to the base year 2025



Source: own calculations, ifeu/ Oeko-Institute

GHG reductions in the trend development are predominantly the result of the shift to electromobility with a simultaneous energy transition in the power sector, and additionally of the decarbonisation of car production processes in Europe. All 10 options examined build on these fundamental development paths.

For the individual variants within the 10 options, see explanations in the respective sub-chapters.

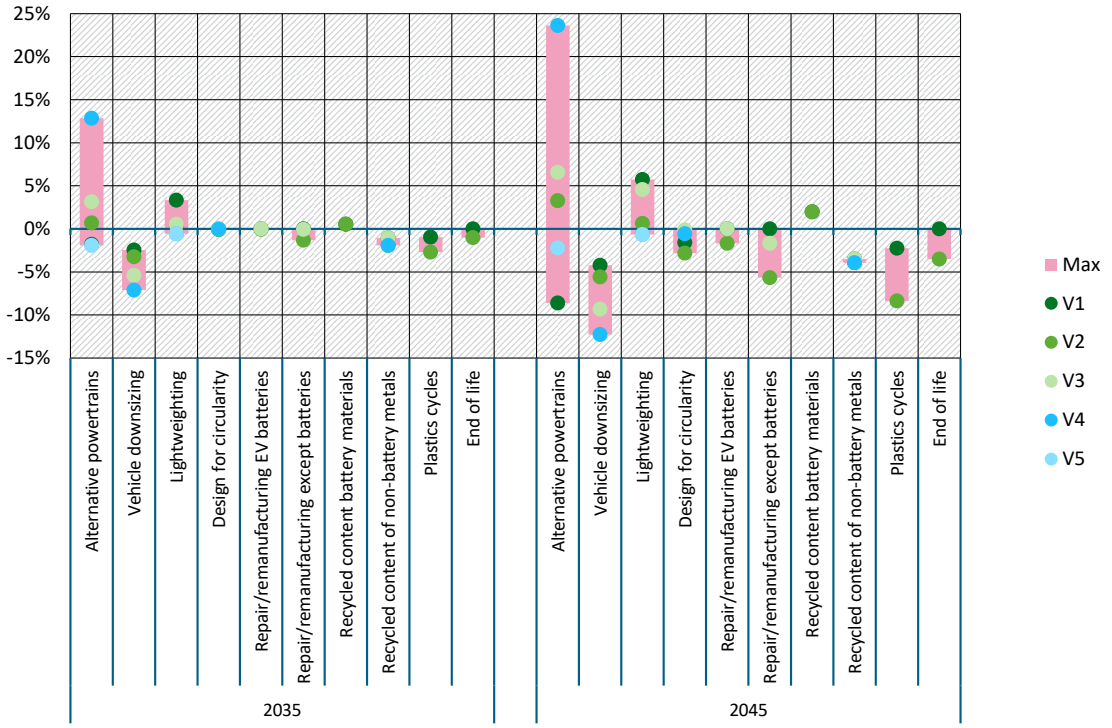
Figure 105 shows the range of GHG impacts in comparison to the emissions in the baseline in 2035 and 2045. The comparison clearly shows that it is not possible to make a simple conclusion about which of the analysed options can achieve higher GHG savings than others. The specific approaches and their implementation intensity within the individual options must also be included in the assessment. This can be illustrated using the following examples:

- Different technical approaches: Two very different approaches are being investigated in the plastics recycling/renewable option: a) increased recycling and b) use of non-fossil plastics made from biomass and captured carbon. Different technical designs are also being analysed for „alternative powertrains“ and „lightweighting“, leading to a wider range of GHG results.
- Implementation intensity: In the option „downsizing“, there is a wide range of GHG results due to a) different size assumptions for small car concepts, b) different new registration shares of small car concepts.

Overall, the highest additional GHG savings in the options are achieved with a substantial reduction in overall material requirements (downsizing, reduced number of new registrations due to longer vehicle lifetimes) and through the reduction of fossil-based vehicle materials.

But we can also have conflicting goals between additional GHG savings and material savings. The “Alternative powertrains” option analyses different battery technologies and highlights potential conflicts between the targeted reduction of selected critical raw materials (e. g. lithium, cobalt) and the additional reduction of GHG emissions across all life cycle stages. We must therefore consider such interactions also in the definition of a GHG and resource saving car.

Figure 105: GHG emission changes of car transport in Germany 2035 & 2045 (all life stages) compared to the baseline of the respective scenario year



Source: own calculations, ifeu/ Oeko-Institute

All 10 options examined build on the fundamental baseline assumptions of a shift to electromobility with a simultaneous energy transition in the power sector, and additionally of the decarbonisation of car production processes in Europe. For the individual variants within the 10 options, see explanations in the respective sub-chapters.

A comparison of the model results only shows which options can have how much additional GHG impact on their own. By combining several options, significantly greater additional GHG savings can be achieved in the long term than with the individual options. Alternatively, additional GHG emissions associated with the saving of critical raw materials (e.g. alternative battery technology) can be offset by savings elsewhere (e.g. downsizing). In the definition of criteria for a GHG and resource saving car, several options are therefore considered together.

3.12.2 Material impacts for new cars production

In this chapter, we compare the impacts of the 10 technical and social options examined in AutoRess on total and primary material requirements. The comparison focuses on material requirements in new vehicle production. Changes in material requirements in vehicle maintenance and repair were addressed in individual options. However, they could not be included in a modelling of the overall system due to the very limited data available for repair/maintenance requirements for the majority of vehicle materials.

The scope of the AutoRess model only assesses material impacts within the automotive sector in Europe. Interactions with other sectors (e.g. use of steel from vehicle recycling in the building sector) or with other regions (e.g. purchase of recycled battery materials from China to fulfil European legal requirements on recycled content) are discussed in the analyses of the individual options (see previous chapters), but are not included in the comparison of the model results.

Annual total material demands in new cars production

Figure 106 shows the annual material demand for steel & iron in newly registered cars as an example of the vehicle materials required across all powertrain variants. Figure 107 shows the annual demand for lithium for the battery materials that will be increasingly required with the ramp-up of electromobility. Annual requirements for all materials investigated in AutoRess can be found in Appendix A.3.

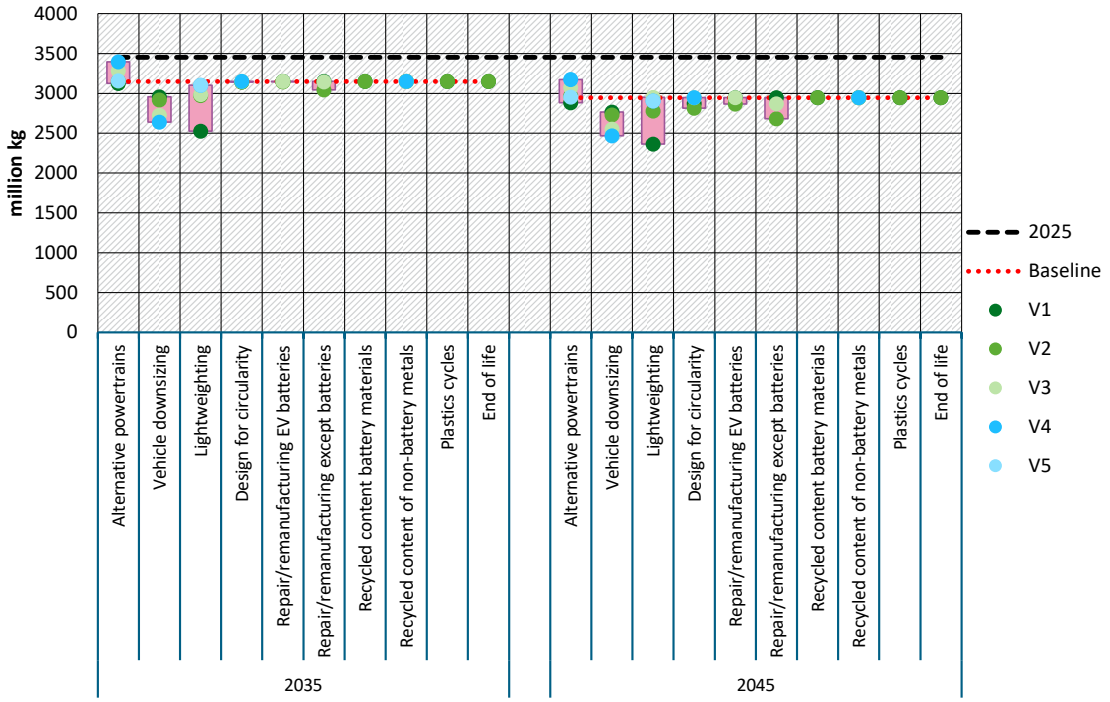
- The material demand in all powertrains will fall slightly by 2035 and 2045 (red dashed lines) compared to 2025 (black-dashed line) despite the increase in vehicle sizes. The reason for this is the decrease in annual new registrations assumed in the trend development (chapter 3.1.2).
- In contrast, the demand for battery materials will rise sharply, driven by the ramp-up of electromobility and the additional trend towards increasing battery sizes.

The columns and dots in Figure 106 show the effects of the 10 options on the total annual material requirements compared to the baseline. Depending on their focus, the options examined have specific effects on the individual material groups:

- Approaches with a focus on the entire vehicle (e.g. “downsizing”, “design for circularity: longevity”) have a proportional effect on all material groups due to reduced new registrations or due to reduced vehicle sizes and accompanying reduced battery sizes.
- Options with a focus on electromobility (“alternative powertrains”, “reuse/repurpose batteries”, “recycled content battery”) primarily affect the demand for battery materials. Depending on the approach, all battery materials can be proportionally affected (e.g. change of battery capacities, repurpose of batteries), but there can also be significant differences between individual battery materials. Changing battery technology (solid-state, sodium ion) reduces the demand of selected materials, but at the same time increases demands of others.
- Some options only affect selected material groups, in particular lightweighting (steel, aluminium) and plastics recycling/renewable (plastics).
- Options that deal with the decommissioning of cars (plastics recycling, end of life) have no effect on the total material demands in car production.

In most cases, the options examined lead to a reduction in annual material requirements. In the “Alternative powertrains” and “Lightweighting” options, however, there is also a partial increase in individual material requirements if the reduction in one material is accompanied by a shift to other materials. Under “lightweighting”, a possible reduction in vehicle lifetime was also included in one variation. In the model, this leads to an increase in the annual number of new registrations and thus the total material requirements.

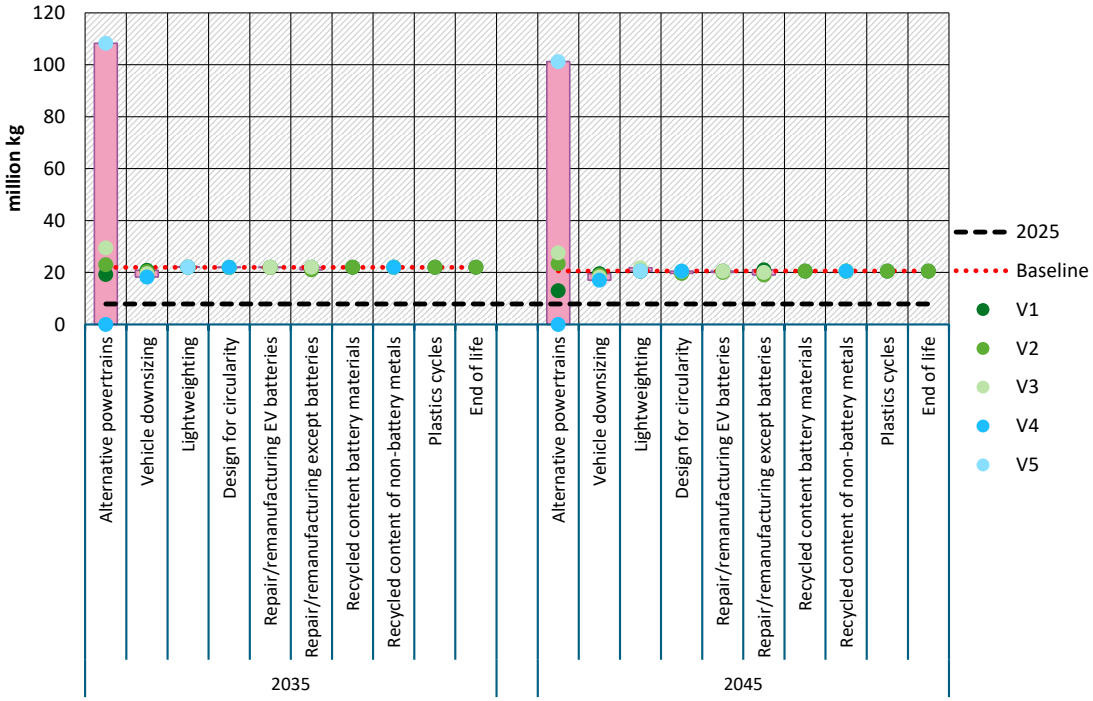
Figure 106: Annual total material demand of steel & iron



Source: own calculations, ifeu/ Oeko-Institut

For the individual variants within the 10 options, see explanations in the respective sub-chapters.

Figure 107: Annual total material demand of lithium



Source: own calculations, ifeu/ Oeko-Institut

For the individual variants within the 10 options, see explanations in the respective sub-chapters.

Overall, it can therefore be stated that comparisons of potential material savings of the options can be made for individual materials, but not across all selected material groups. Options that perform better for one material may be less (or not at all) effective for another material. The

reason for reducing material requirements in car production is to reduce overall resource consumption and associated ecological and social consequences of car production. By reducing the overall material requirements, these consequences will also be reduced to the same degree. However, if options address only selected materials, we cannot compare the effectiveness of different options against each other in a simple way. To do this, we will need suitable and accepted evaluation parameters that can be applied across all materials.

Annual primary material demands in car manufacturing

Primary material demands depend first on the total material demand and second on the recycled content in the material used. Total material requirements for new cars change due to number and size of new cars and material composition of vehicles. Recycled content depends on:

- Closed-loop recycling: amount of recovered material in vehicle recycling depending on

(1) number, size and material composition of decommissioned cars,
(2) share of decommissioned cars and components, which are sent for recycling,
(3) reuse of functional parts prior to shredding and
(4) (material-specific) recycling efficiency

- Effects of closed-loop recovered materials on the overall recycled content:

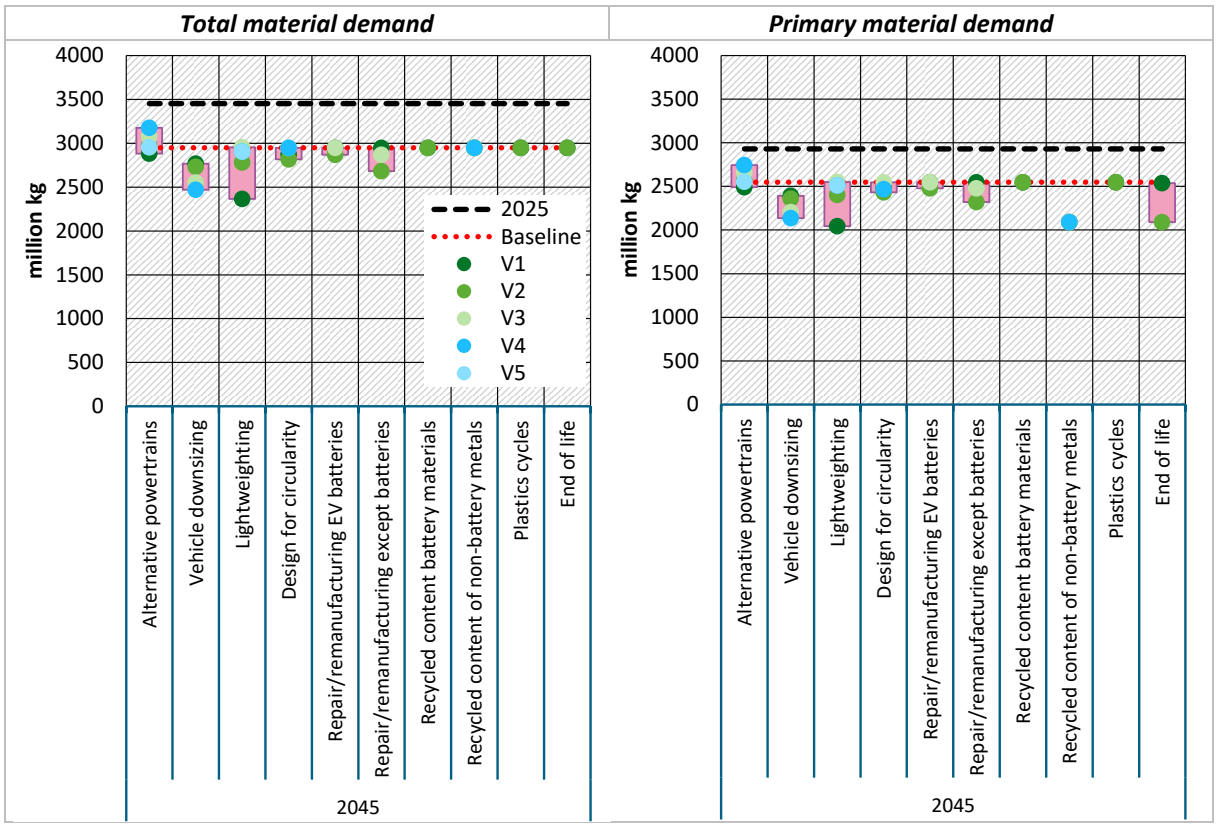
a) increase of overall recycled content or

b) higher closed-loop share within an overall unchanged recycled content.

While some options affect the material demands of new vehicles as a whole, other topics only have a targeted effect on selected material groups. It is therefore not possible to make a comprehensive comparison of the potential primary material savings of the topics examined across all material groups. Comparisons can be made specifically for individual materials. For this purpose, we are looking at steel and iron as examples for materials that are relevant across all powertrains (Figure 108), and at cobalt for battery materials (Figure 109). Annual primary material requirements for all material groups investigated in AutoRess can be found in Appendix A.3.

Steel & iron: The primary material demand in 2025 (Figure 108, right, black dashed line) is lower than the total material demand (Figure 108, left). In the trend development, the primary demand is decreased together with a reduction of total material demand as the recycled content target does not change. In the same way, there is no difference in the results between the primary and total material demand for most options, because they may have an effect on the total demand, but not on the recycled content target. Only the technical options „Recycled content body“ and „End of life“ show a particular potential for saving of primary material as an increase in total recycled content was explicitly examined in these options. The effect of these options aimed at recycled content is of a similar magnitude to the options that reduce overall material demand in new cars.

Figure 108: Annual total and primary material demand – steel & iron



Source: own calculations, ifeu/ Oeko-Institut

For the individual variants within the 10 options, see explanations in the respective sub-chapters.

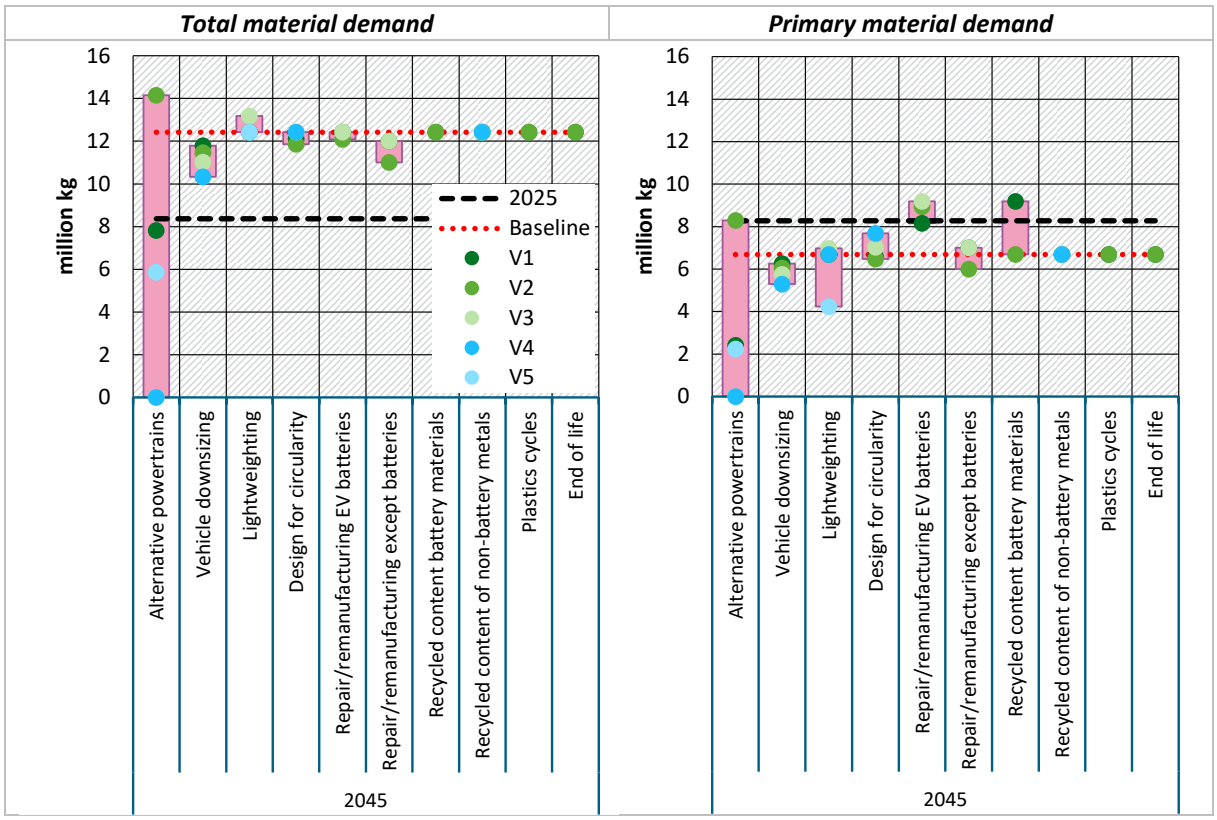
Cobalt: In 2025, the total material demand for new cars is almost entirely met by using primary material, as there is still no significant number of disposed electric cars and therefore hardly any recovery of cobalt. In the baseline development until 2035, the increase in primary material consumption is significantly lower than the increase in total material consumption. In 2045, primary material consumption is even lower than in 2025, despite significantly higher total material consumption. This is due to the existing legal requirements for the recycling of vehicle batteries and the use of recycled content in new car batteries (see chapter 3.6.7). The examined options have different effects on the future demand for primary cobalt:

- A switch to cobalt-free battery technologies would eliminate the need for cobalt in the future.
- Downsizing reduces total and primary cobalt requirements proportionally.
- In the case of lightweighting, the effect also depends on the possible consequences of the analysed cell-to-chassis battery design. Assuming that this makes it more difficult to remove functioning batteries and reuse them in other sectors, the cobalt remains within the vehicle sector and thus increases the available recycled contents for new cars.
- In contrast, if repurposing of batteries (second life as stationary energy storage) is increased, cobalt is withdrawn from the automotive sector and thus reduces the recycled content for

new cars production. At the same time, material for the production of new stationary batteries is saved, which is not depicted in the AutoRess model.[28]

- Options unrelated to electromobility (e.g. plastics recycling, end-of-life recycling efficiencies) have no impact on the overall demand for cobalt or on the demand for primary material.

Figure 109: Annual total and primary material demand – cobalt



Source: own calculations, ifeu/ Oeko-Institut

For the individual variants within the 10 options, see explanations in the respective sub-chapters.

[28] A cross-sectoral view would also raise the question of whether cobalt and other critical battery materials are not required for new stationary energy storage systems even without the second life of used car batteries, if these are designed as cobalt-free technology (e.g. sodium ions).

4 Criteria for a resource-efficient vehicle

4.1 Definition of a resource-efficient, circular-economy conforming vehicle

As summarised in chapter 3.12 the model identified a few major levers which, in addition to the measures already in place (such as the CO_2 fleet targets), in combination have a positive impact both on greenhouse gas emissions as well as resource demand. These are:

- Reducing the total amount of materials used (assuming a constant composition of materials) by reducing the number of vehicles built and prolonging their lifetimes as well as limiting their vehicular and battery size.
- Reducing the amount of primary materials used by enabling the use of recyclates.

As indicated in chapter 3.1.2.2, the defossilisation of the energy supply is expected to lead to a reduction in GHG emissions in the transport sector in the long term. In the meantime, however, the total energy consumption for the production and use of a vehicle is an additional contributing factor to GHG emissions, so that this is also considered part of the definition of a resource-efficient, circular-economy conforming vehicle at the present time.

The aspects mentioned directly contribute to the definition of a resource-efficient, circular-economy conformingvehicle under the definitions used in this project. In addition to the points resulting explicitly from the project goals, the definition also considers other environmental impacts and social aspects such as the extraction of raw materials. While these aspects are not the project's primary focus,they should not be negatively impacted by compliance with the developed criteria; they are therefore included in the definition.

Thus, a vehicle is considered **resource-efficient and circular-economy compatible** if it satisfies the following requirements:

a) The least amount possible of primary raw materials is consumed over the entire lifecycle.

b) The least amount possible of greenhouse gases are emitted over the entire lifecycle.

c) The least amount possible of energy is consumed over the entire lifecycle.

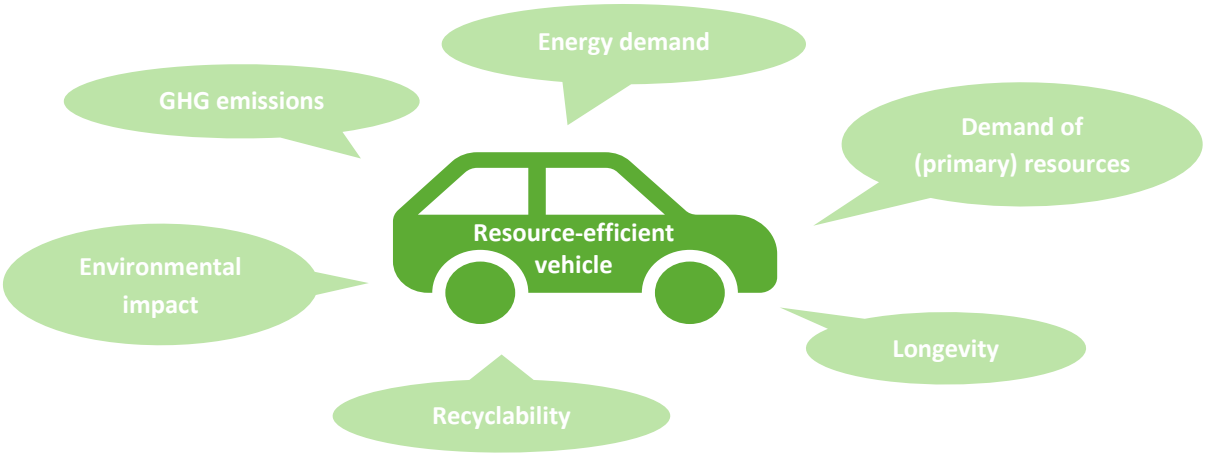
d) The vehicle's life span is as long as possible.

e) The vehicle's components can be recycled in the most efficient way possible without the need for downcycling.

f) Additional negative environmental as well as social impacts are minimized.

The different aspects defining a resource efficient vehicle are also depicted in Figure 110. As discussed in chapter 2, battery electric vehicles are currently the only available technology that can ensure the achievement of greenhouse gas emission targets. For this reason, only these vehicles will continue to be considered explicitly in this analysis. While it is possible that vehicles with internal combustion engines may perform better than battery electric vehicles in certain areas, this should not invalidate this premise.

Figure 110: Proposed definition for a resource-efficient, circular economy compatible vehicle



Source: Own figure Oeko-Institut

4.2 The ideal of a resource-efficient, circular-economy conforming vehicle

The definition of a resource-conserving vehicle that has been established in this way directly informs the ideal of what such a vehicle should look like in the future. As the analysis of the major factors indicates, the most important point here is not technical, but is instead related to sufficiency. The lower limit of a car's resource use and GHG emissions would be the savings from shifting the transport project to public transport or non-motorised means of transport (e.g. bicycle). As this project focuses on reducing emissions and resources from cars in parallel with a transition of transport means, this finding is not prioritized here. Nevertheless, purchasing a vehicle that meets the buyers needs is one of the most crucial factors for resource utilisation and GHG emissions. A resource-efficient vehicle is defined, among other things, by its ability to fulfil the user's specific requirements as precisely as possible without exceeding them. This means purchasing the smallest vehicle with the shortest range, the smallest battery size, and the minimum amount of optional equipment. The question of the ideal resource-saving vehicle therefore initially challenges the sufficiency of the existing vehicle classes defined in Germany and the EU.

Safety versus resource efficiency, vehicle class beyond M1: In order to save resources and reduce GHG emissions as efficiently as possible, it might be justifiable to compromise on the required safety measures, especially for vehicles used exclusively in cities. However, there is a considerable gap between vehicles classes as concern lighter vehicles. Minicars (classified as M1) usually weigh more than 1000 kg due to safety regulations, whereas electric vehicles classified as L7E/L6E (see also chapter 3.3) are subject to very strict weight restrictions (max. 450 kg) and are often perceived by users as unsafe ("VDI" 2023). It has therefore been proposed that this gap be closed by introducing a new vehicle class (M0), which would be suitable for urban and suburban regions and would be subject to weight and size restrictions that would still allow for basic safety features.

In addition to the crucial question of vehicle size and sufficiency, the ideal vehicle naturally should also represent a vision for the future concerning the other big levers that were identified. Thus, in addition to being made from 100% secondary materials, the ideal resource-efficient vehicle should also be optimized for its lifespan and repairability. This requires all vehicle parts, in particular those that might break or wear out quickly, to be easily accessible and interchangeable by being fastened with screws or similar components rather than being welded

or glued. This total modularity would also promote the vehicle's recyclability by facilitating parts' demounting and removal prior to shredding at end of life.

However, as some of these requirements are not yet technologically and/or legally feasible, the development of specific criteria for resource-efficient, circular-economy conforming vehicles conducted in the following chapters will focus on those scenarios and criteria that are currently proven to be feasible.

4.3 Existing criteria for resource-efficient vehicles

The first step in developing specific criteria was to list the criteria that had already been formulated. Research on resource-efficient vehicles addressed existing and proposed regulations on the national and EU levels, eco-label criteria, green public procurement provisions and manufacturers' sustainability strategies. Table 54 summarises the results, with information on the level of obligation and (proposed) methods of validation. This table is not exhaustive but merely reviews the types of criteria formulated to date. All criteria from the respective sources dealing with resource efficiency and greenhouse gas savings were listed. As specific criteria shall be developed for this project, some of them will be dismissed because they either do not correspond exactly to the project objectives or more suitable criteria are found.

Table 54: Summary of existing criteria for resource-efficient, circular-economy compatible vehicles

Source, Year, Domain	Level of obligation	Objectives	Criteria
Proposal for an new End-of-life-vehicles Directive (Procedure 2023/0284/COD) (2023, EU) (European Commission 2023b)	Proposal, legally binding when passed	Improve the environmental performance of all economic operators involved in the life-cycle of vehicles	Provision of basic dismantling information to recycling companies
			Labelling of components with permanent magnets and certain plastics
			Recycled content targets for plastics, rare earths, aluminium, magnesium
			Restrictions of substances under (European Parliament, Council of the European Union 2006) and other existing legislation
			Design requirements for new vehicles to facilitate the removal of components
			Establishment of a digital Circularity Vehicle Passport

Source, Year, Domain	Level of obligation	Objectives	Criteria
			Market support for the use of spare parts
			Extended producer responsibilities
Revised Clean Vehicles Directive (2019/1161) (2019, EU) (European Parliament, Council of the European Union 2019)	Legally Binding	Ensure that contracting authorities and contracting entities take into account lifetime energy and environmental impacts	Minimum percentages of clean vehicles in the total number of road transport vehicles (Zero emissions from 2026)
Green Public Procurement Criteria (Road Transport) and corresponding Technical Report (2021/22, EU)(European Commission 2021b; Rodriguez Quintero, Vidal Abarca Garrido 2022)	Voluntary	Support for public authorities in purchasing goods with reduced environmental impacts	Emissions limits for CO_2 , NOx, particle number (zero emission from 2026)
			Energy consumption display, traffic information and route optimisation
			Minimum battery warranty
			Extended warranty
			Energy consumption
			Use of re-refined lubricant oils

Source, Year, Domain	Level of obligation	Objectives	Criteria
			Use of hydraulic fluids and greases that have no health or environmental hazard statement
			Air conditioning gas global warming potential
			Speed limiter implemented
			Tyre pressure monitoring System
3R type approval directive (2005, EU)(European Parliament, Council of the European Union 2005b)	Legally binding	Ensuring that vehicle component parts and materials can be reused, recycled and recovered	Target values for recyclability/ Reusability/ Recoverability by total vehicle mass
			List of vehicle parts not fit for reuse for safety reasons
EEA report „Electric vehicles from life cycle and circular economy perspectives“ (2018, EU)(European Environment Agency 2018)	Recommendations	Assess environmental impact of BEVs across the stages of their life cycle	Decreased amount of rare earth in permanent magnets by technical means (research)
			Production site location i.e. origin of used energy
			Longevity, repairability
			Preferential treatment of certain battery types
			Interchangeable batteries system in order to facilitate charging with

Source, Year, Domain	Level of obligation	Objectives	Criteria
			renewable energy by decoupling usage and charging timing
			Standardisation and dismantling ability to facilitate reuse and remanufacturing
RESCUE-Study (2021, D) (Purr et al. 2019)	Recommendations	Reaching "ressource-efficient greenhouse gas neutrality in germany"	Reducing energy consumption by switch to electromobility
			Lightweighting (high-strength steels)
			Promotion of smaller vehicles
			Sufficiency of lower battery ranges by extending charging grid
Ecolabel" Blauer Engel" for Car Sharing (2018, D)(Umweltbundesamt, Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit 2018a)	Voluntary	Award for eco-friendly car sharing services	Transformation to electromobility
			Target values for small vehicles in fleet share
Ecolabel "Blauer Engel" for Buses / Guide to green public procurement: buses (Umweltbundesamt) (2018/19, D) (Umweltbundesamt 2019; Umweltbundesamt, Bundesministerium	Voluntary	Award for low-emission and low-noise-emission buses	Interchangeable battery

Source, Year, Domain	Level of obligation	Objectives	Criteria
für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit 2018b)			
			Minimum availability of batteries for exchange
			Air conditioning: natural, non-halogenized coolants
			Extended battery warranty
			Battery return system
			Low-Emission vehicle surface coating
			Limit values for heavy metals
Leaflet "Umsteigen Bitte" (Weed e.V.) (2022, D)(Verena Kröss 2022)	Recommendations	Sustainable procurement of electromobility	Battery carbon footprint
			Transparency concerning supply chains
			Preferential treatment for products with proven best international practise raw material procurement
			Recyclability and reusability

Source, Year, Domain	Level of obligation	Objectives	Criteria
Questionnaire on sustainability of electric busses by Hamburger Hochbahn AG (2022, specific company)(Janina Heel 2022)	Voluntary	Purchasing environment friendly and sustainable products	PCF and LCA provided for vehicle and battery
			Selection of used battery according to environmental impact
			Existing reduction targets for CO_2-emissions, energy and water consumption, waste
			Usage of renewable energy at production site(s)
			Environmental impacts of battery supply
			Responsible procurement of raw materials
Project Report „Umweltverträgliche Beschaffung durch die öffentliche Hand“, ifeu, (2022, D) (Lambrecht et al. 2024)	Voluntary	Recommendations for green public procurement	Extended battery warranty
			Limit on energy consumption
			Emission limits: CO_2, NO_x, Particle number
			Speed limiter

Source, Year, Domain	Level of obligation	Objectives	Criteria
			Information on energy efficiency for user
			Heat pump
			LED headlights
			Omission of special equipment not relevant to safety or comfort
BMW Group Sustainability strategy (2024, specific company) (BMW Group 2024)	Voluntary	Improve sustainability of own product	Enabling data exchange over complete value chain
			Responsible supply chain initiative
			Usage of less diverse materials, preferably mono-materials
			Use of renewable raw materials
			Use of secondary materials
			Use of renewable energy at production sites
			Recycling by manufacturers to facilitate reuse
VW Group Sustainability strategy (2024, specific company)	Voluntary	Improve sustainability of own product	CO_2 emissions of production sites

Source, Year, Domain	Level of obligation	Objectives	Criteria
(Volkswagen Group 2024)			
			Use of recycled materials (textiles/interior)
Mercedes Benz Sustainability strategy (2024, specific company) (Mercedes Benz Group 2024)	Voluntary	Improve sustainability of own product	Higher transparency on use of secondary materials
			Lightweighting by bionic construction that reduces material
			Usage of alternative, sustainable materials
			Battery collection system
			Use of recycled materials (textiles and aluminium)

Source: see table entries

4.4 Development of qualitative criteria

In parallel to compiling already existing criteria, the research team compiled the main issues of concern for all fields of action addressed in chapter 0 with the aim to find or formulate criteria addressing those issues. Table 55 summarises the results of this compilation and assigns them to the respective aspect of the definition. Aspects listed by experts responding to the 'criteria workshop' were added to the list.

Table 55: Aspects of concern and resulting criteria compiled from results in WP 2 and expert consultations

Aspects	Derived from	Possible resulting criteria	Addressed in source
Amount of primary raw material used			
Correlation between use of primary raw materials	Comprehensive, Workshop	Vehicle weight or PCF	(Purr et al. 2019)

Aspects	Derived from	Possible resulting criteria	Addressed in source
and product Carbon footprint			
Responsible sourcing of materials	Comprehensive	Use of certified raw materials (potentially in a defined share of overall material), obligatory disclosure of supply chains	(BMW Group 2024; Janina Heel 2022; Verena Kröss 2022)
Recycled content rates	Chapters 3.8 (Recycled content of battery materials), 3.9 (Recycled content of metals), 3.10 (Recycling of plastics)	Specific rates, Product Carbon Footprint	(BMW Group 2024; European Commission 2023a; European Parliament, Council of the European Union 2005b; Mercedes Benz Group 2024; Volkswagen Group 2024)
Recovery of critical raw materials	Chapters 3.8 (Recycled content of battery materials), 3.9 (Recycled content of metals)	Recovery of electric motors and batteries, recycled permanent magnets	(European Commission 2023a; European Environment Agency 2018)
Closed-loop-recycling	Chapters 3.8 (Recycled content of battery materials), 3.9 (Recycled content of metals), 3.10 (Recycling of plastics)	Combination of recycling efficiency and recycled content rates	(European Commission 2023a)
Quality of recycled Material	Chapters 3.8 (Recycled content of battery materials), 3.9 (Recycled content of metals), 3.10 (Recycling of plastics)	Recycled content rates, design requirements for easy disassembly, provision of recycling concept by manufacturer	(European Commission 2023a)
Post-consumer recyclates	Chapters 3.8 (Recycled content of battery materials), 3.9 (Recycled content of metals), 3.10 (Recycling of plastics)	Targets values specifically for post-consumer recyclates	(European Commission 2023a)
Differentiation between different materials of different environmental effects	Chapters 3.8 (Recycled content of battery materials), 3.9 (Recycled content of metals), 3.10 (Recycling of plastics), Workshop	Weighted factoring of material's PCF and other environmental effects instead of general weight	
Biogenic and renewable materials	Chapter 3.10 (Recycling of plastics), Workshop	Biogenic/CO_2-based plastics,...	(Mercedes Benz Group 2024)

Aspects	Derived from	Possible resulting criteria	Addressed in source
Energy consumption and CO_2-emissions			
CO_2-emissions from production	Comprehensive, Workshop	Part- or material-specific limits	(Janina Heel 2022)
Life cycle assessment	Comprehensive, Workshop	Mandatory submission of a life cycle assessment	(Janina Heel 2022)
Responsible use of energy in production and use phase	Comprehensive	Renewable energies for production and charging, smart charging	(European Environment Agency 2018)
Significance of CO_2 emissions in the future	Workshop	Additional criteria concerning energy consumption in general, other aspects	
Energy efficiency	Chapter 3.3 (Downsizing), Comprehensive	Weight, vehicle area, wind resistance, tire resistance, number of additional energy consumers, implemented speed limit, information for driver	(European Commission 2021b; Lambrecht et al. 2024; Rodriguez Quintero, Vidal Abarca Garrido 2022)
Lightweight materials	Chapter 3.4 (Lightweighting)	Weight	(Purr et al. 2019)
Differences in energy consumption for production of different materials	Comprehensive, Workshop	Product carbon foot print, raw materials index	
Energy-efficient user behaviour	Workshop	Provision of related information for driver	(Rodriguez Quintero, Vidal Abarca Garrido 2022)
Longevity			
Durability		Lifetime guarantees	(European Commission 2023a; Janina Heel 2022; Umweltbundesamt 2019; Umweltbundesamt, Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit 2018b)
Longevity	Chapters 3.5 (Design for circularity, 3.6 (Repair and manufacturing of parts	Mandatory software updates, availability of spare parts	(European Commission 2021b; Rodriguez

Aspects	Derived from	Possible resulting criteria	Addressed in source
	and components), Workshop		Quintero, Vidal Abarca Garrido 2022)
Right to Repair / Cost-effectiveness of repairs	Chapters 3.6 (Repair and manufacturing of parts and components), 3.6 (Repair and manufacturing of EV batteries), Workshop	Provision of design information, design requirements for easy disassembly, standardization, digitalization of information	(European Environment Agency 2018)
Upgradeability	Chapter 3.5 (Design for circularity)	Provision of design information, design requirements for easy disassembly, standardization	(European Environment Agency 2018)
Modularity	Chapter 3.5 (Design for circularity)	Standardization	(European Environment Agency 2018)
Battery-friendly user behaviour	Chapter 3.6 (Repair and manufacturing of parts and components)	Provision of related information for driver	
Circularity			
Disassembly at end of life	Chapter 3.11 (End of life)	Provision of design information, design requirements for easy disassembly, standardization	(European Commission 2023a)
Cell-to-Car / Elimination of battery housing	Chapter 3.4 (Lightweighting)	Exchangeability of battery	(European Commission 2023a; European Environment Agency 2018; Umweltbundesamt 2019; Umweltbundesamt, Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit 2018b)
Use of composite materials	Chapters 3.10 (Plastics cycles, 3.11 (End of life)	Rate of composite materials used	(BMW Group 2024)
Variety of used materials	Chapters 3.10 (Plastics cycles, 3.11 (End of life)	Number of materials used per part	(BMW Group 2024)

Source: see table entries

A list of specific criteria that define a resource efficient, circular-economy conforming vehicle was compiled by combining the reviewing existing criteria and the greatest levers and aspects of concern from the modelling results described in Chapter 0, and discussing these with various experts and stakeholders. As the transition to electromobility was assumed to be a prerequisite throughout the project (see Chapter 1), the following criteria were also developed exclusively with regard to battery electric vehicles. Therefore, they cannot neccesarily be transferred to vehicles with combustion engines or alternative drive systems.

Furthermore, based on the project description and the scope, it was determined that the criteria cover the life phase of a vehicle up to the time of purchase. It is difficult to influence the subsequent life cycle phases of a vehicle by means of criteria defined in advance. For example, although the project team considers aspects of recycling to be very important, they are only addressed in the list of criteria to the extent that they must be considered in the design. Criteria and measures relating to the actual recycling process are considered in the measures developed in chapter 5. It is, however, important to take into account the interaction between effects on different phases in the vehicle's lifespan. Criteria set for one of those phases should not negatively impact others. Lightweighting is the most prominent example of such conflicts of interest. Especially when achieved by substituting materials with lighter ones (e.g. steel with aluminium), lightweighting can lead to a decrease in recyclability at the end of a vehicle's lifespan. The catalogue could contain two different types of criteria: Comprehensive or proxy criteria are those that can be (in an ideal case) easily quantified to a key value summarising a number of aspects to be addressed. Detailed criteria cover one specific aspect which cannot be adequately addressed in the form of comprehensive criteria. Ideally, the final criteria list will be a combination of both types of criteria, with the goal to create a list (or several lists for different levels of demand) that is as short and concise as possible by using adequate proxy criteria while adding detailed criteria for important aspects not yet fully addressed by the former. One aspect that must be considered when establishing comprehensive and detailed criteria is verifiability. Ideally, potential buyers should be able to verify most criteria without any further bureaucratic steps. In terms of the use of primary raw materials, for example, vehicle weight would be an easily accessible proxy criterion. However, the wish for as few bureaucratic hurdles as possible should not take precedence over ensuring that the relevant criteria are clearly giving the right incentive towards resource efficiency in all cases.

Whenever possible, criteria should take into consideration future technological advancements, which would favour using comprehensive criteria rather than more detailed ones. Restrictions on individual materials, for example, could quickly become obsolete if innovations arise in their manufacturing or recyclability processes or if they are substituted entirely.

Feasibility of compliance is a critical aspect when determining the criteria. Since the limited scope of the project did not allow performing a feasibility study for every potential criterion, it initially seemed essential to formulate criteria whose feasibility had already been verified elsewhere. During the development process, it became clear that this was possible and sensible in many cases. However, in some cases it was concluded that no useful, verifiable criteria yet existed; although alternatives could be identified, further in-depth investigation of the relevant aspects was still recommended.

Another aspect that arose during the compilation of specific criteriawas that it was not useful to set uniform target values for quantifiable criteria for every type of passenger vehicle. Due to the very different daily life requirements of different user groups, it seemed appropriate to divide the broad category of passenger vehicles into subsets based on requirements such as the number of seats, transport capacity and range. Schemes in which passenger vehicles can be categorised according to their size and/or functionality already exist. The most prominent

examples are the categorisation of M1 motor vehicles into segments according to to Regulation (EU) 2018/858 or the Federal Motor Transport Authority (Kraftfahrtbundesamt, KBA). As discussed in Chapter 4.2, however, these lack the flexibility to accommodate smaller, lighter vehicles. Additionally, there are no specific requirements for transport capacity and minimum range. Thus, as a basis for the criteria developed here, three independent user profiles were defined that differentiate between three different, widespread use-cases:

- **City(2)** - Transport of (mainly) one person in urban traffic
- **Family(5)** - Transport of up to 5 people and luggage (e.g. families), over longer distances
- **Transport(9)** - Transport of up to 9 people and luggage **or** especially bulky luggage (e.g. transporter vans)

Table 56 describes the minimum functional requirements set for the respective user profiles. The name of each user profile consists of its prevailing method of use followed by the maximum number of passengers in parentheses.

Although they are not fully identical, some correspondence with the existing vehicle class M1 segments can be identified: User profile City(2) (a means of transport for 1-2 persons in urban traffic) might correspond to the A(mini) segment in the European categorisation scheme, although the segment specifications allow for four Seats. Therefore, it should be possible to limit the vehicle size of user profile City(2) user profile further than that of the 'mini' segment in the existing categorisation schemes. The smaller vehicle classes (e.g. L7E/L6E) that currently exist have to comply with significantly lower safety standards than M1 vehicles. While this might be acceptable for use in urban traffic only, it is not necessarily an acceptable trade-off for every user. This study therefore leaves open the decision on where exactly vehicles in user profile City(2) will be categorized in the future.

For Family(5) and Transport(9) user profiles, it is assumed that the vehicle will be used extensively on motorways. The applicable safety requirements should therefore be the provisions of Regulation (EU) 2019/2144 on the type-approval of motor vehicles with regard to general safety and the protection of vehicle occupants and vulnerable road users. Vehicles that fulfil the requirements of these user profiles can thus be assigned to the M1 category segements.: The minimum requirements for user profile Family(5) are fulfilled by most of the D(large) segment; user profile Transport(9) corresponds to segment M(multi-purpose).

Table 56: Characterisation and minimum requirements of the defined user profiles

User profile	Seats	Prevailing mode of usage	Range (WLTP)[29]	Transport capacity
City(2)	2	Urban environment (up to 50 km/h)	200 km	0
Family(5)	5	Urban and suburban environment, Motorways	500 km	ca. 600 l

[29] Worldwide Harmonised Light-Duty Vehicles Test Procedure

User profile	Seats	Prevailing mode of usage	Range (WLTP)[29]	Transport capacity
Transport(9)	up to 9 or especially bulky luggage	Urban and suburban environment, Motorways	500 km	ca. 1500 l

Source: own considerations

As outlined in the project specifications, it is also possible to establish criteria lists for different scenarios with varying levels of demand.

Scenarios applying these criteria:

- A basic set of criteria that could apply to every vehicle registered in the future.
- An advanced set of criteria for a subset of vehicles, e.g. creating an eco-label or recommendations for public procurement.

An alternative to setting strict requirements for every vehicle registered in the future with the basic set of criteria might also be advisable to employ the criteria for the various user profiles in a different and more flexible way. For example, the differentiation between user profiles could be used to determine graduated taxation or insurance fees. The explicit placing of the different lists of criteria in a legal context will be part of further discussions about the measures discussed in Chapter 4.

On the one hand, an advanced set of criteria could be implemented in an eco-label e.g. the "Blauer Engel" format for vehicles. On the other hand, it could also be used for preferential public procurement. As eco-labelling might be much more demanding than public procurement, both will be considered as two separate levels of demand. Green public procurement in Germany in general is addressed in the administrative regulations on the procurement of climate-friendly services (Bundesministerium für Wirtschaft und Klimaschutz 2021). However, specifications for vehicles are explicitly referred to in the law and administrative regulation on the procurement of clean vehicles(Bundesministerium für Wirtschaft und Klimaschutz 2022; Bundestag, Bundesrat 2021). Although these do not contain any resource-saving aspects, these laws seem like a logical place to specify such aspects on a federal level. At the EU level, the corresponding anchor legislation is the Revised Clean Vehicles Directive (European Parliament, Council of the European Union 2019) and the Green Public Procurement Criteria for Road Transport (European Commission 2021b).

Once all prerequisites were settled, in the next step the team formulated qualitative criteria that addressed all aforementioned aspects. The initial list proposed for further discussion contained the following points:

a) Restriction of the vehicle weight

b) Limitation of energy consumption in use

c) Limitation of the product carbon footprint [in CO_2e] (differentiated per usage profile)

d) Limitation of battery capacity [in kWh] (differentiated per utilisation profile)

e) Recycled content targets for the following materials:

- Steel
- Stainless steel

- Aluminium
- Copper
- Plastics
- Lithium
- Nickel
- Cobalt
- Rare earths

f) Compliance with due diligence obligations in the supply chains or use of certified raw materials

g) Interchangeability/modular structure: Parts can be removed and replaced using conventional tools and with a pre-determined maximum amount of time. The list of parts, which in turn have a modular structure, allow for individually affected components, removeable components , or component that can be replaced using conventional tools in a predefined length of time. The modular structure can be used to support repairability (replacement of parts), upgradeability or recyclability (disassembly at the end of life), e.g.

- Battery
- Electric motor incl. control unit and cable
- Discs
- Headlights, rear lights
- Bumpers
- Liquid tanks
- Wear parts

h) The availability of spare parts and software updates is guaranteed for a specified period of time.

i) The manufacturer provides a lifetime guarantee on the traction battery with a minimum capacity after a specified mileage/lifetime.

j) Renunciation of the use of environmentally harmful or poorly recyclable materials, e.g.

- Refrigerants for air conditioning systems with greenhouse gas potential >1
- Components made of different, inseparable materials

k) Limitation of the energy requirements of auxiliary consumers (heating, seat/steering wheel heating, air conditioning, electrically adjustable seats, entertainment, ...)

l) Special equipment or materials that does not serve safety are not used. This includes, for example

- Panorama glass roofs

- Use of precious or critical materials in the interior trim (precious woods, precious metals, carbon fibres)
- Sensors and control units with precious metals or critical raw materials as well as electric motors (e.g. servomotors) with Nd magnets

m) Continuous provision of information on energy-efficient and battery-friendly use

n) The vehicle has a heat pump in order to optimize energy efficiency

This list was discussed in various groups of experts and stakeholders and subsequently thoroughly revised. The main aspects discussed as inadequate in this process were:

- Vehicle weight as a proxy criterion for (raw) material consumption: Discussions revealed the need to take into account the further qualities and aspects that accompany different materials used in vehicle construction. For example, to avoid heavier, easily procured and recycled materials like e.g. steel being substituted by lighter ones, which come with different problems, not only a material's weight should be taken into account.
  Furthermore, it was suggested that an ideal criterion for addressing vehicle downsizing should consider land use (e.g. for parking spaces) in urban areas.
- In terms of recycled content targets, expert opinions supported the hypothesis, that these only contribute to a decrease in the overall use of raw materials if the necessary secondary materials to fulfil such targets are not taken away from other sectors. For recycled-content targets to positively influence the provision of high-quality recyclates, it must be ensured that the overall quantity of secondary materials is increased and not just shifted. This can in some cases be achieved by implementing closed-loop recycled content targets. In the case of materials (e.g. most basis metals) where these premises are not proven to be met, the introduction of recycled content targets might have no or even negative effects on the overall primary material consumption. Therefore, the list of materials was shortened to include only those for which feasibility and positive impact were already determined. For those materials for which no recycled-content targets have been set, the criteria concerning overall material use/vehicle weight and size as well as longevity would still decrease overall resource consumption.
- The restriction of the use of specific materials, whether for environmental or recyclability reasons, was deemed neither feasible nor entirely effective. Firstly, creating an exhaustive list of all materials that should not be contained in a vehicle would be a massive undertaking. In addition, some of these issues are already addressed in existing legal frameworks (e.g. the "Registration, Evaluation, Authorisation and Restriction of Chemicals" Regulation on an EU level addresses materials with negative environmental impacts). Furthermore, it is impossible to consider all possible material alternatives and their potential problems. For instance, the recyclability of a specific material might be vastly improved by technological advances within a few years. In combination, evaluating specific materials used is not something that can and should be done in the context of this project, but rather it needs to be set in a more general framework.
- The omission of certain optional equipment features was the subject of controversial discussions. It is clear that an ideal, resource efficient vehicle that conforms to the principles of the circular economy should not have any unnecessary extras. However, the needfor certain equipment, especially those relevant to safety, is a personal decision. Although certain equipment features contribute to vehicle weight and overall energy consumption (see chapter 3.3), they are usually negligible compared to the essential components,

especially from a raw materials perspective. One example is servomotors with neodymium magnets, which are so small that they are insignificant compared to the drive motor. The possibility of technological progress could lead to special equipment that consumes far less material and energy. Instead of naming individual sub-optimal equipment features and thus also evaluating them, the approach chosen here is to address features by assessing the total raw material content and total energy consumption of the vehicle. For this same reason, the implementation of a heat pump was omitted as a specific criterion and instead incorporated into the criteria addressing energy efficiency. The only restriction of specific special equipment features in favour of resource conservation and energy consumption seems to come from (Lambrecht et al. 2024). Here, however, only equipment not relevant to safety **or** comfort was explicitly mentioned, so that the suggestions are limited to the use of precious woods in the interior and panoramic glass roofs (see also Table 54). Similar to heat pumps, these are implicitly included here.

- The need to provide information on energy efficiency and battery saving exceeds what can be displayed in the vehicle in real time. Therefore, such information should be made available to users separately from the vehicle. This approach has thus been moved from the criteria list to the measures.

Considering the arguments mentioned above, the proposed list of criteria for a resource efficient, circular economy compatible vehicle contains the following aspects:

1. Vehicle dimensions

As pointed out above, vehicle weight did not prove to be a reliable criterion in all cases; vehicle size and thus general raw material use is better represented by vehicle dimensions (length x width). The list of criteria contains maximum dimension values that a vehicle of a certain use case can have in a certain level of demand.

2. Raw materials index

In addition to vehicle size, it turned out that the possibility to differentiate between specific raw materials used and their production processes and supply chains is essential when evaluating a vehicle's resource efficiency. As currently there is no standardized method to differentiate between materials used and production processes, a follow-up study is recommended to research and propose how to calculate a vehicle's so-called **raw materials index**. Instead of just contributing to resource efficiency by their weight, raw materials would be evaluated by different aspects within a point system. These aspects might include:

- Quantity of the respective raw materials
- Primary/secondary raw materials
- Energy required for extraction/processing
- Criticality
- Environmental impacts

Thus, instead of just evaluating a vehicle's weight or size, it would score a certain amount of points that consists of the sum of points for all materials used. The specific material's score would be higher if its retraction or refining uses a greater amount of energy or if it is categorised as a critical raw material or has known negative environmental impacts. Recycled materials would be assign fewer or no points. The possibility to include the recyclability of a material in

the raw material index could also be investigated, although it may be difficult at the present time. As the exact design of a raw material index is outside the scope of this project, it would make sense to examine the feasibility of such an inclusion in more detail in this context.

Introducing this kind of index would coordinate and solve several of the issues mentioned above, such as lightweighting by substituting other, lighter materials with more energy-intensive supply chains, which would be prevented by this approach. It would also limit the unnecessary use of critical raw materials in special equipment items. However, introducing such an index shall take time and development. Since vehicle dimensions are already an adequate proxy criterion for overall raw material consumption, it is unproblematic to consider only them until the list of criteria can be further optimized by employing the raw materials index additionally.

3. Product carbon footprint

With the shift to electric vehicles, it is no longer sufficient to only consider a vehicles' GHG emissions during its use phase. The **product carbon footprint** (PCF) (Umweltbundesamt 2025) also takes into account GHG emissions and fossil fuel consumption from the production phase. To avoid a distorted perception of the values determined, it is particularly important that this criterion only be used in this form for comparing battery electric vehicles with each other instead of comparing different drive trains which should contain all life-cycle phases.

Although there are several ISO-standards in place as well as ongoing projects aiming for (international) harmonization of vehicle PCF's (Juliane Mundt, Marina Kemper 2024), to date there is no generally accepted standardized method in place. As soon as this has been achieved, however, it is proposed that the maximum permissible PCF for each usage profile be restricted.

4. Material-specific recycled content targets

To support the market for high-quality recyclates and thus as a driver for the development of recycling capacities, substance-specific recycled content targets are proposed for selected materials. To avoid gaps in supply to other sectors, the results from WP 2 suggest that these are only expedient in conjunction with closed-loop targets. Since the purpose of recycled content targets very much depends on the specific material, its use in different sectors and their influence on each other, only values for materials for which the necessity and usefulness have already been proven elsewhere are explicitly proposed here. For the following materials, the definition of (closed-loop) recycled content targets is considered:

- Steel: Recycled content targets for steel in vehicle construction have been intensively investigated in a recent study conducted by Öko-Institut (Sutter et al. 2025).
- Plastics: increasing the amount of recycled plastics in vehicles is one goal of the proposal for the new ELV regulation (European Commission 2023d)
- Battery materials: as battery materials such as lithium, nickel, cobalt and graphite are all resources with a critical supply chain, supporting their recycling in the EU has been an issue for some time now. Recycled-content targets are therefore set in the new EU Batteries Regulation (European Parliament, Council of the European Union 2023)
- Rare earth elements: especially following the current developments in spring 2025 (Tagesschau 2025), is has become clear that the EU's supply of rare earth elements is not currently safe. It is thus crucial that magnets contained in ELV are not shredded and lost but are instead recycled. Recycled-content targets for rare earth elements are laid out in the Critical Raw Materials Act (CRMA) (European Parliament, Council of the European Union

2024a) discussed in the proposal for an ELV Regulation, but their determination and realisation was postponed to a later date.

5. Battery capacity

A simple and largely reliable criterion for saving battery materials is the use of smaller batteries. The maximum permissible battery capacity per utilisation profile is therefore limited. In particular, this approach is more robust in the face of technological developments than, for example, restricting the use of specific materials would be. In the future, it can be expected that the demand for larger batteries will tend to decrease as charging infrastructure improves (especially with fast charging).

6. Energy consumption in use

In order to prevent energy consumption from increasing indefinitely even after the switch to electromobility with renewable energies, the maximum permissible energy consumption in use (according to the WLTP protocol) is restricted.
In addition, the use of non-safety-relevant special equipment is to be restricted via the energy requirements of auxiliary consumers. An additional maximum energy requirement is therefore defined, in which the auxiliary consumers are included in the annual average. This takes into account that heat pumps should be (and widely already are) used for temperature regulation.

7. Modular design

A modular vehicle design where certain components can easily be exchanged has a positive effect on various aspects of the definition of a resource-saving vehicle: Firstly, the time required for and therefore the cost of repairs is often unnecessarily high if defective parts are difficult to replace. This means that parts that are subject to wear and tear or are susceptible to defects must be easily replaceable within a reasonable amount of time. On the other hand, better interchangeability of certain vehicle parts would also mean that upgrades of those parts are easily possible, which can also extend the vehicle's service life. The third aspect is recyclability. Separating the various materials used in the vehicle is also made easier, if, for example, larger mono-material components can be easily removed before shredding.

A modular design in order to achieve easier dismantling has already been taken into account in the proposal for the EU's ELV regulation (European Commission 2023a). This contains a list of parts that must be dismantled by recyclers prior to shredding (Annex VII C). It also requires that the vehicle design ‘does not hinder the removal’ of these parts. In addition to the work documented here, the AutoRess project contained some ad-hoc support for ongoing legislative processes. In this context, the list proposed for Annex VII C was revised by the project team.

As high quality recycling is only one of the aspects that are to be achieved using this criterion, it is clear that it would also make sense to add parts that are generally prone to defects or subject to wear and tear to that list (see chapter 3.7). However, as it was not within the scope and timeframe of this project to analyse in detail which parts are particularly problematic in this respect, as a first approach, the list proposed to the European commission in context of the ELV regulation was adapted here. However, as the criteria here, in contrast to the ELV regulation, are based specifically on design, the term ‘does not hinder removal’ should be further specified here. It is therefore required that the parts on the list in Annex V of the proposal for the ELV regulation can be removed or replaced by third parties with freely available tools and a reasonable amount of time (meaning that the repair should be economically reasonable for both repair shop and user).

Only one addition to the list was made, as it was quite obvious: When it comes to reparability, it is not only the exchangeability of the traction battery that is important, as is the case for recycling, but also the reparability of the battery itself (see chapter 3.6). For this reason, it was added that not only the entire battery but also individual cells/modules should be replaceable.

The specific parts that are demanded to be exchangeable in (European Commission 2023a) Annex VII C are

- Electric vehicle batteries including their battery management systems, onboard chargers for EVs, casing or housing if present ; the battery in itself is constructed in a modular way such that individual modules are also interchangeable;
- E-drive motors, including their casing, generators or alternators and cooling fan motors if present, control units, wiring and other parts, components and materials directly fastened or attached to E-drive motors;
- SLI (Starting, Lighting, Ignition) batteries and portable batteries as defined in Article 3, point (12) of (European Parliament, Council of the European Union 2023);
- Combustion engine blocks with generators, starter alternators, radiator/cooling fan motors and associated devices;
- Catalytic converters;
- Gear boxes;
- Windshields, rear and side windows made of glass, rooftop glass installations;
- Rims;
- Rubber tyres;
- Directly accessible parts of the infotainment system, including sound, navigation (including radar or lidar control units and sensors if present), multimedia controllers, including displays of surface area greater than 100-squared centimetres and further electronic devices as described in item 19 of Part C embedded in dashboards including airbag control units;
- Head-and tail lights (front and rear), including their actuators;
- Main wire harnesses, internal and external charging cables if present;
- Crash Management System, including bumper cover, bumper beam, crash boxes Fluid containers;
- Heat exchangers;
- Any other mono-material components, heavier than 10 kg;
- 19. Electrical and electronic components:
    - inverters and DC-DC converters above 24V of the electric vehicles;
    - printed circuit boards with a surface area, larger than 10 cm2;
    - photo-voltaic (PV) panels with a surface area, larger than 0.2 m2;
    - control modules and valve boxes for the automatic transmission.

- Oxygen, radar and lidar sensors if present.

8. Due diligence obligations in the supply chains

In addition to the above-mentioned requirements to reduce the amount of resources used in vehicle construction, it is also important that their extraction and further processing are subject to certain standards. Even if this is not the explicit focus of the project, the social conditions in the extraction of raw materials in non-EU countries, for example, should also be taken into account. There are already proposals for supply chain guidelines at federal and European level (European Parliament, Council of the European Union 2024c). As vehicles often have complicated and unclear supply chains due to the large number of parts and materials, only indirect suppliers are currently considered in the current proposals. in this case in particular, however, it is actually all the more important that these are monitored along the entire route and that due diligence is carried out, so that compliance with the due diligence standards according to the EU directive is required for direct **and** indirect suppliers.

9. Provision of spare parts and software updates

In order to support repairability and longevity, the provision of spare parts and software updates is guaranteed for the entire lifespan of the vehicle.

10. Lifetime warranty for traction batteries

As the (perceived) service life of the traction battery is still one of the biggest barriers to the purchase of BEVs, there should be a guarantee on the service life of the battery for a vehicle that is as resource-efficient as possible. According to the current state of the art, this should roughly correspond to the service life of the vehicle (Hackmann et al. 2024).

Table 57 contains a compilation of all proposed criteria and their contribution to the aspects defining a resource-efficient vehicle as proposed in chapter 4.1.

Table 57: Proposed criteria for a resource-efficient, circular economy-compatible vehicle and their contribution to the different aspects of its definition

Demand of (primary) resources	GHG emissions	Longevity	Recyclability	Energy consumption	Environmental impact
Raw materials index	Product Carbon Footprin	Modular design	Modular design	Product Carbon Footprint	Due diligence obligations
Vehicle dimensions	Recycled content targets	Lifetime guarantee for batteries	Raw materials index	Energy demand in use	Raw materials index
Battery capacity	Vehicle dimensions	Provision of spare parts and software updates	Recycled content targets	Vehicle size	Vehicle dimension
Recycled content					

Source: own considerations

4.5 Determination of specific values

In order to determine specific target values for the chosen criteria, there are, again, several issues that have to be taken into account. First, what are the objectives? The top priority in this context is saving resources. There are however no specific targets set for this goal. A target value for GHG emissions on the other hand has already been implemented, with the aim of achieving GHG neutrality by 2045. This should be taken into account.

Another important point is technological feasibility. For example, vehicle size and weight are largely limited by safety requirements for vehicle class M1. It is difficult to the limit of impossible to predict the potential of technical developments in terms of energy consumption in the near future.

The third point is the market. Despite all the idealism, even a resource-saving vehicle must be economically viable for the manufacturer and attractive for the buyer in order to establish itself on the market.

For those reasons it has been determined, that the criteria for resource-efficient vehicles in the near future have to be oriented on models that are being built right now, especially for criteria where extensive feasibility studies have not been conducted yet. The exact timeframes in which the respective criteria will come into effect depends on the associated measures. A classification of the time frame can be found in the characterization of the measures in chapter 1.1

In order to set specific values, the data sheets of about 400 models of BEV currently available on the German market have been analysed (ADAC o.J.; EV database 2024), see annex A.4. Table 58 shows the value range of different parameters by vehicle segment of the models analysed. Vehicle width is always referring to the width excluding side mirrors.

Table 58: Range of the values of technical data for electric vehicles on the market in Germany in 2025

Segment	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Dimensions (length x width)	Heat pump [yes / optional / no]
L7E/L6E	4.1 - 18.0 kWh	51 - 228 km	58 -123 Wh/km	400 - 743 kg	1704 - 3074 x 1107 - 1500 mm	Information not contained in data
A (mini)	26.8 - 49.0 kWh	230 - 370 km	109 - 136 Wh/km	1020 - 1418 kg	3620 - 3825 x 1610 - 1625 mm	0 / 2 / 3
B (small)	23.8 - 81.4 kWh	190 - 605 km	112 - 160 Wh/km	1255 - 2035 kg	3631 - 4432 x 1683 - 1836 mm	28 / 12 / 15
C (medium)	54.0 - 91.0 kWh	200 - 701 km	119 - 209 Wh/km	1536 - 2300 kg	4200 - 4805 x 1770 - 1940 mm	64 / 42 / 3
D (large)	53.0 - 101.0 kWh	420 - 750 km	104 - 196 Wh/km	1804 - 2595 kg	4606 - 4871 x 1849 - 2011 mm	48 / 9 / 6
E (executive)	75.0 - 115.0 kWh	406 - 756 km	121 - 205 Wh/km	2095 - 2705 kg	4790 - 5060 x 1862 - 2008 mm	42 / 12 / 0
F (luxury)	75.0 - 125.0 kWh	390 - 839 km	123 - 245 Wh/km	2150 - 3085 kg	4624 - 5453 x 1925 - 2080 mm	62 / 0 / 0

Segment	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Dimensions (length x width)	Heat pump [yes / optional / no]
M (multi-purpose)	48.0 - 100.0 kWh	220 - 487 km	145 - 254 Wh/km	1811 - 2788 kg	4983 - 5333 x 1920 - 1920 mm	33 / 6 / 0

Source: (ADAC o.J.; EV database 2024), see annex A.4

Target values for maximal vehicle dimensions and energy consumption (WLTP) were each based on the smallest vehicles (by segment), that fulfil the minimal requirements listed in Table 56. As there is no Segment that directly corresponds to user profile City(2), the target values for all vehicles licensed in the future were based on A(mini) vehicles. As those contained in the data sheet exclusively can transport 4 passengers, however, it is assumed, that with a broadened range of models it will be possible to adapt these. For the more ambitious scenarios, L7E and L6E vehicles were additionally considered for the calculation. Target values for user profile Family(5) were based on the C(large) segment, as these are the smallest vehicles that fulfil minimal requirements. Segments E(executive) and F(luxury) were not taken into consideration as the contained vehicles are much larger without gaining any additional function demanded for the user profile. User profile Transport(9) corresponds to segment M(multi-purpose) as the choice of models in this model is still very limited at the moment, the target values have been interpreted somewhat more generously here.

In order to set ambitious yet achievable target values, the requirement is, for all vehicles registered in the future to be better than the current average. Thus, taking into account all vehicles of the corresponding segments that fulfil the minimal requirements, the span between worst case and best case was calculated and the target value set to the average between them. For public procurement, the target values were set to be amongst the better 10% of the current models calculated accordingly, for a potential eco label the best cases currently available were taken into consideration.

The maximal battery capacity for each case was calculated from the required range and the target values for maximal energy consumption.

For all other criteria, target values have been set employing the results of previously conducted studies, which are listed in Table 59.

Table 59: Sources for target values

Criterion	Source for target values
Dimensions	Analysis of current models
Raw materials index	Further investigation necessary
Product carbon footprint	Further investigation necessary
Recycled content targets	Steel: (Sutter et al. 2025) Plastics: (European Commission 2023a) Battery materials: (European Parliament, Council of the European Union 2023) Permanent magnets: (European Commission 2023a)
Energy consumption	Analysis of current models; (Helms et al. 2023)

Criterion	Source for target values
Battery capacity	Calculation from use case minimal range requirements and energy consumption
Modular design	(European Commission 2023a)
Due diligence in supply chains	(European Parliament, Council of the European Union 2024c)
Spare parts and software updates	Own consideration
Lifetime warranty for traction batteries	(Hackmann et al. 2024)

Source: see table entries

For the recycled content targets for steel and plastics, the varyingly ambitious suggestions from (Sutter et al. 2025) and (European Commission 2023a), respectively, have been adapted. As there are only two suggestions for plastics, and the feasibility of higher recycled plastic targets on a large scale could not be proven beyond doubt, the values for green public procurement and eco-labelling are the same. For battery materials, the overall expert opinion from the workshops is that the values set in the EU battery regulation (European Parliament, Council of the European Union 2023) are already very ambitious and that the feasibility of higher targets even for part of the fleet is by no means guaranteed, so that these were set at the same level for all three ambition levels. For permanent magnets with rare earth elements, the proposal for the new EU ELV regulation (European Commission 2023a) states the importance of improving the recycling standards and building capacities, but refers the determination of possible recycled content targes to a later point in time. As there are to date no viable feasibility studies on this matter, sensible target values could not be set here, so that at least the disclosure of recycled content is demanded for all ambition levels. As mentioned above, the vehicles‘ energy consumption in use has been oriented on WLTP values for the current models in each use case. The WLTP protocol however does not take into account optional auxiliary consumers like air conditioning or entertainment systems. Thus, an additional value has been set for each use case, where the average energy consumption of the most common auxiliary consumers according to (Helms et al. 2023) have been taken into account. The result is a maximal value for energy consumption that is allowed including all auxiliary consumers.

For the determination of realistic target values for battery lifetime guarantees, actual current battery life cycles have been taken as a basis (Hackmann et al. 2024). These show that even now, the average traction battery lasts at least as long as the average vehicle, so that battery warranties are demanded to correspond to average vehicle lifetimes. In the baseline of the AutoRess model for BEVs it is assumed that the average lifetime is 15.8 years based on the ELV-assessment (European Commission 2023c). As the source indicates, that even today batteries do last longer than that (for average mileages see chapter 3.1.2.1) and extending vehicle life spans is one of the main objectives here, the battery lifespan requirements are set to at least 80% of capacity at 300.000 km or 20 years.

The compilation of all criteria and their respective target values for future battery electric cars in different use cases and ambition levels is contained in Table 60.

Table 60: Complete list of criteria and target values proposed for future battery electric cars in different use cases and ambition levels

	Ambition level	Eco-labelling			Public procurement			Basic		
	Use case30	City(2)	Family(5)	Transport(9)	City(2)	Family(5)	Transport(9)	City(2)	Family(5)	Transport(9)
Raw material index		Further investigation required			Further investigation required			Further investigation required		
Vehicle size length/width [mm]		2390 x 1320	4500 x 1850	4980 x 1920	2740 x 1480	4650 x 1900	5000 x 1980	3700 x 1650	4740 x 1930	5200 x 2200
Product Carbon Footprint		Further investigation required			Further investigation required			Further investigation required		
Recycled content target	Steel	50% post consumer, thereof 30% closed-loop			30% post-consumer, thereof 20% closed loop			25% post-consumer, thereof 15% closed-loop		
	Plastics	30% post consumer, thereof 25% closed-loop			30% post-consumer, thereof 25% closed loop			25% post-consumer, thereof 25% closed loop		
	Battery materials31	Cobalt: 16% recycled content by 2031, 26% by 2036. Lithium: 6% recycled content by 2031, 12% by 2036. Nickel: 6% recycled content by 2031, 15% by 2036.			Cobalt: 16% recycled content by 2031, 26% by 2036. Lithium: 6% recycled content by 2031, 12% by 2036. Nickel: 6% recycled content by 2031, 15% by 2036.			Cobalt: 16% recycled content by 2031, 26% by 2036. Lithium: 6% recycled content by 2031, 12% by 2036. Nickel: 6% recycled content by 2031, 15% by 2036.		

[30] Use cases see Table 56

[31] As discussed in the previous paragraph, due to the questionable feasibility of potential higher recycled content targets for battery materials, there is no differentiation in values between ambition levels.

	Ambition level	Eco-labelling			Public procurement			Basic		
	Rare earths	Disclosure of the quantity of recycled material used, compliance with targets set in context of CRMA in the future			Disclosure of the quantity of recycled material used, compliance with targets set in context of CRMA in the future			Disclosure of the quantity of recycled material used, compliance with targets set in context of CRMA in the future		
Battery capacity [kWh]		12	65	95	18	70	100	22	88	130
Energy demand [Wh/km]		60	130	190	90	140	200	110	175	260
Energy demand including auxiliary consumers [Wh/km]		70	150	220	105	165	230	130	205	300
Modular design		List of parts that can be removed using conventional tools in a reasonable time span (see p. 274)			List of parts that can be removed using conventional tools in a reasonable time span (see p. 274)			List of parts that can be removed using conventional tools in a reasonable time span (see p. 274)		
Due diligence obligations in the supply chains		Due diligence obligations in accordance with the Supply Chain Directive for direct and indirect suppliers			Due diligence obligations in accordance with the Supply Chain Directive for direct and indirect suppliers			Due diligence obligations in accordance with the Supply Chain Directive		
Provision of spare parts and software updates		20 years			20 years			20 years		
Battery lifetime guarantee		80% of capacity after 300,000 km or 20 years			70% of capacity after 300,000 km or 20 years			60% of capacity after 300,000 km or 20 years		

4.6 Exemplary application of the criteria

The criteria should be applied to some current and future vehicle models as examples to check feasibility. It should be noted again here that the development of the criteria focussed on battery electric vehicles exclusively due to the already established ban on combustion engines from 2035. Thus, it is only sensible to apply them to existing and future battery electric vehicles.

Current models

The key criteria vehicle size, battery capacity and energy consumption are already easy to determine and verify today and are provided by the manufacturer for every vehicle on the market. User profile City(2) (2 seats for journeys in an urban environment) is nearly unrepresented within vehicle class M1. Almost all vehicles on the market (see A.4) have 4 seats and are therefore larger than the maximum values proposed in Table 60. In vehicle classes L7E and L6E (electric light mobility), however, it is clear that further space can be saved by dispensing with unused seating and transport capacity. The models analysed here all meet the minimum size requirements for usage profile 1. Compliance with the criteria for battery size and energy consumption is similar. Here too, however, it can be assumed that a reduction in vehicle size makes it technically possible to reduce energy consumption and thus battery size, and in this case there is mainly a lack of options on market to date. User profile Family(5) is based on the D(large) vehicle class according to the EU categorization scheme. Of these, around 70% already fulfil the criteria for battery capacity and energy consumption, while only around 30% meet the minimal requirements for maximum size. In addition, around 40% of newly registered cars in Germany are 'SUV's (Figure 3), which are not included in the value calculation and are mostly larger than the target values. In user profile Transport(9), the range of all-electric vehicle models on offer has so far been very limited, which is why the requirements are initially less strict and all of the models on the market fulfil the minimum requirements.
The challenge here will be to achieve sufficiency in the requirements for vehicle and battery sizes and to support the demand for small, lightweight vehicles. This topic will be addressed again in the measures. Replacing the vehicle weight as a criterion with the dimensions has the advantage that BEV's, which are fundamentally somewhat heavier due to the batteries, are not at disadvantage here. No statement can be made for the raw material index due to the elaboration still to be carried out (see chapter 0).

Table 61: Overview of proposed criteria, their status of fulfilment of ambition level „Basic" in electric vehicles available on market in 2025 and measurability/verification

Criterion	Target Value for ambition level „Basic" (user profile Family(5))	Measurability[32]	Status fulfilment of Basic requirements 2025	Verification
Dimensions	4740 x 1930 mm	Simple	~30% of vehicles analysed in vehicle class (D(large) (see A.4), larger classes not	Vehicle license

[32] Measurability was categorized as follows: **Simple**: can easily be verified by authorities; **Medium**: is reasonably easy to determine and could be verified by authorities; **Challenging:** Standards for detemining and veryfiying respective values will have tob e set carefully.

Criterion	Target Value for ambition level „Basic“ (user profile Family(5))	Measurability[32]	Status fulfilment of Basic requirements 2025	Verification
			taken into consideration for user profile	
Raw material index	-	Challenging	-	Manufacturer information following corresponding standards (to be set)
Product Carbon Footprint	-	Medium	-	Manufacturer information following corresponding standards (to be set)
Recycled content target	Steel: 25% post-consumer, thereof 15% closed-loop	Medium	Usually <30% pre- and post-consumer (see chapter 3.9.2)	Manufacturer information following corresponding standards (European Commission 2023a)
	Plastics: 25% post-consumer, thereof 25% closed loop	Medium	< 10% pre- and post-consumer (see chapter 3.10.2)	Manufacturer information following corresponding standards (European Commission 2023a)
	Cobalt: 16% / 26% Lithium: 6% / 12% Nickel: 6% / 15%	Medium	Negligible (see chapter 3.8.2)	Manufacturer information following corresponding standards (European Parliament, Council of the European Union 2023)
Battery capacity [kWh]	88	Simple	~70% of vehicles analysed in vehicle class (D(large) (see A.4)	Battery pass according to (European Parliament, Council of the

Criterion	Target Value for ambition level „Basic“ (user profile Family(5))	Measurability[32]	Status fulfilment of Basic requirements 2025	Verification
				European Union 2023)
Energy demand [Wh/km]	175	Simple	~70% of vehicles analysed in vehicle class (D(large) (see A.4)	Manufacturer information; WLTP protocol
Energy demand including auxiliary consumers [Wh/km]	205	Medium	Uncertain	Manufacturer information following corresponding standards (to be set)
Modular design	List of exchangeable parts	Challenging	Uncertain	Manufacturer information following corresponding standards (European Commission 2023a)
Due diligence obligations in the supply chains	According to supply chain directive (European Commission 2023a)	Challenging	Uncertain	Manufacturer information following corresponding standards
Provision of spare parts and software updates	20 years	Medium		
Battery lifetime guarantee	60% of capacity after 300,000 km or 20 years	Simple	Fulfilled by most batteries tested (Hackmann et al. 2024) , but most manufacturers grant lower guarantee	Manufacturer guarantee

Source: own considerations

For greenhouse gas emissions, it is important that the production phase is included in the calculation of the product carbon footprint. As shown in (Biemann et al. 2024), combustion vehicles perform better in the production phase than battery electric vehicles. However, this is reversed in the utilisation phase, so that the negative environmental impacts of combustion vehicles are correctly reflected here.

The required use of recycled materials has not even come close to being met in any known vehicle to date. This emphasises the importance of recycled content targets as a driver for high-quality vehicle recycling.

The requirements for modular design have also only been met in places at most. In the case of traction batteries in particular, there are currently a number of models on the market in which cell-to-pack approaches have been implemented (Köllner 2024) and it is not possible to replace individual modules.

The requirements of the supply chain due diligence have also not yet been met. Many manufacturers are strongly opposed to the planned requirements, arguing that the supply chains are too complicated and compliance with tracking and tracing is too costly, especially for medium-sized companies. The provision of spare parts and software updates as well as battery life do not appear to be acute problems at the moment, but standardisation through minimum requirements still seems to be the safe option

Probable future models (without additional measures)

As indicated in Chapter 2 (see Figure 3), the trend continues towards larger, heavier vehicles with longer ranges, i.e. larger batteries. Compliance with the key criteria for resource conservation will therefore not improve in the future if no measures are taken.

In terms of CO_2 emissions, the pure emissions of the use phase are often still taken into account (e.g. in the CO_2 fleet limits), which makes sense in order to avoid favouring combustion vehicles, but causes other problems in the long term. After the switch to battery electric drives, the emissions in the production phase will also be relevant, which have often not been taken into account to date.

There are already activities by individual manufacturers regarding the use of recycled materials even without corresponding specifications (see e.g. (BMW Group 2024; Mercedes Benz Group 2024; Volkswagen Group 2024)), but these mostly relate to interior fittings such as textiles and rarely to body parts. Here too, compliance with the criteria is therefore unlikely in the near future without additional measures.
Repairability is also hardly reflected in the sustainability strategies of car manufacturers In particular, cell-to-chassis approaches for batteries are a development that would make future compliance with the criteria developed here even more difficult.
Although some manufacturers are endeavouring to comply with due diligence in a limited form, the strong resistance to the corresponding directive shows that this is not compatible with the strictness required here.
Meeting the criteria for the provision of software updates and replacement parts as well as the lifetime warranty on the battery should not pose any technical difficulties, but standardisation is nevertheless an advantage for the user.

Future models (with additional measures)

In order to ensure that the proposed criteria are met by models brought onto the market in the future, some organisational measures must first be taken by the legislator and the manufacturer. Standardised determination and verification procedures must be developed and defined for the raw material index, product carbon footprint and recycled content targets (where these do not yet exist).
In addition, demand is extremely important for future vehicles to comply with the criteria. In particular for the criteria that are based on the reasonableness of the purchase decision, such as vehicle size, appropriate incentives must be set in the measures to make these attractive or the larger alternatives less attractive. For the advanced level of ambition in public procurement, the

demand would be inherent if it were enshrined in the relevant legislation. Here too, however, it is essential that demand is determined as closely as possible to the minimum requirement. With regard to an eco-label to be awarded, the question of the feasibility of complying with the criteria is also less relevant, as technological feasibility has already been taken into account in the development. Here, too, it is much more important to make a vehicle with a corresponding label attractive for both manufacturers and customers.

4.7 Implementation of criteria

Finally, the possibilities of implementation of the criteria for the various ambition levels will be discussed.

4.7.1 Minimal ambition level

The minimal ambition level was supposed to contain criteria , that every vehicle registered in the future should comply with. Since the list of criteria now contains two different types, it is sensible to differentiate here. Among the factors that vary for different use cases, the greatest lever for saving resources and greenhouse gases is the purchase decision based on minimum requirements. However, since this cannot be excessively regulated, an incentive must be created for the sale and/or purchase of a vehicle that uses as little resource as possible.

On the producer side, fee modulation could be applied here, as already set out in the EU Waste Framework Directive (European Parliament, Council of the European Union 2008) as well as the proposal for the new European ELV-Regulation (European Commission 2023a). Here, the financial contributions of producers to a producer responsibility organisation are staggered depending on which sustainability criteria the corresponding product fulfils. Vehicle and battery size are particularly suitable criteria for implementation. On the one hand, they are among the biggest identified levers, but on the other hand, they are difficult to define across the board due to the different demand situations. However, they are well suited to ensuring smaller, resource-saving cars on the supply side. The options for encouraging private customers to buy resource-efficient vehicles are described in the measures in chapter 4 in more detail.

Other criteria, which apply across use cases in the same form, especially all recycled content related ones, are better suited to be implemented as a minimal requirement for all cars put on market in the future.

The establishment of high-quality recycling capacities and the further development of recycling can only be driven forward by ensuring that recycled content targets are met across the board. These should therefore be integrated directly into type approval or, for example, the revision of fleet limits following the switch to electric vehicles.
The criteria for durability and reparability should also be minimum requirements for every vehicle built in the future.

For raw materials index and Product Carbon Footprint, a mix of both approaches would even be possible. In order to support the goal of greenhouse gas neutrality, it would certainly be necessary to set a fixed upper limit for the total emissions of each future vehicle. The maximum use of resources per vehicle should also be subject to a fixed upper limit in order to prevent the unnecessary consumption of resources. In addition, however, it would also be conceivable that the supply and purchase of models that exceed this limit could be further incentivised through fee modulation or, for example, tax or insurance benefits.

4.7.2 Public procurement

Ideally, the criteria for public procurement proposed in the previous chapter could in the near future serve as a minimum standard for all vehicles procured by public institutions. There are already requirements and criteria for the vehicles procured on a German Federal as well as EU level (Bundestag, Bundesrat 2021; European Commission 2021b). So far, however, these relate exclusively to tailpipe emissions. In the future, it would also be conceivable to extend these legal requirements to other aspects. The German Circular Economy Law (Bundestag, Bundesrat 2012) § 45 states, that public institutions should preferentially procure services and products, that were manufactured in (amongst other factors) a resource- and energy-efficient way and stand out due to durability, repairability, recyclability and reusability. The criteria proposed in Table 60 for ambition level public procurement would thus be a good fit for an elaboration of § 45 concerning the public procurement of vehicles. An essential aspect in order to apply the criteria concerning vehicle and battery size is the needs assessment. This issue has already been tackled elsewhere:

A proposal for an extension of guidelines for the public procurement of vehicles by further environmental factors was made in (Lambrecht et al. 2024). In the project 'Entwicklung von Instrumenten für die umweltverträgliche Beschaffung von Pkw durch öffentliche Stellen', which was completed at the end of 2024, in addition to emissions during use, further criteria for the environmental effectiveness of public vehicle procurement were proposed: These include upper limits for total energy consumption, a minimum battery guarantee and noise emission limits (for an overview also see Table 54). Further aspects such as information on energy-saving use, the use of a heat pump and the omission of certain special features are listed as award criteria.
As part of the project, a detailed online tool was created (ifeu 2024) with which the respective procurer can carry out a needs assessment according to various steps before the tender and thus select the most environmentally friendly vehicle that fulfils the purpose.

In order to include the criteria proposed for public procurement here, the assessment of needs is also an important step, so that it seems sensible to pursue this approach in addition to the anchoring of minimum criteria in a legal context for all use cases in the present case and, if necessary, to combine the results and criteria from both projects.

There are different options for the legal framing of the criteria concerning public procurement: Green public procurement in Germany in general is addressed in the administrative regulations on the procurement of climate-friendly services (Bundesministerium für Wirtschaft und Klimaschutz 2021). However, specifications for vehicles are explicitly referred to in the law and administrative regulation on the procurement of clean vehicles(Bundesministerium für Wirtschaft und Klimaschutz 2022; Bundestag, Bundesrat 2021). Although these do not contain any resource-saving aspects, these laws seem like a logical place to specify such aspects on a federal level. At the EU level, the corresponding anchor legislation is the Revised Clean Vehicles Directive (European Parliament, Council of the European Union 2019) and the Green Public Procurement Criteria for Road Transport (European Commission 2021b).

4.7.3 Eco-labelling

The information in chapter 0 should additionally serve as a basis for potential eco-labelling for passenger cars. The orientation towards the best cases of the vehicle fleet available today chosen in this context ensures on the one hand an ambitious level of criteria, but on the other hand also the feasibility, so that a detailed and precise proposal for criteria for a possible labelling scheme is hereby available.
The 'Blauer Engel' eco-label awarded by the German Federal Environment Agency and the

Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN) is of particular interest in this context. So far, there is a label for buses and one for car sharing services (Umweltbundesamt, Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit 2018a; b), but none explicitly for the purchase of cars.
As the awarding of the label is again linked to a detailed selection process for the relevant criteria with the help of a jury, it is not possible to make any predictions about the explicit adoption of all the criteria proposed here. The principles for awarding the label, however, align very well with those of this project (Umweltbundesamt, Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit 2025) :

- Resource-saving production (water, energy)
- Preferential consideration of recycled materials, e.g. for paper and plastics
- Sustainable production of raw materials
- Avoidance of harmful substances in the product
- Reduced emissions of harmful substances into soil, air, water and indoor air
- Reduction of noise and electromagnetic radiation
- Efficient use, e.g. energy- or water-saving products
- Longevity, reparability and recyclability
- Usability
- Take-back systems and services with shared use, e.g. car sharing

Thus, the criteria proposed for eco-labelling presented in chapter 0 , Table 60, column “eco-labelling” seem to be a sensible initial proposal for the potential award of a blue angel for passenger cars.

5 Development of instruments and measures

In this chapter, possible measures and instruments are described that are necessary to implement the targets in chapter4. The development up to 2030 and the potential after 2030 are taken into account for the time frame. Instruments and measures can be, for example, economic incentive structures, regulatory and political requirements, information obligations, promotion of research and development, voluntary measures in the industry, etc.

- Step 1: The first step is to screen possible measures and instruments, those that have already been implemented, defined or are foreseeable and those that have already been designed or developed by various actors or stakeholders, see chapter 5.1.
- Step 2: In an evaluation, the measures and instruments are classified and evaluated according to the specific criteria, see chapter 1.1.
- Step 3: The measures and instruments are prioritized based on the results of the evaluation, see chapter 0.

5.1 Description of potential measures and instruments to be analysed

The following tables show the possible measures and instruments that are analysed and evaluated. Sources for these potential measures and instruments were:

- measures and instruments from the proposal of the European Commission on the new ELV directive (European Commission 2023)
- measures and instruments from the Impact Assessment on the ELV directive (European Commission 2023c)
- measures and instruments from the Impact Assessment supporting study (Baron et al. 2023)
- measures and instruments from the new EU battery regulation (European Parliament, Council of the European Union 2023)
- measures and instruments that have already been designed or developed by various actors or stakeholders (desktop research)
- measures and instruments that have been discussed with experts in AutoRess in interviews and workshops

This subchapter first describes the measures and instruments according to life cycle phases

5.1.1 Overarching measures and instruments

Table 62 gives an overview on potential overarching measures and instruments with a description and comments on current status

Table 62: Description of potential overarching measures and instruments

No.	Measure / Instrument	Description	Status
O1	Bonus-malus system in tax system based on vehicle size	In a bonus-malus system, buyers of a smaller car receive a bonus, whereas a malus must be paid when buying a car with higher dimensions, which also increases with increasing size. One-off payments when buying a car have a greater effect than annual vehicle taxes.	
O2	Introduction of funding instruments	Funding instruments should support research and development for, e.g. graphite recycling, new battery cell technologies and new recycling sorting technologies, and the upscaling of innovations from laboratory scale to pilot plants to (large-scale) industrial solutions. It should provide long term funding outlooks for industry and research community. Other focus of the funding instruments could be dedicated for activities that aiming cooperation between manufacturers and recyclers and for other purposes.	Exist on the EU level for instance Eureka (co-programmed partnership for Advanced Materials, (M-ERA.NET 2025), (eureka 2025). In Germany there is Technologietransfer-Programm Leichtbau (BMWK 2024) with limited funds.
O3	Raise political awareness of remanufacturing	Educating political advocates about remanufacturing can raise the industry's profile and showcase its significant contribution to a circular economy by actors of remanufacturing process, outcomes of scientific projects (e.g. policy papers).	
O5	Raw materials index	Development of a raw material index (see decription in chapter 0). If such an index is methodically calibrated, the next step is to set a limit on the maximum score.	To be developed
O1	Bonus-malus system in tax system based on vehicle size	In a bonus-malus system, buyers of a smaller car receive a bonus, whereas a malus must be paid when buying a car with higher dimensions, which also increases with increasing size. One-off payments when buying a car have a greater effect than annual vehicle taxes.	

No.	Measure / Instrument	Description	Status
O1	Bonus-malus-system in tax system based on CO_2 emissions (Kreye et al. 2024), (Blanck et al. 2020)	In a bonus-malus system (Blanck, Zimmer 2021), buyers of a particularly low-CO_2 emission car receive a bonus (such as the current purchase premium for electric cars), whereas a malus must be paid when buying a car with higher CO_2 emissions, which also increases with CO_2 emissions. One-off payments when buying a car have a greater effect than annual vehicle taxes.	Already being implemented in selected countries in EU however in diverse approach: Germany, France (Bensalah 2025), the Netherlands, Portugal, Sweden.
O2	Bonus-malus system in tax system based on vehicle weight	In a bonus-malus system (Blanck, Zimmer 2021), buyers of a low weightedweighted car receive a bonus, whereas a malus must be paid when buying a car with higher weight, which also increases with increasing weight. One-off payments when buying a car have a greater effect than annual vehicle taxes.	Already being implemented in France. (Bensalah 2025)
O3	Bonus-malus system in tax system based on vehicle size	In a bonus-malus system, buyers of a smaller car receive a bonus, whereas a malus must be paid when buying a car with higher dimensions, which also increases with increasing size. One-off payments when buying a car have a greater effect than annual vehicle taxes.	
O4	Introduction of funding instruments	Funding instruments should support research and development for, e.g. more sustainable technologies. This measure could scale up innovations all the way to industrial solutions. It should provide long term funding outlooks for industry and research community. Other focus of the funding instruments could be dedicated for activities that aiming cooperation between manufacturers and recyclers and for other purposes.	Exist on the EU level for instance Eureka (co-programmed partnership for Advanced Materials, (M-ERA.NET 2025), (eureka 2025). In Germany there is Technologietransfer-Programm Leichtbau (TTP LB) programme (BMWK 2024) with limited funds.
	Introduction of EPR scheme to finance proper ELV treatment operations	Ensure that producers are made financially responsible for vehicles when they become waste, to ensure proper financing for mandatory ELV treatment operations and incentivise recyclers to improve quality.	Part of ELV Regulation Proposal
O5	Introduction of OEM voluntary pledges campaign to increase circularity	To support circularity, the future legislation of ELVs shall refer to activities that MS are encouraged to embark on as a means (Good Participatory Practices) of supporting the circularity of vehicles, including the following: • Introduce incentives or financial benefits (e.g., reduction of VAT rate on labour costs for employees or reduction of taxes) for products that contain remanufactured products or for remanufacturing operations,	

No.	Measure / Instrument	Description	Status
		• Introduce criteria into green public procurementprocurement guidelines that promote the use of reused and remanufactured components, for example: • In relation to vehicle services: criteria that favour insurance policies of vehicles that commit to the use of reused/remanufactured parts when available, • In relation to the purchase of vehicles: criteria that favour of vehicles assembled with a minimum share of remanufactured parts (i.e., remanufactured vehicles).	
	Voluntary activities of OEMs and supply chain to promote application of reused/ remanufactured components	EU product classification, which would distinguish between remanufactured, used and newly manufactured components could help increase the awareness of consumers to the applicability of such components and subsequently will potentially increase the demand for partly or fully reused or remanufactured components. The vehicle production sector should be encouraged to develop a clear classification of such components into the groups, based on the identity of the manufacturer (e.g., OEM, third party), process specifications (e.g., new manufacture, cleaning, testing, repairs) and the quality specification (e.g., warranty). The classification could be used on marketed components through the labelling of products, also distinguishing between components manufactured by authorised operators and those marketed by illegal facilities. Such a scheme could distinguish between: • newly manufactured OEM components, • newly manufactured supplier (not OEM) components, • remanufactured components, • reused components processed by an ATF.	
O6	Raise political awareness of remanufacturing	Educating political advocates about remanufacturing can raise the industry's profile and showcase its significant contribution to a circular economy by actors of remanufacturing process, outcomes of scientific projects (e.g. policy papers).	
O7	Raise awareness in society of the benefits of	Raise awareness in society of the benefits of repaired/remanufactured spare parts in order to increase demand for such parts.	

No.	Measure / Instrument	Description	Status
	repaired/remanufactured spare parts		
O8	Raw materials index	Development of a raw material index (see decription in chapter 0). If such an index is methodically calibrated, the next step is to set a limit on the maximum score.	To be developed

Source: own table Oeko-Institut

Table 63 shows which aspects of concern the overarching measures and instruments address.

Table 63: Aspects of concern of overarching measures and instruments

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
O1	Bonus-malus-system in tax system based on CO_2 emissions		high			
O2	Bonus-malus system in tax system based on vehicle weight					medium
O3	Bonus-malus system in tax system based on vehicle size	high	high			high
O4	Introduction of funding instruments	low	low	low	low	low
	Introduction of EPR scheme to finance proper ELV treatment operations	x			x	
O5	Introduction of OEM voluntary pledges campaign to increase circularity	low	low		low	

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
	Voluntary activities of OEMs and supply chain to promote application of reused/ remanufactured components	x	x	x	x	
O6	Raise political awareness of remanufacturing	low	low	low	low	
O7	Raise awareness in society of the benefits of repaired/remanufactured spare parts	low	low	low	low	
O8	Raw materials index	high				

Source: own table Oeko-Institut

5.1.2 Measures and instruments in vehicle design

Table 64 gives an overview on potential measures and instruments in vehicle design with a description and comments on current status.

Table 64: Description of potential measures and instruments in vehicle design

No.	Measure / Instrument	Description	Status
D1	Set minimum reusability, recyclability and recoverability targets	Article 4 of the ELV regulation proposal lays down minimum requirements on the reusability, recyclability and recoverability of vehicle types, specifying the rates to be achieved by each type. It empowers the Commission to adopt implementing acts setting out the methodology for calculating and verifying these rates.	Part of ELV Regulation Proposal
D2	Obligation on OEMs to provide detailed instructions on how to replace and remove parts and components together with the obligation that the design of new vehicles shall allow easy removal	Article 7 focuses on the physical design of the vehicle to ensure that key parts and components can be easily removed, which is crucial for repair, reuse, remanufacturing, and high-quality recycling. Article 11 complements Article 7 by mandating that manufacturers provide the detailed instructions necessary to perform the removal and replacement of parts, components, and materials.	Part of ELV Regulation Proposal

No.	Measure / Instrument	Description	Status
	and replacement for certain parts and components		
D3	Obligation to provide information on battery chemistry		Already implemented in Battery Regulation.
D4	Introduction of Circularity Vehicle Pass	The information of the percentages of recycled materials achieved, would also be included in the Circularity Vehicle Passport proposal as a measure to inform consumers of the circularity of vehicles. It includes a declaration of the manufacturer of all the percentages of recycled materials present in a new vehicle type.	Part of negotiations on ELV Regulation
D5	Introduction of obligatory reporting requirements on the use of materials that affect dismantling and recyclability to facilitate identification of incompatible practices	The use of a specific material and/or fastening technique in the assembly of one component may be beneficial (or at least not harmful) but that it can hinder reuse and recycling in other cases. Thus, rather than prohibiting the use of certain components, materials or techniques, the focus would be on developing a feedback mechanism that ensures that information on how certain design elements affect EoL is communicated and integrated into the design D7process. To this end, feedback is to be facilitated boD8th between different departments of an OEM (designers of the model and its components and those dealing with type approval or performing internal dismantling tests) and between OEMs and waste management operators.	
D6	Improved communication on hazardous substances in the automotive value chain	This measure addresses the communication needs at the end of life of vehicles on the hazardous substances to allow improved reuse and recycling by sorting (out). An improvement in the communication on hazardous substances in the automotive value chain would also contribute to the elimination of hazardous substances in material fractions generated by the ELV waste management sector. There are information systems in place covering the details on material composition, however, the missing element is the availability of the information at waste treatment facilities on the one hand side, and the information for dismantling on the other side. Thus, there is a need for additional dismantling information for recyclers in addition to the current information provided by SCIP or GADSL in IMDS. This proposed measure is to introduce an obligation that the information on the content of substances with hazardous classifications or substances under assessment for classification needs to be documented along the value chain. Should a need for depollution arise, the information on the content of hazardous substances would need to be made available to treatment facilities in a way that the	

No.	Measure / Instrument	Description	Status
		information is linked to • single parts/components, • the location of the parts/components in the vehicle combined with dismantling information and • to safe use instructions for dismantling and recycling processes. This communication would enable the dismantling prior to shredder, combined with subsequent decisions on whether to sort out components or materials, from the material flow, for disposal due to their content of hazardous substances (as is the case for parts containing the POP decaBDE) or to sort out such components or materials to allow their diversion to specific treatment that allows controlling the content of hazardous substances (e.g., separating aluminium wrought and cast alloys) or eliminating it from the general material stream.	
D7	Establish a statutory lifetime guarantee for the entire vehicle	Establish a statutory lifetime guarantee for the entire vehicle based on realistically achievable lifetimes (leave out wearing parts)	
D8	Obligation on OEMs to provide a product carbon footprint (PCF)	For the PCF, PCFs must be available for all installed components (and upstream components/materials installed there), which the OEMs combine to calculate the model PCF (also for batteries)	Work in progress on EU level.(Mundt, Kemper 2024)
D9	Promoting sustainable vehicle in public procurement guidelines	There is a list in the UBA's ""Guide to Green Public Procurement"", but not for vehicles, especially not for the fleet of vehicles purchased by public authorities. A guideline could cover sustainable issues in the whole life cycle of vehicles, including their design, raw material value chain (including due diligence aspects), production (e.g. recycled content), use (including emissions and repairability) and end of life (e.g. recyclability). This policy could also focus on promoting the use of remanufactured parts in the production of the purchased vehicles and the use of rethreaded tyres in the maintenance phase.	
D10	Introduction of standards for resource efficient technologies	Specifications for recyclability/design for recycling	
D11	Introduction of EC non-binding guidelines on how to improve circularity in vehicles	The European Commission will develop and publish a document with recommendations on best practices for improving the circularity of vehicles. Due to the relevance of circularity to environmental performance, it is proposed to develop a document of Best Environmental Management Practices (BEMP) with focus on establishing circularity in the automotive sector. The document shall be developed based on consultation with frontrunners in the sector as to their circularity practices. It shall	

No.	Measure / Instrument	Description	Status
		be developed in a similar format to EU Eco-Management and Audit Scheme (EMAS) BEMP documents, explaining the relevant actions, their expected achievements, expected relation of costs and benefits of the action, potential cross-media affects to be avoided, benchmarks, etc. The document shall be adopted as a non-binding guideline for improving circular design and production of vehicles and shall be updated from time to time according to technical and scientific progress. The document should focus on: • Design practices that support dismantling (through shortened dismantling time, increased dismantlability with common ATF tools, avoidance of damage to component removed or its surroundings), • Design practices that support high quality recycling (through the use or avoidance of certain materials or the mass of materials used in parts that are commonly removed prior to shredding), • Environmental management practices that encourage exchange of information between designers and dismantling facilities.	
D12	Development of strategies/programmes in R&D	Key strategies are to work in chains of industry, research organisations and authorities. Research/R&D into new cell technologies (low-cobalt/no-cobalt, without lithium and improvement of energy density). An example is the lightweight construction strategy for the German federal government. The aim of this strategy is to systematically activate the potential of lightweight construction across all departments for the first time. Five programme lines were announced in a Lightweight Construction Technology Transfer Programme (TTP LB).	Exists in Germany and is under development in EU. The works has been started on the European Lightweighting Strategy. (The European Lightweighting Network 2025), (elca 2024)
D13	Financial support for corporate resource management	Accelerate the spread of environmental management systems, identify and realise resource efficiency potentials.	

No.	Measure / Instrument	Description	Status
D14	Introduction of an obligation for OEMs to develop and implement strategy for increasing the circularity of vehicles	Elements to be addressed in the OEM "Strategy for increasing the circularity of vehicles" (at vehicle fleet level as a general strategy: • General considerations on the composition of vehicles for increasing the share of recyclable materials. As a minimum OEMs shall explain the criteria and methods that they apply to consider whether to use materials with low recyclability (or unestablished recycling). This shall include explanation of methods applied to compare environmental impacts related to such material in the various vehicle life cycle phases (e.g., life cycle or carbon footprint balance validation methods). Strategies shall also be detailed application of which ensures that components composed of such materials can be separated from the waste fraction at EoL to avoid contamination of other fractions, i.e., dismantling consideration for components or available treatment technologies that ensure separation and sorting of such materials from shredded fractions. • General considerations on the composition of vehicles for increasing the share of recycled content used in vehicles. As a minimum, in the first strategy document, OEMs shall report on the total amount of recyclables used in the construction of their vehicles, how this is allocated between various materials and example components where such materials have been introduced. In addition, OEMs shall set a target for the next 5 years as to the increase in use of recycled materials that is planned in their vehicle fleet. Values referred to shall reflect an average for the vehicles to be placed on the market by an OEM in the next 5 years and not the "best in class" in this respect in their product portfolio, • Considerations on the assembly and dismantling of vehicles that support the removal of vehicle components and materials and facilitate reuse and/or high-quality recycling. As a minimum, OEMs shall report on changes that they have introduced in their vehicle design in the last 3 years to promote dismantling of material components with a high potential for reuse and or for improved recycling (quality or quantity) when removed prior to mechanical treatment processes. This should include as minimum detail on components for which dismantling obligations exist or for which ATFs have reporting obligations on reuse. OEMs shall also be required to report on how they ensure that such information reaches ATFs and what feedback mechanisms they have introduced to allow input of such stakeholders to flow back into the considerations of their vehicle design." ELV IA Study Introduction of provisions for improving the relation between the 3R Type approval process and ELV waste management performance Declarations on fulfilment of the reuse, recycling, and recovery (3R) targets submitted by vehicle manufacturers and checked by approval authorities (through the technical services/competent bodies) as part of the 3R Type Approval process do not always reflect the achievable rates of the 3Rs at end-of-life. To address shortcomings and to further facilitate waste management in achieving the targets, changes are to be introduced in the process. These shall address	

No.	Measure / Instrument	Description	Status
		how to take into consideration limitations in the predictability of treatment for certain materials at end-of-life with the objective that results of the 3R calculation performed as part of the 3R type approval process are closer to the actual level of reuse, recycling and recovery that is achievable at the vehicle's EoL. Additionally, information requirements shall be introduced into the 3R Type approval application for data needed for developing fee modulation as part of EPR schemes and for data that must be made accessible to waste management operators.	
D15	Introduction of provisions for improving the relation between the 3R Type approval process and ELV waste management performance	Declarations on fulfilment of the reuse, recycling, and recovery (3R) targets submitted by vehicle manufacturers and checked by approval authorities (through the technical services/competent bodies) as part of the 3R Type Approval process do not always reflect the achievable rates of the 3Rs at end-of-life. To address shortcomings and to further facilitate waste management in achieving the targets, changes are to be introduced in the process. These shall address how to take into consideration limitations in the predictability of treatment for certain materials at end-of-life with the objective that results of the 3R calculation performed as part of the 3R type approval process are closer to the actual level of reuse, recycling and recovery that is achievable at the vehicle's EoL. Additionally, information requirements shall be introduced into the 3R Type approval application85 for data needed for developing fee modulation as part of EPR schemes and for data that must be made accessible to waste management operators.	
D16	Introduction of option for OEMs to submit life cycle data as part of 3R type approval process	The intention of this measure is to enable the use of life cycle data as evidence in the 3R Type approval process to justify the use of non-recyclable materials at the time a vehicle is POM. Such data could support a future 3R Type Approval where the use of certain materials hinders waste management but also results in a significant reduction in environmental impact during the use phase which compensates for not achieving the recycling targets at EoL. To ensure that life cycle data for different vehicles is comparable, a standardised method for the calculation and compilation of such information would need to be developed. This could be developed as Product Environmental Footprint (PEF) rules for vehicles that would need to be applied for preparing self-declarations for submission at the type-approval stage or as a guidance document. The development of an LCA method that may be pursued under Regulation 2019/631/EU could also include elements addressing non-recyclable materials at EoL, to make sure that when the method is followed, resulting data can be used in all cases of EU legislation that requires provision of life cycle data. The focus is expected to be on comparisons between costs and benefits related to the use of a specific material in the use phase and EoL phase (though manufacturing should not be excluded). Though currently it would be sufficient for a comparison to be performed based on a total carbon footprint (CO_2e), in the future, as the market advances towards a larger share of renewables in the energy mix, it will become more relevant to focus on energy	

No.	Measure / Instrument	Description	Status
		consumption as the weight of emissions decreases as will the consumption of fuel. It is assumed that at least two years would be needed to develop PEF rules or a guidance for vehicles and possibly longer. OEMs would be consulted with as part of the development process and are understood to be in the position of contributing to this process, seeing as many OEMs already use life-cycle-analysis to model the environmental performance of new vehicles. This shall also allow time for training type approval authorities so that in the case of submission of such data, the way that it is reviewed by authorities is harmonised across all MS. After the publication of the PEF rules or guidance, a transition period shall be provided, after which 3R type approval (and POM) of vehicles that are expected not to fulfil the 3R targets (3R Type Approval calculation) shall be conditioned with the submission of life cycle data that shows that such materials provide significant environmental benefits that outweigh their environmental costs."	
D17	Introduction of obligatory due diligence for materials used in vehicles	The manufacture of vehicles and vehicle components makes use of numerous materials of both primary and secondary nature. Some of these are sourced from countries (outside the EU) where the local governing conditions and/or the level of performance of mining and processing facilities may not ensure the provision of human rights, the health of workers and/or of nearby residents, or the prevention of adverse impacts on the environment. Where the manufacture of vehicles has a high dependency on material sourcing from such countries, this can contribute to adverse impacts on society and on human health and the environmental. To prevent such impacts, vehicle manufacturers could be required to perform due diligence when sourcing materials to produce vehicles and their components from high- risk countries. This can be related either to primary materials that are sourced from conflict-affected or high-risk areas or to secondary materials sourced from countries that do not ensure a minimum level of environmental performance and/or of minimum social working conditions.	

Source: own table Oeko-Institut

5.1.3 Measures and instruments in vehicle production

Table 65 gives an overview on measures and instruments in production phase with a description and comments on current status.

Table 65: Description of measures and instruments in production phase

No.	Measure / Instrument	Description	Status
P1	Establishment of recycled content target for steel	Article 6 of the ELV regulation proposal empowers the Commission to adopt delegated acts setting recycled content targets for other materials, like steel. Setting such potential targets must be underpinned by a detailed assessment. Findings of current Oeko study: Four scenarios were examined, with targets ranging from 25% to 50% recycled content by 2035. The study found that achieving these targets would require significant improvements in scrap quality and increased collection rates of ELVs. A mandatory recycling target of 25% by 2030 and 30% by 2035 would be feasible with closed loop recycling, a target of 50% by 2035 does not appear achievable under the foreseeable conditions as the quantities of recycled steel from closed loop recycling could just cover 84% of the required recycled content. With open loop recycling, there would at least be sufficient quantities of recycled steel available for a 50% target. However, further research is needed to investigate how much flat steel in new passenger cars can really be replaced by flat steel from high-quality recycled steel. However, in order to achieve the recommended targets, the corresponding capacities for post shredding treatment for high-quality recycling steel must also be built up.	ELV Regulation Proposal: a feasibility study is proposed
P2	Establishment of recycled content target for aluminium	Article 6 of the ELV regulation proposal empowers the Commission to adopt delegated acts setting recycled content targets for other materials, like aluminium. Setting such potential targets must be underpinned by a detailed assessment.	ELV Regulation Proposal: a feasibility study is proposed
P3	Establishment of recycled content target for plastics	Article 6 of the ELV regulation proposal requires that each vehicle type contains at least 25% of plastic recycled from post-consumer plastic waste, and that 25% of such material should come from recycled end-of-life vehicles. In JCR Study: Recycled content targets for plastics 25% in 2030 and 30% in 2035, 25% of which closed loop"	Part of ELV Regulation Proposal
P4	Establishment of recycled content target for cobalt	Article 8 of the Battery regulation sets targets for recycled content for Cobalt: from 2031: 16% and from 2036 26%.	Already implemented in Battery regulation.
P5	Establishment of recycled content target for nickel	Article 8 of the Battery regulation sets targets for recycled content for nickel: from 2031: 6% and from 2036 15%.	Already implemented in Battery regulation.

No.	Measure / Instrument	Description	Status
P6	Establishment of recycled content target for lithium	Article 8 of the Battery regulation sets targets for recycled content for lithium: from 2031: 6% and from 2036 12%.	Already implemented in Battery regulation.
P7	Establishment of recycled content target for lead Phase-out-strategy for lead from batteries	Article 8 of the Battery regulation sets targets for recycled content for lead: 85% from 2031. As the price of lithium-ion batteries falls, it is becoming increasingly attractive to replace lead-acid batteries (Kowalyk 2021). With decreasing market share of lead-acid batteries, battery recycling brings a large amount of lead into the market - without demand from a suitable end product. Considering the hazardousness of lead, a phase-out strategy for lead is needed to prevent improper, polluting disposal of lead from lead-acid batteries. It should be investigated, whether aspects of the mercury phase out might serve as a blueprint.	Recycled content target is already implemented in Battery regulation.
P8	VAT reduction for resource-efficient vehicles		
P9	Develop and promote industry guidance on design for remanufacturing	Promoting industry guidance on design for remanufacturing by sharing best practices and business cases can encourage suppliers to adopt these methods. Additionally, independent remanufacturers can provide valuable feedback to OEMs on failure modes and ways to improve remanufacturability	
P10	Further development of standardisation in the field of EV batteries and related components	As the Batteries Directive does not contain provisions to promote a standardised structure and design of EV batteries and components, further development of standardisation in the field of EV batteries and related components is necessary to improve resource efficiency, especially development of standards for repurposed batteries, including conformity assessment of EV batteries for use in stationary applications and, such as assessment of SoH, performance and remaining service life.	

Source: own table Oeko-Institut

5.1.4 Measures and instruments in vehicle usage

Table 66 gives an overview on measures and instruments in usage phase with a description and comments on current status.

Table 66: Description of measures and instruments in usage phase

No.	Measure / Instrument	Description	Status
U1	Car insurance: environmental bonus for electric cars and cars with low CO_2 emissions	Regardings a car's CO_2 emissions, many car insurance companies now offer environmental discounts if you want to insure an environmentally friendly vehicle. For owners of an electric car, there is even a discount on the insurance premium in some cases, as the vehicle's emission values are very low. It can therefore be worthwhile not only for the environment, but also for your wallet, if you take the average / annual CO_2 emissions of your car into account when buying.	An example from Germany is the R+V: Umweltbonus (R+V 2025): 10% discount on the insurance premium for electric and hybrid cars and 5% for cars with low CO_2 emissions (up to 95 g/km).
U2	Company car taxation	An estimated 20 to 25% of newly registered cars in Germany are company cars that are also used privately (UBA 2021). (Blanck et al. 2020), (Kreye et al. 2024) The reason for the attractiveness of the car as a salary component is the low taxation: for employees, the taxable non-cash benefit can be significantly cheaper than the cost of a privately purchased car (on average only 40% of the true benefit). Companies can deduct the purchase of cars for business use as business expenses without a maximum price limit and regardless of the CO2 emissions of the vehicles. In other European countries, a higher percentage is usually used to calculate the non-cash benefit than in Germany. The consideration of environmentally relevant vehicle characteristics (e.g. CO2 emissions, fuel consumption, benefits for electric vehicles) for the spread of the calculation is also widespread (FÖS 2018a). A CO2 spread of the non-cash benefit as part of company car taxation can provide an incentive to purchase particularly efficient vehicles. However, if company cars become cheaper as a result of a CO2 spread, this could make them even more attractive as a salary component and lead to more rather than	Exists in various EU countries, however following diverse approaches: Belgium takes CO_2 emissions into account when taxing company cars, with the tax rate increasing linearly with increasing emissions per kilometer. The calculated rate is applied to the list price and an age-related correction factor. Employees also have the option of applying for a mobility allowance/“cash for car” or a mobility budget. These two alternatives are intended to create incentives to give up the company car and switch to more environmentally friendly transport options or to make use of them from the outset. The maximum annual mobility allowance (“cash for car”) when giving up an existing company car is calculated as follows according to a formula.

No.	Measure / Instrument	Description	Status
		fewer cars in the long term. The higher taxation of company cars with combustion engines would also have the advantage that the promotion of electric company cars would no longer be borne by all taxpayers, but only by those who drive a - less environmentally friendly - company car themselves. For plug-in hybrids, which currently bring hardly any benefits for the climate as company cars, a short-term abolition of the tax reduction is an option. In the medium term, a CO2 spread in company car taxation is no longer necessary or sensible. Instead, such a differentiation should be applied to every vehicle, regardless of whether it is purchased for private or business use - for example in the form of a CO_2 dependent vehicle tax. Otherwise, an additional preference for low-emission company cars would risk continuing to establish company cars as a salary component. This would slow down the modal+C6 shift, lead to substantial tax losses and perpetuate socially unbalanced distributions.	
U3	European CO_2 emission performance standards for cars and light commercial vehicles (Regulation (EU) 2019/631)	This document regulates the average CO_2 emissions of a car manufacturer's new vehicle fleet. In principle, they can act as an efficiency standard for cars with combustion engines and, thus, encourage vehicle lightweighting..	Already implemented.
U4	Introduction of platforms for ridesharing	Introduction of a platform for exchange on country level for private person looking for ridesharing.	
U5	Mandatory corporate sustainability reports on remanufacturing	Mandatory corporate sustainability reports on remanufacturing can increase awareness of benefits of remanufacturing since the aspect of sustainability (i.a. resource use and circular economy) is part of the reporting.	
U6	Remanufacturing certification and labelling	Certification schemes for remanufacturing could help distinguish high-quality remanufacturers from those not adhering to accepted standards, thereby improving consumer confidence. These schemes, along with product labelling and potential	

No.	Measure / Instrument	Description	Status
		regulatory support, could enhance trust and support circular practices. However, stakeholders have mixed views on their effectiveness and cost.	
U7	Easy access to sufficient information on how to repair and maintain EV batteries „Right to repair“	An aftermarket initiative would require vehicle manufacturers to provide affordable access to software and spare parts for a set period after production ends, supporting legitimate remanufacturing activities. A right to repair ensures that independent repairers have access to the information, tools and parts necessary to repair and maintain EV batteries without legal or technical restrictions.	
U8	Minimum Targets for re-use and repurposing	In line with the waste hierarchy, which favours reuse and repurposing over recycling, separate targets for reuse and repurposing of automotive batteries will be introduced in addition to the recycling targets.	
U9	Promotion of battery friendly user behaviour	Raising EV owners' awareness of "battery-friendly" usage patterns. Improve and deploy intelligent onboard battery management technologies to protect them from degradation.	
U10	Incentives for charging infrastructure	Development of charging infrastructure may also indirectly contribute to frugal batteries.	
U11	Batteries: set minimal values for energy density	In this measure minimum specifications for energy density would be set. The Battery Regulation defines energy turnover as a functional unit (as a rule, the warranty service life is probably used), which is already an incentive in this direction - with fixed limit values, this could become more important. Limit values for battery weight per car be achieved by limiting battery capacity as well as through higher energy densities.	
U12	Batteries: minimum warranty	In this measure a mandatory minimum warranty for batteries is set.	Currently, there is no legal obligations for further incentives for long warranty periods for batteries, except general 2-year product warranty, only

No.	Measure / Instrument	Description	Status
			voluntary manufacturer warranties (e.g. 160 thousand kilometres, 8 years) with certain conditions (e.g. authorised workshops).
U13	Spare parts (not batteries): minimum warranty	In this measure a mandatory minimum warranty of 2 years for spare parts is set.	Part of ELV Regulation Proposal
U14	Obligation on all national vehicle registration system to exchange information between countries	To put a stop to "missing" ELVs, enforce the current rules and increase transparency. The proposal aims to ensure that national vehicle registration systems can exchange data, enabling authorities to track vehicles across borders. This includes better identification of end-of-life vehicles and ensuring they are treated properly, rather than being illegally dismantled or exported. The proposal aims to stop the export of non-roadworthy vehicles and ensure that only high-quality, technically fit vehicles are exported to third countries.	Part of ELV Regulation Proposal
U15	Introduction of incentive to encourage the sale of spare parts	To encourage the sale of spare parts the following aspects are implemented: 1. Lower fees when the use spare parts. Insurance companies: Allianz Beispiel, Adjusted insurance fees, EU-weit, Markt instrument 2. Lower prices for second-hand parts and components, meaning it will be cheaper to maintain and repair vehicles 3. Owner of vehicle: Campaigns to increase awareness of use of reused/remanufactured parts 4. Requirement for maintenance and repair operators to offer customers to repair a vehicle with used, remanufactured or refurbished spare parts and components alongside offer to repair the vehicle with new parts and components, provided that such a requirement is formulated not to create excessive costs or administrative burdens for micro- and small enterprises 5. Use of economic incentives, including the establishment of a reduced rate of value added tax for used, remanufactured or refurbished spare parts and components.	Part of ELV Regulation Proposal

No.	Measure / Instrument	Description	Status
U16	Introduction of (economic) incentives to promote reuse and remanufacturing	Incentives to lower repair, re-use and repurposing costs as well as incentives to promote repairable vehicles: Possible instruments in this field would be tax reductions for repairs and the use of reused or repurposed EV batteries. In addition, purchase incentives and lower insurance costs for repairable cars could make EVs more affordable and attractive to consumers.	
U17	Specifications for software update warranties	Specifications for software update warranties (beyond previous warranty periods of e.g. 160,000 km). This would probably have to be based on vehicle age in years rather than lifetime mileage.	DUH proposes 20-year software update guarantee (DUH 2024)
U18	Obligation for repair shops to offer customers to repair a vehicle with used, remanufactured or refurbished spare parts and components alongside offer to repair the vehicle with new parts and components (Baron et al. 2023)	As part of its Circular Economy legislation, France established an obligation to increase the demand for reused/remanufactured components in 2018: car repair shops must make an offer to repair a vehicle with used components in parallel to the offer to repair it with new components. Together with this measure the use of economic incentives, including the establishment of a reduced rate of value added tax for used, remanufactured or refurbished spare parts and components (see below) as formulated in Article 33 of ELV Regulation Proposal. French insurance companies established partnerships with a network of qualified ATF and repair companies, to increase application of reused/remanufactured components. For this purpose, the insurance company has been requesting every partner to systematically dismantle economically irretrievable vehicles older thar 8 years and vehicles technically irretrievable (i.e., classified by the insurance company as a “total loss” after an accident). Dismantled used components from these vehicles can then be proposed by the company to its insurance policy holders to repair their vehicles in cases that the repair is performed under an insurance policy. The procedure assumes that the partners dismantle mainly economically valuable components. Since the majority of irretrievable vehicles are	Exists in France. Allianz in Germany develop similar system as French insurance company. (JOURNAL OFFICIEL DE LA RÉPUBLIQUE FRANÇAISE 2018)

No.	Measure / Instrument	Description	Status
		vehicles after collision accidents, the insurance company mainly deals with components such as bodywork, doors, and optical elements. Since 2012, the insurance company managed to increase the application of used components systematically every year, so that the initial target to repair 10% of the 300 000 insured vehicles with re-used components by 2022 was already achieved in 2020. Aside from the environmental benefits of this practice, it has additional economic and social advantages, as it allows offering lower insurance policy costs to vehicle owners that agree to repair their cars with used spare parts (in cases of insured repairs) --> lower fees (premium) to vehicle owners who agree to use reused spare parts in repair when such parts are available. In Germany, Allianz allows car repairs with used spare parts, which source will be vehicles that have been totally damaged and are often sold abroad for scrapping. Allianz wants to reuse parts such as doors, front and tailgates, as well as mirrors, headlights and rear lights. Safety-relevant parts such as steering systems, axle parts or wheels will not be used. The implementation of this activity has required a development of a database for the exchange between garages of existing remanufactured spare parts that can be used to repair vehicles insured by Allianz. (Tagesschau 2024), (Stellantis 2023)	
U19	Establishment of a reduced rate of value added tax for used, remanufactured or refurbished spare parts and component	This measure might be established together with Obligation for repair shops to offer customers to repair a vehicle with used, remanufactured or refurbished spare parts and components alongside offer to repair the vehicle with new parts and components (see above) as formulated in Article 33 of ELV Regulation Proposal, e.g. Tax initiatives that support remanufacturing. In 2016, Sweden reduced the Value Added Tax (VAT) on repair services for items like clothing, footwear, and household linen from 25% to 12% to encourage repairs over replacements. In 2022, the VAT was further reduced to 6%, but it was increased back to 12% in 2023.	Exists in Sweden (The Guardian 2016)

No.	Measure / Instrument	Description	Status
U20	Clarify definition of re-use in the ELV Directive vs re-use and preparing for re-use in the Waste Framework Directive	Article 3 of the ELVA regulations proposal Aligning the definition of recycling and aligning the calculation methodology for recycling rates with other waste legislation	Part of ELV Regulation Proposal
U21	Introduce a definition of remanufacturing and specific provisions to support remanufacturing	Article 3 of the ELVA regulations proposal New definition of 'remanufacturing' and new monitoring requirements for reuse/ remanufacturing	Part of ELV Regulation Proposal
U22	Alignment of the terms of the ELV Directive with the terms of Directive 1999/37/EC on registration documents	Article 3 of the ELVA regulations proposal Article 3 lays down the definitions needed for the purposes of this regulation. Several definitions are carried over from existing EU legislation, such as Directives 1999/37/EC. 'registration', 'registration certificate', 'suspension', 'holder of registration certificate' and 'cancellation of registration' laid down in Article 2, points (b), (c), (d), (e) and (f), of Directive 1999/37/EC.	Part of ELV Regulation Proposal
U23	Introduction of new definition: "temporary deregistration"	"Temporary deregistration": based on a request (not ex officio) of the vehicle holder and/or owner a vehicle is temporarily not permitted to be used in road traffic. The definition was discussed by DG ENV with DG MOVE and proposed by DG MOVE in 2016/2017. The explanation "not ex officio" expresses that it is not an authority but e.g. the owner/holder of the vehicle which asks for a temporary deregistration. Insofar it is different from the term suspension. The term "temporary deregistration" is mentioned in recital 17 of the current ELVD139. However, the term not addressed in any article of the current ELVD nor is the term defined in the current ELVD. "Temporary deregistration" is typically applied by dealers when they keep used vehicles on private grounds before selling them but also can be applied by private person for any reason	Part of ELV Regulation Proposal

No.	Measure / Instrument	Description	Status
		defined in the national legislation. It is necessary to define the term as it is necessary to define some obligations for the owner / holder of vehicles during the time of temporary deregistration. In absence of a well-defined term, the term (temporary/ indefinite) off-road notification is often used as synonym for (temporary/ indefinite) deregistration.	
U24	Voluntary activities of Member States to promote circularity	To support circularity, the future legislation of ELVs shall refer to activities that MS are encouraged to embark on as a means (Good Participatory Practices) of supporting the circularity of vehicles, including the following: • Introduce incentives or financial benefits (e.g., reduction of VAT rate on labour costs for employees or reduction of taxes) for products that contain remanufactured products or for remanufacturing operations, • Introduce criteria into green public procurement guidelines that promote the use of reused and remanufactured components, for example: • In relation to vehicle services: criteria that favour insurance policies of vehicles that commit to the use of reused/remanufactured parts when available, • In relation to the purchase of vehicles: criteria that favour of vehicles assembled with a minimum share of remanufactured parts (i.e., remanufactured vehicles).	
U25	Voluntary activities of OEMs and supply chain to promote application of reused/ remanufactured components	EU product classification, which would distinguish between remanufactured, used and newly manufactured components could help increase the awareness of consumers to the applicability of such components and subsequently will potentially increase the demand for partly or fully reused or remanufactured components. The vehicle production sector should be encouraged to develop a clear classification of such components into the groups, based on the identity of the manufacturer (e.g., OEM, third party), process specifications (e.g., new manufacture, cleaning, testing, repairs) and the quality	

No.	Measure / Instrument	Description	Status
		specification (e.g., warranty). The classification could be used on marketed components through the labelling of products, also distinguishing between components manufactured by authorised operators and those marketed by illegal facilities. Such a scheme could distinguish between: • newly manufactured OEM components, • newly manufactured supplier (not OEM) components, • remanufactured components, • reused components processed by an ATF.	

Source: own table Oeko-Institut

5.1.5 Measures and instruments in end-of-life of vehicles

Table 67 gives an overview on measures and instruments in end-of-life phase with a description and comments on current status.

Table 67: Description of measures and instruments in end-of-life phase

No.	Measure / Instrument	Description	Status
E1	Introduction of criteria for determination whether a used vehicle is an end-of-life vehicle	In order to reduce the number of missing vehicles, this measure proposes more inspections, interoperability of national vehicle registration systems, improved distinction of used vehicles from end-of-life vehicles and a ban on exporting used vehicles that aren't roadworthy: - Indicative list of criteria for end-of-life vehicles Article 37 Distinction between used vehicles and end-of-life vehicles For the purpose of transferring ownership of a used vehicle, the vehicle owner shall be able to demonstrate to any natural or legal person interested in acquiring ownership of the concerned vehicle or to the competent authorities that the vehicle is not an end-of-life vehicle. When assessing the status of a used vehicle, the vehicle owner, other economic operators and competent authorities shall verify if the criteria laid down in Annex I are met in order to determine whether it is not an end-of-life vehicle.	Part of ELV Regulation Proposal
E2	Obligation to check for reusability	Introducing a mandatory check on the suitability for re-use or repurposing of EV batteries during dismantling.	

No.	Measure / Instrument	Description	Status
E3	Introduction of criteria for assessing of repairability of vehicles	The Annex I to the proposed Regulation contains specific criteria, aimed to address circumstances where the replacement of some key parts of a vehicle would be of such magnitude that its identity of origin would be irreversibly lost, and the vehicle could not pass the periodic technical inspection: - Criteria for assessment of reparability of vehicles Article 26 Obligations for the vehicle owner The owner of a vehicle that becomes an end-of-life vehicle shall: (a) deliver the end-of-life vehicle to an authorised treatment facility or, in cases referred to in Article 23(4), to a collection point, without undue delay after receiving information that the vehicle meets any of the criteria for irreparability laid down in Part A, points 1 and 2, of Annex I; (b) present a certificate of destruction to the relevant registration authority.	Part of ELV Regulation Proposal
E4	Criteria to avoid export of (used) vehicles including controls	It is important to establish a mechanism where the compliance of used vehicles with the export requirements can be effectively verified without impeding the trade between the Union and third countries. An electronic system should therefore be established by the Commission, enabling authorities in the Member States to exchange information in real time on the vehicle identification number and the roadworthiness status of used vehicles to be exported.	Part of ELV Regulation Proposal
E5	Obligation for the owner to deliver an ELV to an ATF	The proposed ELV Regulation sets out the principle that the owner of a car which has become an ELV should deliver it to an ATF, once he received information proving that his vehicle cannot be repaired any longer.	Part of ELV Regulation Proposal
E6	Introduce at EU level a conclusive list of conditions for permanent cancellation of the registration including regulations for how to apply “temporary de-registrations” (and in addition to cars that are deregistered after COD)	Conclusive list of reasons for permanent cancellation of the registration: a) CoD submitted to national vehicle register, b) Submission of a police report demonstrating that the vehicle is stolen and missing, c) Documents demonstrating that the vehicle is exported, d) Exemptions upon specific request: e.g. a vintage vehicle is stored in a (private) kind of Museum: accompanying documents demonstrate the conditions where and how the vehicle is stored. Management of temporary deregistration: i. Prohibition of “automatic” permanent cancellation of the registration after a certain period of temporary deregistration (or (indefinite) off-road notification). ii. The use on private ground shall not be a reason for permanent cancellation of the	

No.	Measure / Instrument	Description	Status
		registration but it shall fall under temporary deregistration. iii. Require the owner of a vehicle to report changes in ownership to the registration authority during temporary deregistration. 142 iv. A monthly administrative fee (at minimum to recover the related administrative effort) is charged for the entire duration of the temporary deregistration. By legal reasons not all of the above-mentioned aspects might be not regulated by the new ELV Regulation but by other revisions as for instance in the context of the Roadworthiness legislation under DG MOVE supervision.	
E7	Provide economic incentives for the last owner of an end-of-life vehicle to deliver it to an ATF and report the certificate of destruction (CoD) to the administration	The EU legislation may require Member States to ensure that there are economic incentives for the last owner of an end-of-life vehicle to deliver it to an ATF and receive a CoD in return. Tree alternative options might apply for such incentives: a) Link the (end of the) payment of insurance schemes to provision of CoD; b) Link the end of administrative fees to provision of CoD; c) Member States set up other financial incentives (premium / pay out) for last owners to hand over ELVs to ATFs, possibly as part of EPR scheme.	
E8	Obligation for more inspections / Enforcement	To put a stop to “missing” ELVs, enforce the current rules and increase transparency. Member State authorities are expected to face limited costs associated with monitoring and enforcing compliance with the new legislation. The costs will primarily be due to inspections, checks on the export of ELVs and used vehicles and the need to adapt registration systems. In return, increased digitalisation (for reporting on the certificate of destruction, for exchange of information from national vehicle registration registries on export of ELVs and used vehicles and with interoperability with single windows system) will increase efficiency for both enforcement authorities and businesses and will also reduce their burden. The estimated overall cost for public authorities to supervise the EPR schemes, carry out enforcement work and adapt national vehicle registration systems is around EUR 24 million, less than EUR 2 per vehicle. Article 46 obliges Member States to carry out regular inspections of authorised treatment facilities, repair and maintenance operators and other facilities and economic operators who may treat end-of-life vehicles. The inspections should cover compliance with the provisions on export of used vehicles and on treatment of end-of-life vehicles. Each year, the inspections should cover at least 10% of authorised treatment facilities and operators. Sites of repair and maintenance operators should also be subjected to inspection. It needs to be underlined, that inspections carried out	Part of ELV Regulation Proposal

No.	Measure / Instrument	Description	Status
		under this Regulation should be complementary to inspections on the shipment of end-of-life vehicles, which are comprehensively regulated in Regulation [OP: new Waste Shipment Regulation].	
E9	Penalties on treating ELVs without a valid permit	Any establishment or undertaking treating end-of-life vehicles without a valid permit, or in breach of conditions or requirements set out in the permit, should therefore be subject to penalties. Also other measures, such as withdrawing the permit or suspending the operations of an operator should be considered by Member States to ensure effective compliance with this Regulation. Member States should lay down rules on penalties applicable to infringements of this Regulation and ensure that those rules are implemented. The penalties should be established in particular for violations of the provisions on export of used vehicles, on delivery of end-of-life vehicles to authorised treatment facilities or collection points and on trading used, remanufactured or refurbished parts and components. The penalties provided for should be effective, proportionate and dissuasive.	Part of ELV Regulation Proposal
E10	Implementation of mandatory removal of valuable parts, components and materials	Article 30 of the ELV regulation proposal obliges authorised treatment facilities to remove the parts and components listed in Annex VII Part C before shredding and sets out the conditions authorising an exemption from this requirement.	Part of ELV Regulation Proposal
E11	Introduction of recycling rates of plastics (30%)	Article 34 of the ELV regulation proposal sets out that waste management operators achieve a yearly target for the recycling of plastics of at least 30% of the total weight of plastics contained in the vehicles delivered to the waste management operators.	Part of ELV Regulation Proposal
E12	Set material-specific recycling targets	Many different materials are used in cars, but their treatment at end-of-life differs. Steel, alumi-nium and copper are recovered to a large extent, but other materials are not. As certain materials, such as plastic and glass, account for only a small portion of the vehicle weight, they are often discarded and/or only recovered after shredding, leading to a reduced quality of the recovered material. Rare earth elements (REEs) are used for permanent magnets, platinum group metals (PGMs) for catalytic converters and printed circuit boards, gallium for lighting equipment and integrated circuits, magnesium and niobium for metal alloys, and natural rubber for production of tyres. Electric and electronic (EE) systems in vehicles also contain e.g., precious metals, gallium, tantalum, and REE. The main goal of the proposed measures is to promote an increase in the quality of resulting recycled materials together with the increase of the amount of recycled material as opposed	

No.	Measure / Instrument	Description	Status
		to forms of treatment of a lower hierarchy like energy recovery, backfilling or disposal. Additionally, the material-specific recycling target should also consider the materials and components dismantled from the ELV before shredding for reuse, remanufacturing, and recycling.	
E13	Regulate shredder/post shredder facilities to ensure high quality/quantity of materials obtained for recycling and to improve final treatment process	This measure aims to set up a threshold on the maximum Cu-contamination on steel scrap of 0.1 wt %, as main outcome from shredder/PST processes, could lead to higher quality secondary steel as well as higher quantity of copper for recycling.	Part of ELV Regulation Proposal (Annex VII G(2) of general approach of Council)
E14	Align definition of “recycling” with the WFD	Article 3 of the ELVA regulations proposal Aligning the definition of recycling and aligning the calculation methodology for recycling rates with other waste legislation	Part of ELV Regulation Proposal
E15	Landfill restrictions: ban for landfilling of non-inert waste that is not processed through post shredder technology.	Article 35 of the ELV Regulation Proposal introduces a ban for landfilling of non-inert waste that are not processed through post shredder technology. To ensure a consistent implementation of this aspect, it makes sense to introduce a ban on the disposal of ELV post shredder fractions to landfills and a ban on material recycling of these fractions for a) the entire SLF, if not sent for further treatment to PST, and b) the output fractions of PST with a specific weight of > 1.3 g/cm3. A ban of landfilling and material recycling of these fractions will have different effects: If landfilling and material recycling is not allowed, the SLF (respectively the PST fraction mentioned) will be directed to waste incineration (D10) or energy recovery operations (R1) or to chemical recycling. Considering the high caloric value of these fractions such treatment is energy efficient and all these treatment options are higher in the Waste Treatment hierarchy.	Part of ELV Regulation Proposal
E16	Deposit Refund system (DRF) for vehicles (national)	Linked to certificate for destruction. Incentive for consumers to dispose of them properly. Approachs against missing vehicles. Preliminary results of a German study indicate that the illegal sector would have in different scenarios higher benefits compared to ATFs of about 250€ to 300€ per ELV. Insofar the three sources demonstrate that almost the same level of premium is necessary to make it attractive to the last owner to provide the ELV to an ATF instead to the illegal sector. If a premium of €300 for each CoD presented would be paid to the last owner, this would be a very effective way of ensuring that more ELVs are supplied to ATFs rather than to the illegal	exists in DK, NO, DE

No.	Measure / Instrument	Description	Status
		sector. The funds for paying the premium could be collected when new cars are sold or during the use phase. The main risk is that implementation is hampered by missing information for other 24 national markets than the three (DK, NO, DE) mentioned above and subsequent discussions about the correct level of a premium. There might be also needs to adjust the premium from time to time with adverse effects as observed in Denmark when the premium was reduced between 2014 and 2017 to 1500 DKK.	
E17	European-wide deposit refund scheme for vehicles supervised by a single European body	MS or OEMs are obliged to pay into a European fund a minor amount per year for vehicles registered for the use on public roads (alternative: for each new vehicle placed on the market in the EU). The European fund pays out a fixed amount to the last owner of a vehicle when it becomes an ELV, and a CoD is issued. The European approach is more just for the Member States which import a high share of used vehicles. All car drivers pay the same fee, and all last owners get the same pay out.	
E18	Obligations for dismantlers /recyclers to check and report on ELVs / CoDs	Requirement that ATFs issue a CoD for each dismantled vehicle through an electronic notification procedure to the registration authority along with the delivery of the CoD to the last owner (hardcopy or electronic statement). Obligation for shredders to not accept bulks of vehicle carcasses or shear scrap that apparently comes from end-of-life vehicles without accompanying copy of CoDs Shredders should be able to assess the VIN number at the delivered bulks (as it is the regulation in the Netherlands).	
E19	Include Vehicle Identification Number (VIN) in customs declaration	For extra-EU export: registration of the exported vehicle VIN and obligatory information of the MS of origin (the MS where the vehicle was last registered) on the export. This measure enables spot checks / cross checks between the export files and the vehicle registers e.g. whether the vehicle is already considered waste (CoD issued), mentioned as stolen or regards information on the emission level / age / roadworthiness certificate as far as registration paper are not accompanying the export of the vehicle. Once digitalisation is more advanced and interfaces between the export data and registration data are available the cross check can be done as standard procedure.	
E20	Improve reporting obligations on the current vehicle market and the ELVs on their territory	Member States report on the national vehicle stock and detailed changes from one year to the next in the total number of vehicles registered, new registrations, imports and exports of used vehicles, temporary de-registrations and permanent de-registrations.	

No.	Measure / Instrument	Description	Status
		The purpose of this reporting is that a) Member States demonstrate that all ELVs are directed to ATFs and b) to overcome the current situation where it is for a large number of vehicles unknown whether they are exported or treated as ELV (without CoD issued).	
E21	Establish collection target based on the reporting obligations on the national vehicle market	As mentioned during the stakeholder involvement of the ELV impact assessment one challenge, hampering proving that all ELVs that are domestically generated are treated according to the EU requirements is the lack of cooperation between the Ministries of Environment, in charge for the enforcement of the ELVD, and the Ministries in charge for the vehicle registration procedures, the last often with the Ministry of interior of Ministry of transport. Establishing a reporting obligation (see measure before) might not enough stimulus to overcome the problems is cooperation. A distinct target, where the collection of the data is inevitable to prove compliance is easier to communicate on pilots and EU infringement procedures too.	
E22	Exchange on MS best practice (national implementation and enforcement incl. sector inspection campaigns)	Most of the Member States did not change their approach (e.g. regards inspections) or legislation substantially with the aim to address the aspect of missing vehicles and only few Member States can provide detailed data on the whereabout of all used vehicles and ELVs. One basic problem is that such changes are not exclusively in the domain of the participating representatives of TAC meetings (almost all from Ministry of Environment and/or Environmental agencies), while changing e.g. registration procedures is the task of other Ministries in the Member States.	
E23	Requirement for the Member States to establish collective or individual EPR schemes, including monitoring compliance costs and minimum financial obligations	Section 2 of the ELV regulation proposal lays down requirements for the Member States to establish collective or individual Extended producer responsibility (EPR) schemes, including monitoring compliance costs and minimum financial obligations.	Part of ELV Regulation Proposal
E24	Reporting obligations for producers	Article 16 of the ELV regulation proposal establishes a general obligation of producers on responsibility and indicates its scope. Article 17 requires Member States to create a register that will monitor compliance of producers with these requirements. Producers who are not registered shall not make available vehicles on the market within a territory of a Member State. Article 18 concerns producer responsibility organisations. Article 19 lays down conditions for the authorisation of producers, in case of individual fulfillment of extended producer responsibility obligations, and producer responsibility organisations. Article 20	Part of ELV Regulation Proposal

No.	Measure / Instrument	Description	Status
		indicates the costs related to managing end-of-life vehicles that should be covered by financial contributions of producers. Article 21 lays down harmonised criteria for modulating these fees. Article 22 sets out rules on the cost allocation mechanism for vehicles becoming end-of-life vehicles in another Member State. It empowers the Commission to adopt delegated acts concerning detailed rules on the application of fee modulation criteria and on the cost allocation mechanism of cross-border extended producer responsibility. Producers should be able choose whether they will exercise their extended producer responsibility obligations individually or collectively, by means of producer responsibility organisations taking responsibility on their behalf. Producer responsibility organisations should ensure the confidentiality of data provided to them by producers. In order to ensure that the interests of all economic operators are properly taken into consideration and avoid that waste management operators are placed at a disadvantage in the decisions taken in extended producer responsibility schemes, a fair representation of producers and waste management operators should be ensured in the governing bodies of such organisations.	
E25	Introduction of EPR scheme to finance proper ELV treatment operations	Ensure that producers are made financially responsible for vehicles when they become waste, to ensure proper financing for mandatory ELV treatment operations and incentivise recyclers to improve quality.	Part of ELV Regulation Proposal

Source: own table Oeko-Institut

Table 67 shows which aspects of concern the measures and instruments a in end-of-life phase address.

5.2 Characterisation of measures

In this subchapter, the measures and instruments are characterised according to the following questions:

- In which life cycle phase does the measure start?
- Which stakeholders are affected by the measure?
- What is the impact mechanism: sticks (regulations), carrots (economic) and sermons (information) according to Vedung (1997:122ff and 1998:30ff)?
- Does the measure relate to the entire vehicle fleet, to individual vehicles or to parts and components?
- To which parts of the fleet does the measure apply (entire fleet, private vehicles, commercially used company cars)?
- At what level of action should the measure be implemented (international, European, national)?
- What is the time horizon for implementing the measure?
- What is the level of obligation? Is it binding or voluntary?

The following tables give an overview on the characterisation of the analysed measures and instruments.

The characterisation of the measures and instruments are then used for the evaluation in subchapter 0 and the prioritisation in subchapter 0.

5.2.1 Characterisation of overarching measures and instruments

Table 68 shows the characterisation of the overarching measures and instruments.

Table 68: Characterisation of overarching measures and instruments

No.	Measure / Instrument	Stakeholders	Impact mechanism	vehicles, fleet, spare parts, recycling	total fleet / private / commercial / public	national / EU	time horizon
O1	Bonus-malus system in tax system based on vehicle size	OEM, buyer	carrot	new vehicles	total fleet	DE	short
O2	Introduction of funding instruments	OEM, research, authorities	carrot	new vehicles	total fleet	DE EU	short
O3	Raise political awareness of remanufacturing	Remanufacturers, ATFs, garage that dismantle spare parts or	sermon	spare parts	total fleet	EU	short

No.	Measure / Instrument	Stakeholders	Impact mechanism	vehicles, fleet, spare parts, recycling	total fleet / private / commercial / public	national / EU	time horizon
		remanufacturing					
O4	Raise awareness in society of the benefits of repaired/remanufactured spare parts	Owner, remanufacturers, ATFs, garage	sermon	spare parts	total fleet	EU	short
O5	Raw materials index	OEM	sermon	new vehicles	total fleet	EU	long

Source: own table Oeko-Institut

5.2.2 Characterisation of measures and instruments in vehicle design

Table 69 shows the characterisation of the measures and instruments in vehicle design.

Table 69: Characterisation of measures and instruments in vehicle design

No.	Measure / Instrument	Stakeholders	Impact mechanism	vehicles, fleet, spare parts, recycling	total fleet / private / commercial / public	national / EU	time horizon
D1	Set minimum reusability, recyclability and recoverability rates	OEM	stick	spare parts recycling	total fleet	EU	short
D2	Obligation on OEMs to provide detailed instructions on how to replace and remove parts and components together with the obligation that the design of new vehicles shall allow easy removal and replacement fo certain parts and components	OEM	stick	new vehicles spare parts	total fleet	DE EU	short

No.	Measure / Instrument	Stakeholders	Impact mechanism	vehicles, fleet, spare parts, recycling	total fleet / private / commercial / public	national / EU	time horizon
D3	Obligation to provide information on battery chemistry	OEM	stick	new vehicles	total fleet	EU	short
D4	Introduction of Vehicle Circularity Pass	OEM, ATFs, garage, recycler, owner	sermon	new vehicles	total fleet	EU	medium
D5	Introduction of obligatory reporting requirements on the use of materials that affect dismantling and recyclability to facilitate identification of incompatible practices	OEM, ATFs, garage	sermon	new vehicles spare parts	total fleet	EU	short
D6	Improved communication on hazardous substances in the automotive value chain	OEM, recycler	sermon	new vehicles	total fleet	EU	short
D7	Establish a statutory lifetime guarantee for the entire vehicle	OEM	stick	new vehicles	total fleet	EU	medium
D8	Obligation on OEMs to provide a product carbon footprint (PCF)	OEM, Suppliers	sermon	new vehicles	total fleet	EU	medium
D9	Establishing a resource footprint	OEM, Suppliers	sermon	new vehicles	total fleet	EU	long
D10	Promoting sustainable vehicle in public procurement guidelines	Public institutions, OEMs, remanufacturers	stick	new vehicles	public vehicles	DE	short
D11	Introduction of standards for ressource efficient technologies	OEM	stick	new vehicles	total fleet	EU	short

No.	Measure / Instrument	Stakeholders	Impact mechanism	vehicles, fleet, spare parts, recycling	total fleet / private / commercial / public	national / EU	time horizon
D12	Introduction of EC non-binding guidelines on how to improve circularity in vehicles	OEM, EC	carrot	new vehicles spare parts	total fleet	EU	short
D13	Development of strategies/programmes in R&D	OEM, research, authorities	carrot	new vehicles spare parts recycling	total fleet	DE	short
D14	Financial support for corporate resource management	OEM	carrot	new vehicles spare parts recycling	total fleet	DE	short
D15	Introduction of an obligation for OEMs to develop and implement strategy for increasing the circularity of vehicles	OEM	stick	new vehicles spare parts recycling	total fleet	EU	short
D16	Introduction of provisions for improving the relation between the 3R Type approval process and ELV waste management performance	OEM	stick	new vehicles	total fleet	EU	short
D17	Introduction of option for OEMs to submit life cyle data as part of 3R type approval process	OEM	sermon	new vehicles	total fleet	EU	short
D18	Introduction of obligatory due diligence for materials used in vehicles	OEM	stick	new vehicles	total fleet	EU	medium

Source: own table Oeko-Institut

5.2.3 Characterisation of measures and instruments in vehicle production

Table 70 shows the characterisation of the measures and instruments in production phase.

Table 70: Characterisation of measures and instruments in production phase

No.	Measure / Instrument	Stakeholders	Impact mecha-nism	vehicles, fleet, spare parts, recycling	total fleet / private / commer-cial / public	national / EU	time horizon
P1	Establishment of recycled content target for steel	OEM	stick	new vehicles	total fleet	EU	medium
P2	Establishment of recycled content target for aluminium	OEM	stick	new vehicles	total fleet	EU	medium
P3	Establishment of recycled content target for plastics	OEM	stick	new vehicles	total fleet	EU	medium
P4	Establishment of recycled content target for cobalt	OEM, battery manufactures	stick	new vehicles	total fleet	EU	already implemented
P5	Establishment of recycled content target for nickel	OEM, battery manufactures	stick	new vehicles	total fleet	EU	already implemented
P6	Establishment of recycled content target for lithium	OEM, battery manufactures	stick	new vehicles	total fleet	EU	already implemented
P7	Establishment of recycled content target for lead	OEM, battery manufactures	stick	new vehicles	total fleet	EU	already implemented
P8	VAT reduction for resource-efficient vehicles	buyers	carrot	new vehicles	total fleet	DE	short
P9	Develop and promote industry guidance on design for remanufacturing	OEMs, Remanufacturers	sermon	spare parts	total fleet	EU	short
P10	Further development of standardisation in the field of EV batteries and related components	OEMs, garage, remanufacturers, ATFs	stick	new vehicles	total fleet	EU	medium

Source: own table Oeko-Institut

5.2.4 Characterisation of measures and instruments in vehicle usage

Table 71 shows the characterisation of the measures and instruments in usage phase.

Table 71: Characterisation of measures and instruments in usage phase

No.	Measure / Instrument	Stake-holders	Impact mecha-nism	vehicles, fleet, spare parts, recycling	total fleet / private / commer-cial / public	national / EU	time horizon
U1	Car insurance: environmental bonus for electric cars and cars with low CO_2 emissions	owners, OEMs, insurance companies	carrot	fleet	total fleet	DE (voluntary)	short
U2	Company car taxation	Companies/institutions providing company cars, Employers/owners, Authorities (tax Departments)	carrot	new vehicles	company vehicles with private use	DE EU	short
U3	European CO_2 emission performance standards for cars and light commercial vehicles (Regulation (EU) 2019/631)	OEM	stick	new vehicles	total fleet	EU	already implemented
U4	Introduction of plattforms for ridesharing	Sharing service provider	carrot	fleet	total fleet	DE	short
U5	Mandatory corporate sustainability reports on remanufacturing	Private sector preparing CSRs	sermon	spare parts	total fleet	EU	short
U6	Remanufacturing certification and labelling	Garage, ATFs, remanufacturers	sermon	spare parts	total fleet	DE EU	short
U7	Easy access to sufficient information on how to repair and maintain	OEMs, garages, ATFs, remanufacturers	sermon	spare parts	total fleet	DE EU	short

No.	Measure / Instrument	Stake-holders	Impact mecha-nism	vehicles, fleet, spare parts, recycling	total fleet / private / commer-cial / public	national / EU	time horizon
	EV batteries „Right to repair“						
U8	Minimum Targets for re-use and repurposing	Remanufacturers, OEMs, ATFs, garage, authorities	stick	spare parts	total fleet	EU	medium
U9	Promotion of battery friendly user behaviour	owners	sermon	usage	total fleet	DE EU	short
U10	Incentives for charging infrastructure	Investors including public and private, owners	carrot	fleet	total fleet	DE EU	short
U11	Batteries: set minimal values for energy density	OEM, battery manufactures	carrot	new vehicles spare parts	total fleet	EU	medium
U12	Batteries: minimum warranty	OEM, battery manufactures	carrot	new vehicles	total fleet	DE EU	medium
U13	Spare parts (not batteries): minimum warranty	OEM, ATFs, garage, owners	carrot	new vehicles	total fleet	EU	medium
U14	Obligation on all national vehicle registration system to exchange information between countries	Registration autorities, Registration system provider	sermon	fleet	total fleet	EU	medium
U15	Introduction of incentive to encourage the sale of spare parts	ATFs, car repair shops, OEMs, insurance companies	carrot	spare parts	total fleet	EU	short
U16	Introduction of (economic) incentives to promote reuse	ATFs, car repair shops, OEMs, insurance companies	carrot	spare parts	total fleet	DE	short

No.	Measure / Instrument	Stake-holders	Impact mecha-nism	vehicles, fleet, spare parts, recycling	total fleet / private / commer-cial / public	national / EU	time horizon
	and remanufacturing						
U17	Specifications for software update warranties	OEMs, ATFs, garages	carrot	new vehicles	total fleet	EU	medium
U18	Obligation for repair shops to offer customers to repair a vehicle with used, remanufactured or refurbished spare parts and components alongside offer to repair the vehicle with new parts and components	Garage, ATFs, owners	carrot	spare parts	total fleet	DE	short
U19	Establishment of a reduced rate of value added tax for used, remanufactured or refurbished spare parts and component	owners	carrot	spare parts	total fleet	DE	short
U20	Clarify definition of re-use in the ELV Directive vs re-use and preparing for re-use in the Waste Framework Directive	Authorities, ATFs, garage	sermon	spare parts	total fleet	EU	short

No.	Measure / Instrument	Stake-holders	Impact mecha-nism	vehicles, fleet, spare parts, recycling	total fleet / private / commer-cial / public	national / EU	time horizon
U21	Introduce a definition of remanufacturing and specific provisions to support remanufacturing	Authorities, ATFs, garage, Remanufacturer, OEMs	sermon	spare parts	total fleet	EU	short
U22	Alignment of the terms of the ELV Directive with the terms of Directive 1999/37/EC on registration documents	EC, Authorities	sermon	fleet	total fleet	EU	short
U23	Introduction of new definition: “temporary deregistration”	EC, Authorities	sermon	fleet	total fleet	EU	short
U24	Voluntary activities of Member States to promote circularity	Authorities, owners	carrot	fleet	total fleet	EU	short
U25	Voluntary activities of OEMs and supply chain to promote application of reused/ remanufactured components	OEM	sermon	spare parts	total fleet	EU	short

Source: own table Oeko-Institut

5.2.5 Characterisation of measures and instruments in end-of-life of vehicles

Table 72 shows the characterisation of the measures and instruments in end-of-life phase.

Table 72: Characterisation of measures and instruments in end-of-life phase

No.	Measure / Instrument	Stake-holders	Impact mecha-nism	vehicles, fleet, spare parts, recycling	total fleet / private / commer-cial / public	national / EU	time horizon
E1	Introduction of criteria for determination wheather a used vehicle is an end-of-life vehicle	authorities: custom service	sermon	fleet	total fleet	EU	short
E2	Obligation to check for reusability	ATFs, garage, remanufacturers	sermon	spare parts	total fleet	EU	short
E3	Introduction of criteria for assessing of repairability of vehicles	authorities: custom service	sermon	spare parts	total fleet	EU	short
E4	Criteria to avoid export of (used) vehicles including controls	Autorities performing controls at ATFs, garages; Customs	sermon	fleet	total fleet	EU	short
E5	Obligation for the owner to deliver an ELV to an ATF	owners, recycler, ATFs, garages, remanufacturer	stick	fleet	total fleet	EU	short
E6	Introduce at EU level a conclusive list of conditions for permanent cancellation of the registration including regulations for how to apply “temporary de-registrations” (and in addition to cars that are deregistered after COD)	owner, Registration authority	sermon	fleet	total fleet	EU	short
E7	Provide economic incentives for the last owner of an end-of-life vehicle to deliver it to an ATF and report the certificate of destruction (CoD) to the administration	Owner, ATFs	carrot	fleet	total fleet	EU	short

No.	Measure / Instrument	Stake-holders	Impact mecha-nism	vehicles, fleet, spare parts, recycling	total fleet / private / commer-cial / public	national / EU	time horizon
E8	Obligation for more inspections / Enforcement	Autorities performing controls at ATFs, garages; Customs	stick	fleet	total fleet	EU	short
E9	Penalties on treating ELVs without a valid permit	Autorities performing controls at ATFs, garages; Customs	carrot	fleet	total fleet	DE EU	short
E10	Implementation of mandatory removal of valuable parts, components and materials	Garages, ATFs, recyclers	stick	spare parts	total fleet	DE EU	short
E11	Introduction of recycling rates of plastics (30%)	Garages, ATFs, recyclers	stick	recycling	total fleet	EU	medium
E12	Set material-specific recycling targets	ATFs, garages, authorities	stick	recycling	total fleet	EU	medium
E13	Regulate shredder/post shredder facilities to ensure high quality/quantity of materials obtained for recycling and to improve final treatment process	ATFs, garage, recyclers	stick	recycling	total fleet	EU	medium
E14	Align definition of “recycling” with the WFD	ATFs, garages, authorities	sermon	recycling	total fleet	EU	short
E15	Landfill restrictions: ban for landfilling of non-inert waste that is not processed through post shredder technology.	ATFs, garages, authorities	stick	recycling	total fleet	EU	short
E16	Deposit Refund system (DRF) for vehicles (national)	MS, autthorities	carrot	fleet	total fleet	EU	medium

No.	Measure / Instrument	Stake-holders	Impact mecha-nism	vehicles, fleet, spare parts, recycling	total fleet / private / commer-cial / public	national / EU	time horizon
E17	European-wide deposit refund scheme for vehicles supervised by a single European body	Owner, OEMs, autorities	carrot	fleet	total fleet	EU	medium
E18	Obligations for dismantlers /recyclers to check and report on ELVs / CoDs	Autorities, ATFs, garage, recyclers	sermon	recycling	total fleet	EU	medium
E19	Include Vehicle Identification Number (VIN) in customs declaration	Autorities, ATFs, garages, Customs	sermon	fleet	total fleet	EU	medium
E20	Improve reporting obligations on the current vehicle market and the ELVs on their territory	Authorities, ATFs, garages, recyclers	sermon	fleet	total fleet	EU	medium
E21	Establish collection target based on the reporting obligations on the national vehicle market	Authorities, ATFs, garages, recyclers	sermon	fleet	total fleet	EU	medium
E22	Exchange on MS best practice (national implementation and enforcement incl. sector inspection campaigns)	Autorities	sermon	fleet	total fleet	EU	medium
E23	Requirement for the Member States to establish collective or individual EPR schemes, including monitoring compliance costs and minimum financial obligations	OEM, authorities	sermon	fleet	total fleet	EU	short
E24	Reporting obligations for producers	OEM	sermon	new vehicles	total fleet	EU	short
E25	Introduction of EPR scheme to finance	OEMs, recyclers, ATFs, garage	stick	new vehicles	total fleet	DE EU	medium

No.	Measure / Instrument	Stake-holders	Impact mecha-nism	vehicles, fleet, spare parts, recycling	total fleet / private / commer-cial / public	national / EU	time horizon
	proper ELV treatment operations			spare parts			

Source: own table Oeko-Institut

5.3 Evaluation of measures and instruments

This subchapter gives an evaluation of the measures and instruments

In a first step, t is shown to what extent the measures and instruments can contribute to the aspects of concern that were derived from the model results in the chapter on criteria for a resource-efficient vehicle (see chapter 4):

- Potential to reduce raw material consumption
- Potential to reduce greenhouse gases
- Potential to increase durability
- Potential to promote recycling
- Potential to reduce energy consumption

5.3.1 Evaluation of overarching measures and instruments

Table 73 shows which aspects of concern the overarching measures and instruments address.

Table 73: Aspects of concern of overarching measures and instruments

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
O1	Bonus-malus system in tax system based on vehicle size	high	high			high
O2	Introduction of funding instruments	low	low	low	low	low
O_3	Raise political awareness of remanufacturing	low	low	low	low	
O4	Raise awareness in society of the benefits of repaired/remanufactured spare parts	low	low	low	low	
O5	Raw materials index	high				

Table 73 shows the prioritisation of the overarching measures and instruments

Table 74: Prioritisation of overarching measures and instruments

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
O1	Bonus-malus system in tax system based on vehicle size	high	high			high
O2	Introduction of funding instruments	low	low	low	low	low
O_3	Raise political awareness of remanufacturing	low	low	low	low	
O4	Raise awareness in society of the benefits of repaired/remanufactured spare parts	low	low	low	low	
O5	Raw materials index	high				

Source: own table Oeko-Institut

5.3.2 Evaluation of measures and instruments in vehicle design

Table 75 shows which aspects of concern the measures and instruments in vehicle design address.

Table 75: Aspects of concern of measures and instruments in vehicle design

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
D1	Set minimum reusability, recyclability and recoverability targets	high	high		high	
D2	Obligation on OEMs to provide detailed instructions on how to replace and remove parts and components together with the obligation that the design of new vehicles shall allow easy removal and replacement for certain parts and components	medium	medium	medium	medium	
D3	Obligation to provide information on battery chemistry	medium	medium		medium	

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
D4	Introduction of Circularity Vehicle Pass				medium	
D5	Introduction of obligatory reporting requirements on the use of materials that affect dismantling and recyclability to facilitate identification of incompatible practices				medium	
D6	Improved communication on hazardous substances in the automotive value chain				low	
D7	Establish a statutory lifetime guarantee for the entire vehicle	high	high	high	high	
D8	Obligation on OEMs to provide a product carbon footprint (PCF)		medium			
D9	Establishing a resource footprint	medium				
D10	Promoting sustainable vehicle in public procurement guidelines	low	low	low	low	low
D11	Introduction of standards for resource efficient technologies	low		low	low	
D12	Introduction of EC non-binding guidelines on how to improve circularity in vehicles	low	low		low	
D13	Development of strategies/programmes in R&D	low	low	low	low	low
D14	Financial support for corporate resource management	low			low	
D15	Introduction of an obligation for OEMs to develop and implement strategy for increasing the circularity of vehicles	medium	medium		medium	
D16	Introduction of provisions for improving the relation between the 3R Type approval process and				low	

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
	ELV waste management performance					
D17	Introduction of option for OEMs to submit life cyle data as part of 3R type approval process					
D18	Introduction of obligatory due diligence for materials used in vehicles					

Source: own table Oeko-Institut

5.3.3 Evaluation of measures and instruments in vehicle production

Table 76 shows which aspects of concern the measures and instruments in production phase address.

Table 76: Aspects of concern of measures and instruments in production phase

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
P1	Establishment of recycled content target for steel	medium	low			
P2	Establishment of recycled content target for aluminium	medium	low			
P3	Establishment of recycled ontent target for plastics	medium	medium			
P4	Establishment of recycled content target for cobalt	high	low			
P5	Establishment of recycled content target for nickel	high	low			
P6	Establishment of recycled content target for lithium	high	low			
P7	Establishment of recycled content target for lead Phase-out-strategy for lead from batteries	low	low			
P8	VAT reduction for resource-efficient vehicles	medium	medium		medium	

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
P9	Develop and promote industry guidance on design for remanufacturing	low	low	low	low	
P10	Further development of standardisation in the field of EV batteries and related components	low	low	low	low	

Source: own table Oeko-Institut

5.3.4 Evaluation of measures and instruments in vehicle usage

Table 77 shows which aspects of concern the measures and instruments in usage address.

Table 77: Aspects of concern of measures and instruments in usage phase

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
U1	Car insurance: environmental bonus for electric cars and cars with low CO_2 emissions		medium			medium
U2	Company car taxation	medium	medium	medium	medium	medium
U3	European CO_2 emission performance standards for cars and light commercial vehicles (Regulation (EU) 2019/631)		high			high
U4	Introduction of platforms for ridesharing	high	high			
U5	Mandatory corporate sustainability reports on remanufacturing	low	low	low	low	
U6	Remanufacturing certification and labelling				low	
U7	Easy access to sufficient information on how to repair and maintain EV batteries „Right to repair“				low	
U8	Minimum Targets for re-use and repurposing	high	high	high	high	
U9	Promotion of battery friendly user behaviour	low	low	low		low

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
U10	Incentives for charging infrastructure	medium	medium			
U11	Batteries: set minimal values for energy density	high	high			high
U12	Batteries: minimum warranty	high	medium	high		
U13	Spare parts (not batteries): minimum warranty	high	medium	high		
U14	Obligation on all national vehicle registration system to exchange information between countries	low	low			
U15	Introduction of incentive to encourage the sale of spare parts	medium	low	medium	medium	
U16	Introduction of (economic) incentives to promote reuse and remanufacturing	medium	low	medium	medium	
U17	Specifications for software update warranties	medium	medium	high		
U18	Obligation for repair shops to offer customers to repair a vehicle with used, remanufactured or refurbished spare parts and components alongside offer to repair the vehicle with new parts and components	medium	low	medium	medium	
U19	Establishment of a reduced rate of value added tax for used, remanufactured or refurbished spare parts and component	medium	low	medium	medium	
U20	Clarify definition of re-use in the ELV Directive vs re-use and preparing for re-use in the Waste Framework Directive				low	
U21	Introduce a definition of remanufacturing and specific provisions to support remanufacturing				low	

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
U22	Alignment of the terms of the ELV Directive with the terms of Directive 1999/37/EC on registration documents	low	low		low	
U23	Introduction of new definition: “temporary deregistration”	low	low		low	
U24	Voluntary activities of Member States to promote circularity	low	low		low	
U25	Voluntary activities of OEMs and supply chain to promote application of reused/ remanufactured components	low	low	low	low	

Source: own table Oeko-Institut

5.3.5 Evaluation of measures and instruments in end-of-life of vehicles

Table 78: Aspects of concern of measures and instruments in end-of-life phase

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
E1	Introduction of criteria for determination whether a used vehicle is an end-of-life vehicle	low	low		low	
E2	Obligation to check for reusability	medium,	low	medium,	medium,	
E3	Introduction of criteria for assessing of repairability of vehicles	low	low	low	low	
E4	Criteria to avoid export of (used) vehicles including controls	low	low		low	
E5	Obligation for the owner to deliver an ELV to an ATF	medium,	low		high	
E6	Introduce at EU level a conclusive list of conditions for permanent cancellation of the registration including regulations for how to apply “temporary de-registrations” (and in addition to cars that are deregistered after COD)	low	low		medium,	

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
E7	Provide economic incentives for the last owner of an end-of-life vehicle to deliver it to an ATF and report the certificate of destruction (CoD) to the administration	low	low		medium,	
E8	Obligation for more inspections / Enforcement	low	low		low	
E9	Penalties on treating ELVs without a valid permit	low	low		medium,	
E10	Implementation of mandatory removal of valuable parts, components and materials	medium,	low		high	
E11	Introduction of recycling rates of plastics (30%)	medium,	medium		high	
E12	Set material-specific recycling targets	high	medium		high	
E13	Regulate shredder/post shredder facilities to ensure high quality/quantity of materials obtained for recycling and to improve final treatment process	medium	low		high	
E14	Align definition of “recycling” with the WFD				low	
E15	Landfill restrictions: ban for landfilling of non-inert waste that is not processed through post shredder technology.	low	low		medium	
E16	Deposit Refund system (DRF) for vehicles (national)	medium	low		medium	
E17	European-wide deposit refund scheme for vehicles supervised by a single European body	medium	low		medium	
E18	Obligations for dismantlers /recyclers to check and report on ELVs / CoDs	low	low		medium	
E19	Include Vehicle Identification Number (VIN) in customs declaration	low	low		low	

No.	Measure / Instrument	Primary resources demand	GHG emissions	Longevity	Recyclability	Energy demand
E20	Improve reporting obligations on the current vehicle market and the ELVs on their territory	low	low		low	
E21	Establish collection target based on the reporting obligations on the national vehicle market	low	low		medium	
E22	Exchange on MS best practice (national implementation and enforcement incl. sector inspection campaigns)	low	low		low	
E23	Requirement for the Member States to establish collective or individual EPR schemes, including monitoring compliance costs and minimum financial obligations	medium	low		high	
E24	Reporting obligations for producers					
E25	Introduction of EPR scheme to finance proper ELV treatment operations	medium	low		high	

Source: own table Oeko-Institut

5.4 Prioritisation of measures and instruments

In a second step, the measures and instruments are weighted and prioritised according to the following criteria

- Potential impact on the aspect of concern: high > medium > low
- Identified effective levers (modeling): High effectiveness (vehicle size, number of new vehicles) > medium effectiveness (end-of-life vehicle recovery, recycling efficiency, etc.) > rather low effectiveness (individual material regulations, measures with high risks of displacement to other sectors, etc.)
- Impact approach: Regulation (stick) > Economic incentive (carrot) > Information (sermon)
- Time horizon: short time > medium time > long time

The prioritisation also takes into account whether the measure has already been implemented or whether it has been proposed as part of the EU's ELV proposal (in the first case, the measure is not included in the list; in the second case, it is only included in exceptional cases).

5.4.1 Prioritisation of overarching measures and instruments

Table 79 shows the prioritisation of the overarching measures and instruments.

Table 79: Prioritisation of overarching measures and instruments

No.	Measure / Instrument	Prioritisation	Comment
O1	Bonus-malus system in tax system based on vehicle size	prioritised	
O2	Introduction of funding instruments		long time, not binding
O3	Raise political awareness of remanufacturing		not binding, just information
O4	Raise awareness in society of the benefits of repaired/remanufactured spare parts		not binding, just information
O5	Raw material index		to be developed, long time

Source: own table Oeko-Institut

5.4.2 Prioritisation of measures and instruments in vehicle design

Table 80 shows the prioritisation of the measures and instruments in vehicle design.

Table 80: Prioritisation of measures and instruments in vehicle design

No.	Measure / Instrument	Prioritisation	Comment
D1	Set minimum reusability, recyclability and recoverability rates		Part of ELV Regulation Proposal
D2	Obligation on OEMs to provide detailed instructions on how to replace and remove parts and components together with the obligation that the design of new vehicles shall allow easy removal and replacement for certain parts and components	prioritised	
D3	Obligation to provide information on battery chemistry		Already implemented in Battery Regulation.
D4	Introduction of Vehicle Circularity Pass		Just information
D5	Introduction of obligatory reporting requirements on the use of materials that affect dismantling and recyclability to facillitate identification of incompatible practices		Just information
D6	Improved communication on hazardous substances in the automotive value chain		Just information

No.	Measure / Instrument	Prioritisation	Comment
D7	Establish a statutory lifetime guarantee for the entire vehicle	prioritised	
D8	Obligation on OEMs to provide a product carbon footprint (PCF)	prioritised	
D9	Establishing a resource footprint	prioritised	
D10	Promoting sustainable vehicle in public procurement guidelines	prioritised	
D11	Introduction of standards for ressource efficient technologies		supporting level playing field for recouce efficient technologies but long perspective
D12	Introduction of EC non-binding guidelines on how to improve circularity in vehicles		supporting level playing field for recouce efficient technologies, non-binding
D13	Development of strategies/programmes in R&D		long perspective
D14	Financial support for corporate resource management		long perspective
D15	Introduction of an obligation for OEMs to develop and implement strategy for increasing the circularity of vehicles		long perspective
D16	Introduction of provisions for improving the relation between the 3R Type approval process and ELV waste management performance		indirect impact
D17	Introduction of option for OEMs to submit life cyle data as part of 3R type approval process		information
D18	Introduction of obligatory due diligence for materials used in vehicles		out of focus

Source: own table Oeko-Institut

5.4.3 Prioritisation of measures and instruments in vehicle production

Table 81 shows the prioritisation of the measures and instruments in production phase.

Table 81: Prioritisation of measures and instruments in production phase

No.	Measure / Instrument	Prioritisation	Comment
P1	Establishment of recycled content target for steel	prioritised	
P2	Establishment of recycled content target for aluminium		ELV Regulation Proposal: a feasibility study is proposed
P3	Establishment of recycled content target for plastics	prioritised	
P4	Establishment of recycled content target for cobalt		Already implemented in Battery regulation.
P5	Establishment of recycled content target for nickel		Already implemented in Battery regulation.
P6	Establishment of recycled content target for lithium		Already implemented in Battery regulation.
P7	Establishment of recycled content target for lead		Already implemented in Battery regulation.
P8	VAT reduction for resource-efficient vehicles		implementation in vehicles sector unclear
P9	Develop and promote industry guidance on design for remanufacturing		non-binding
P10	Further development of standardisation in the field of EV batteries and related components		support in second use and recycling, but long perspective

Source: own table Oeko-Institut

5.4.4 Prioritisation of measures and instruments in vehicle usage

Table 82 shows the prioritisation of the measures and instruments in usage phase.

Table 82: Prioritisation of measures and instruments in usage phase

No.	Measure / Instrument	Prioritisation	Comment
U1	Car insurance: environmental bonus for electric cars and cars with low CO_2 emissions	prioritised	voluntary measure of insurances
U2	Company car taxation	prioritised	
U3	European CO_2 emission performance standards for cars and light commercial vehicles (Regulation (EU) 2019/631)		Already implemented.

No.	Measure / Instrument	Prioritisation	Comment
U4	Introduction of plattforms for ridesharing		out of focus
U5	Mandatory corporate sustainability reports on remanufacturing		just information
U6	Remanufacturing certification and labelling		indirect impact
U7	Easy access to sufficient information on how to repair and maintain EV batteries „Right to repair“		information
U8	Minimum Targets for re-use and repurposing		influence on avalability of secondary materials
U9	Promotion of battery friendly user behaviour		non-binding
U10	Incentives for charging infrastructure		out of focus
U11	Batteries: set minimal values for energy density	prioritised	
U12	Batteries: minimum warranty	prioritised	see warranty for entire vehicle
U13	Spare parts (not batteries): minimum warranty	prioritised	see warranty for entire vehicle
U14	Obligation on all national vehicle registration system to exchange information between countries		just information exchange
U15	Introduction of incentive to encourage the sale of spare parts	prioritised	see warranty for entire vehicle
U16	Introduction of (economic) incentives to promote reuse and remanufacturing		just incentive
U17	Specifications for software update warranties	prioritised	see warranty for entire vehicle
U18	Obligation for repair shops to offer customers to repair a vehicle with used, remanufactured or refurbished spare parts and components alongside offer to repair the vehicle with new parts and components		depends on presence of spare parts
U19	Establishment of a reduced rate of value added tax for used, remanufactured or refurbished spare parts and component		depends on presence of spare parts

No.	Measure / Instrument	Prioritisation	Comment
U20	Clarify definition of re-use in the ELV Directive vs re-use and preparing for re-use in the Waste Framework Directive		Part of ELV Regulation Proposal
U21	Introduce a definition of remanufacturing and specific provisions to support remanufacturing		Part of ELV Regulation Proposal
U22	Alignment of the terms of the ELV Directive with the terms of Directive 1999/37/EC on registration documents		Part of ELV Regulation Proposal
U23	Introduction of new definition: “temporary deregistration”		Part of ELV Regulation Proposal
U24	Voluntary activities of Member States to promote circularity		voluntary
U25	Voluntary activities of OEMs and supply chain to promote application of reused/ remanufactured components		voluntary

Source: own table Oeko-Institut

5.4.5 Prioritisation of measures and instruments in end-of-life of vehicles

Table 83 shows the prioritisation of the measures and instruments in end-of-life phase.

Table 83: Prioritisation of measures and instruments in end-of-life phase

No.	Measure / Instrument	Prioritisation	Comment
E1	Introduction of criteria for determination wheather a used vehicle is an end-of-life vehicle		Part of ELV Regulation Proposal
E2	Obligation to check for reusability		
E3	Introduction of criteria for assessing of repairability of vehicles		just information
E4	Criteria to avoid export of (used) vehicles including controls		Part of ELV Regulation Proposal
E5	Obligation for the owner to deliver an ELV to an ATF		Part of ELV Regulation Proposal

No.	Measure / Instrument	Prioritisation	Comment
E6	Introduce at EU level a conclusive list of conditions for permanent cancellation of the registration including regulations for how to apply “temporary de-registrations” (and in addition to cars that are deregistered after COD)		
E7	Provide economic incentives for the last owner of an end-of-life vehicle to deliver it to an ATF and report the certificate of destruction (CoD) to the administration		
E8	Obligation for more inspections / Enforcement		Part of ELV Regulation Proposal
E9	Penalties on treating ELVs without a valid permit		Part of ELV Regulation Proposal
E10	Implementation of mandatory removal of valuable parts, components and materials		According to auto repair shops and remanufacturers, such replacement parts are only kept in stock if there is no demand for them.
E11	Introduction of recycling rates of plastics (30%)		Part of ELV Regulation Proposal
E12	Set material-specific recycling targets		Part of ELV Regulation Proposal
E13	Regulate shredder/post shredder facilities to ensure high quality/quantity of materials obtained for recycling and to improve final treatment process	prioritised	Part of ELV Regulation Proposal (Annex VII G(2) of general approach of Council)
E14	Align definition of “recycling” with the WFD		Part of ELV Regulation Proposal
E15	Landfill restrictions: ban for landfilling of non-inert waste that is not processed through post shredder technology.		Part of ELV Regulation Proposal
E16	Deposit Refund system (DRF) for vehicles (national)		
E17	European-wide deposit refund scheme for vehicles supervised by a single European body		
E18	Obligations for dismantlers /recyclers to check and report on ELVs / CoDs		

No.	Measure / Instrument	Prioritisation	Comment
E19	Include Vehicle Identification Number (VIN) in customs declaration		
E20	Improve reporting obligations on the current vehicle market and the ELVs on their territory		
E21	Establish collection target based on the reporting obligations on the national vehicle market		
E22	Exchange on MS best practice (national implementation and enforcement incl. sector inspection campaigns)		
E23	Requirement for the Member States to establish collective or individual EPR schemes, including monitoring compliance costs and minimum financial obligations		ELV Regulation Proposal
E24	Reporting obligations for producers		ELV Regulation Proposal
E25	Introduction of EPR scheme to finance proper ELV treatment operations	prioritised	

Source: own table Oeko-Institut

5.5 Detailed measures

5.5.1 Bonus-malus system: Vehicle dimension (O1)

Description

In a **bonus-malus system based on vehicle dimensions**, buyers of a smaller car receive a bonus, whereas a malus must be paid when buying a car with higher dimensions, which also increases with increasing size. A bonus can take the form of a purchase premium, while a malus can consist of either a one-time payment when purchasing a new car or higher annual costs in vehicle tax. One-off payments when buying a car have a greater effect than annual vehicle taxes.

What are the examples of similar measures already introduced in other countries?

A bonus-malus system based on CO_2 emission s has been already implemented in several European countries however in diverse approach, e. g. France , the Netherlands, Portugal, Sweden.(Blanck, Zimmer 2021)

A bonus-malus system based on vehicle weight has already been implemented in France.(Bensalah 2025)

How effectively does it guide climate and resource protection?

A study by the German Federal Environment Agency showed how bonus-malus systems based on CO_2 emissions in the Netherlands and France have led to a significant ecological steering effect on new registrations (Blanck et al. 2020) A direct correlation between average CO_2

emissions per kilometer and whether motor vehicle tax is dependent on emissions has also been demonstrated for the other member states of the European Union(Blanck et al. 2020).

What economic and administrative costs and effort are incurred with the introduction?

There are significant costs for the public sector for the purchase premiums. With a corresponding malus, the purchase premium can be fully financed.

What are the possible anchoring in existing or possible legal acts/ standards/ initiatives etc.

In Germany, vehicle tax is set in the Kraftfahrzeugsteuergesetz (KraftStG). Here also the bonus malus system could be implemented.

What is the practical feasibility of the measure, including possible existing obstacles (PROS, CONS)?

PROS:

- High potential for reduction of resource consumption and and O_2 emissions
- Significant ecological steering effect on new registrations
- Feasible at the national level
- Feasible in the short term

PROS / Obstacles:

- According to statements by car manufacturers, the profit margin for smaller cars between the selling price and the costs for conception, design, and production is significantly lower compared to mid-range cars.
- Since higher-income households generally have a higher degree of motorization and higher individual mileage, they benefit more from low tax burdens, subsidies, and government benefits in the area of passenger car transportation.
- Half of the purchase premium for electric vehicles is financed from the federal budget. However, it is largely high-income groups that benefit, and windfall effects must be assumed.

5.5.2 Requirement for the Member States to establish collective or individual EPR schemes (E24, E26)

This report looks at various topic areas, analysing their current status and the future developments required for more environmentally friendly solutions. For example, designing for circularity is an investment in the distant future. This raises the general question of who should bear the costs of enabling the circular economy. These costs should not only be borne by end-of-life and recycling companies. The EU's extended producer responsibility is therefore an important instrument for taking recycling costs into account from the outset and ensuring end-of-life vehicles are returned to the cycle. Appropriate policy measures can ensure that these investments pay off in the long term.

Description

In July 2023, the European Commission published the ELV regulation proposal (European Commission 2023a). This document included a provision for the creation of Extended producer responsibility (EPR) schemes in the automotive sector. The provisions in this regard (mainly Section 2, Chapter IV) were amended during the process of finalising the legal document.

On 3 July 2025, the European Parliament's Environment and Internal Market Committees presented final compromise amendments to the proposal (European Parliament, Council of the European Union et al. 2025). According to this document, vehicle producers financially and organisationally shall be responsible for the vehicles they place on the market once they reach their end-of-life stage. This responsibility requires producers to ensure vehicles are collected and treated according to the regulation's standards and that waste management operators meet reuse and recycling targets. Producers can fulfil these obligations individually or collectively through a non-profit Producer Responsibility Organisation (PRO). The financial contributions paid by producers must cover the net costs of collection, treatment, awareness campaigns, data reporting, and transportation to the nearest facility. For collective schemes, these fees are modulated based on criteria like the vehicle's recyclability, weight, and use of recycled content to incentivise circular design. The scheme also introduces rules for cross-border EPR, ensuring producers cover waste management costs even if a vehicle becomes an end-of-life vehicle in a different Member State from where it was first registered.

Climate impact and resource protection

Proposed EPR scheme within automotive sector shall guide climate and resource protection by making producers financially responsible for the collection and treatment of their end-of-life vehicles, aligning also with the 'polluter-pays' principle (European Commission 2023a). This financial liability creates an economic incentive for producers to design vehicles that are easier to dismantle and recycle, thereby conserving resources from the outset. The scheme further strengthens this incentive through the modulation of producer fees, which are adjusted based on circularity criteria such as the vehicle's recyclability rate and the amount of recycled content used in its construction (European Commission 2023a). By financing comprehensive collection and higher-quality treatment, the EPR scheme shall ensure more valuable materials, including critical raw materials, are recovered and retained within the EU economy, reducing waste and the GHG emissions associated with producing virgin materials. Ultimately, this system fosters a stable market for secondary raw materials, reducing the EU's dependency on primary resource extraction and supporting the industry's transition to a more sustainable, circular model. EPR scheme aims also to reduce the number of "missing vehicles" by improving collection and ensuring they are treated within the EU, through which more recycle materials are available within EU (Baron et al. 2023).

Economic and administrative efforts

The introduction and implementation of the proposed EPR scheme will entail significant economic and administrative costs and efforts for both the addressees (primarily vehicle producers and their responsibility organisations) and the administration (Member State authorities and EU bodies). The scheme is designed to shift the financial and organisational responsibility for end-of-life vehicle management to the producers, in line with the 'polluter-pays' principle (European Commission 2023a).

For producers, this means bearing the net financial costs of collection and treatment, funding awareness campaigns, and covering data reporting expenses. In addition to these financial outlays, producers face considerable administrative effort, including registering in every Member State where they sell vehicles, obtaining authorisations for their EPR schemes, and managing extensive reporting and self-control mechanisms to ensure compliance. (Baron et al. 2023; European Commission 2023c)

European Commission in its accompanying documents to the Proposal for an ELV Regulation, assessed costs linked to the selected preferred option. This option includes, inter alia, financial and organisation incentives via establishment of EPR requirements to increase collection of

ELVs and to compensate costs for improvement treatment quality that cannot be offset by the value of materials and components recovered. Other included measures are recycled contents targets for plastics and introduction of Digital Product Pass (DPP) for vehicles. As a cumulative result costs of all measures contained under preferred option, for Member State authorities, the primary costs are related to supervision and enforcement, estimated less than EUR 2 per vehicle. This is complemented by the administrative effort of establishing and maintaining national producer registers, managing the authorisation procedures for producers and their organisations (PROs), and creating a robust monitoring and enforcement framework, including regular inspections and setting penalties for infringements. The European Commission will also incur costs for additional staff and technical work required to develop numerous implementing acts that will specify the detailed rules for the EPR scheme, such as for fee modulation and cross-border cooperation. (European Commission 2023a)

The impact assessment accompanying the proposal estimates that the total cost of the preferred policy package will reach EUR 66 per vehicle put on the market in 2035, with an estimated EUR 39 per vehicle being passed on to consumers through increased prices and lower prices (by EUR 12 per vehicle) when selling second-hand cars due to the fall in exports. Conversely, measures to support the recovery and sale of used spare parts are expected to result in lower purchase prices and cheaper repair and maintenance for consumers, which is a benefit. (European Commission 2023a)

A EPR scheme shall support the automotive recycling sector by helping SMEs offset costs from new technology adoption through higher collection rates and improved treatment quality. This, in turn, fosters innovation, creates jobs, and generates new opportunities within the industry.

Feasibility with PROS and CONS

An EPR scheme for ELVs is a balance of benefits and obstacles.

PROS:

- Financial incentive: It makes producers responsible for the net costs of ELV management, motivating them to design more recyclable vehicles.
- Fee modulation: Fees will be adjusted based on recyclability and use of recycled content, directly rewarding circular design.
- Harmonized implementation: A single regulation for all of the EU simplifies compliance and ensures a level playing field.
- Cross-Border Mechanism: It ensures producers cover waste management costs even when vehicles are exported to other EU countries.

CONS/Obstacles:

- Industry concerns: Some manufacturers resist the increased financial burden, and the waste management sector is concerned about rising treatment costs.
- Governance: SMEs in the dismantling sector fear that producer-led PROs could limit their independence and create unfair competition.
- Complexity: Cross-border implementation requires complex data exchange and cooperation.
- "Missing Vehicles": The scheme is undermined by the large number of vehicles that are illegally dismantled or exported, a problem the EPR scheme alone cannot solve.

- Administrative burden: Establishing the new system will create a significant administrative workload for both producers and authorities.

The proposed regulation aims to overcome these obstacles by:

- Ensuring fair representation for waste management operators in PROs.
- Empowering the Commission to create detailed rules for fee modulation and cross-border cooperation.
- Integrating the EPR scheme with enhanced traceability measures, such as electronic Certificates of Destruction (CoDs), to combat the "missing vehicle" problem.
- Encouraging the use of digital tools to increase efficiency and reduce administrative costs.

Implementation

While the existing ELV Directive already had some EPR elements, the new regulation significantly strengthens and standardizes these obligations. This would mean also for the member states to adjust their existing EPR schemes to new EU ELV Regulation.

According to the German End-of-Life Vehicles Directive (Altfahrzeug-Verordnung), manufacturers and importers must take back all end-of-life vehicles of their make from the final owner. These vehicles must be accepted free of charge as soon as they are handed over to a recognised collection point or dismantling company designated by a manufacturer for this purpose. Under § 4 of the Directive defines exceptions to free take-back. For instance, vehicles to which waste has been added, or which no longer contain essential parts or components, are not subject to free take-back. To fulfil this obligation, manufacturers and importers have set up a nationwide take-back system. In addition, they cooperate with operators of workshop disposal systems to ensure the return of old parts from vehicle repairs. (VDIK 2025) (GADSYS 2025)

Currently, the profitability of ELV treatment sector is determined by the scrap value for recycling (especially from steel, iron, aluminium, copper) and market value of components/parts for reuse/remanufacturing, thus it is largely driven by the market. German ELV Directive sets on vehicle manufacturers requirement to have the financial and organisational resources necessary to fulfil their obligations under this Directive (AltfahrzeugV, Bundesministeriums der Justiz 2020). A study on "Illegal treatment of end-of-life vehicles" by the German Federal Environment Agency (Umweltbundesamt) indicated that strengthening Extended producer responsibility in Germany can be an approach to contribute to the financial security of ELV treatment activities, especially in the perspective that ELVs will become more complex in the future due to e.g. different refrigerants, the increase in the electromobility, composite materials, etc. Strangthen EPR scheme would transfer the financial responsibility for the ELV treatment to the manufacturers. According to the authors, “Transferring the financial responsibility for dismantling to the manufacturers would go beyond these [current] obligations [in Germany].” (Zimmermann et al. 2022)

The implementation of the new EU ELV provision on EPR scheme will require adaptation of existing legal acts, especially German ELV Regulation. The new EU ELV Regulation will be directly applicable, leaving no room for interpretation of different national approaches. The most significant change will be related to change of financial model, meaning shift from current market-drieven system to producer-funded EPR scheme. The German automotive sector might establish a Producer Responsibility Organization (PRO) for collecting EPR fees, using these fees to cover the net costs of collection and ELVs treatment nationwide.

The new EU ELV Regulation is linked with the EU Battery Regulation what would involve that two legal frameworks work together. That specifically would require update of the German Battery Act (Batteriegesetz) to ensure that the EPR for vehicle batteries is fully aligned with the ELV scheme.

Examples of similar measures

The Netherlands established ARN (Auto Recycling Nederland) which is a well-established EPR system founded by a recycling fee paid by the car buyer upon first registration. In 2002, the fee was €45 per vehicle, which decreased to €30 in 2022. Initially, the funds were used to compensate Authorised Treatment Facilities (ATFs) for dismantling targets (€75 per vehicle). The system later shifted to funding a post-shredder technology (PST) plant to improve material recovery, replacing the direct payments to ATFs for dismantling. ARN now organises, monitors, and optimises the entire recycling chain, providing practical solutions like fluid drainage installations and special battery transport boxes. The Netherlands also has a voluntary EPR for scooters and mopeds (Scooter Recycling Nederland - SRN), founded by importers and dealers, which aims for collection at no cost to the last owner. (Baron et al. 2023)

France recently amended its legislation to strengthen EPR. The "Climate and Resilience" bill (2021) obliges producers to ensure free collection of vehicles from the holder's premises and to pay an "ELV return bonus" to the last owner if it improves collection efficiency. (Baron et al. 2023)

In Republic of Croatia, producers pay an ELV management fee of 0.60 HRK/kg (approx. €0.08/kg) to the Environmental Protection and Energy Efficiency Fund. The Fund covers the entire ELV management system, including compensating the last owner (1,000 HRK/1000 kg for a complete ELV) and collectors for transport costs. (Baron et al. 2023)

Some member states have established deposit refund systems, though they are not managed under an EPR umbrella but by public authorities. These systems provide a financial incentive to the last owner to deliver the end-of-life vehicle (ELV) to an authorized treatment facility (ATF), strengthening the competitiveness of ATFs against the illegal sector. Denmark uses a premium payment system where car users pay an annual fee of 85 DKK (approx. €11) per registered vehicle into the scheme. The last owner receives a pay-out of 2,200 DKK (approx. €286) when they deliver the ELV to an ATF and receive a Certificate of Destruction (CoD). The system is managed by public authorities and has proven effective, as the number of collected vehicles dropped when the premium was temporarily reduced and increased again when it was raised. (Baron et al. 2023)

5.5.3 Establish a statutory lifetime warranty for the entire vehicle based on realistically achievable lifetimes (D7, U12, U13, U17)

Description

The warranty extension measure consists of several parts: a warranty on the entire vehicle, on batteries, on spare parts, and on software updates:

- **Minimum service life warranty for vehicles:** Introduction of a statutory lifetime warranty for the entire vehicle based on realistically achievable service lives; a warranty of 20 years is proposed. Wearing parts are excluded from this.
- **Minimum service life warranty for batteries:** A mandatory minimum warranty for batteries of 60% after 300,000 km or 20 years is specified. Currently, there are no legal obligations for further incentives for long warranty periods for batteries, except for the general 2-year

product warranty and the requirements for traction batteries for M1 and N1 vehicles in the Euro 7 Regulation (Annex II: 5 years and 100,000 km), as well as voluntary manufacturer guaranties (e.g. 160 thousand kilometres, 8 years). DUH has proposed a legally guaranteed minimum service life of 15 years or a mileage of 300,000 km. (DUH 2024b)

- **Minimum service life warranty for spare parts:** A mandatory minimum warranty of two years for spare parts will be established. This measure is part of the proposal for a new end-of-life vehicle regulation presented by the EU Commission on 13 July 2023.
- **Software update warranty:** Vehicle manufacturers will be required to provide software updates over a longer period of time. These must be warrantied for the lifetime of the vehicle, i.e. for 20 years. DUH has proposed a 15-year software update guarantee (DUH 2024b).

How effectively does it guide climate and resource protection?

As shown in the chapters 3.2, 3.6 and 3.7, longevity is one of the most effective measures for reducing resource consumption and greenhouse gas emissions in car transport, as longevity has a direct impact on the number of new vehicles placed on the market.

What economic and administrative costs and effort are incurred with the introduction?

- Public authorities: Inspection and checking, manage data
- Industry: Design and develope new technologies

What are the possible anchoring in existing or possible legal acts/ standards/ initiatives etc.

A mandatory warranty should be set in the European ELV regulation.

EU Sale of Goods Directive (Directive 2019/771): This directive sets a minimum legal guarantee of two years for all goods sold in the EU. This is a foundational consumer protection law, and any new, longer warranty period would have to be built upon this existing framework. It also includes the principle of "conformity" of goods, which a 20-year warranty would radically extend.

In Germany, the Produkthaftungsgesetz (Product Liability Act) holds manufacturers liable for damages caused by their defective products. A statutory 20-year warranty would effectively create a new, stricter definition of "defectiveness," where a product is considered defective if it fails to meet the promised service life.

This regulation sets durability requirements for batteries of M1 and N1 vehicles. The DUH proposal can be seen as a direct challenge to what is considered to be a far too low and insufficient warranty period. The EU Commission's own impact assessments for Euro 7 acknowledge the need for battery longevity but have not gone as far as the DUH proposal.

What is the practical feasibility of the measure, including possible existing obstacles (PROS, CONS)?

PROS:

- High potential for reduction of resource consumption and and CO_2 emissions: A 20-year warranty would force manufacturers to design and build vehicles that are far more durable and reliable. This would drastically reduce the number of new cars produced, leading to a significant decrease in raw material extraction, manufacturing energy consumption, and associated emissions.
- Significant ecological steering effect on new registrations

- With a long-term warranty, consumers would be far more likely to repair their vehicles, rather than discarding them for a new one.
- The focus on repair would create a more robust market for spare parts and independent repair services, fostering competition and potentially lowering costs.
- A long-life battery is more likely to be reused or repurposed for other applications (e.g., in energy storage) after its automotive life, contributing to a circular economy.
- A minimum warranty (2 years) on spare parts is a cornerstone of the right to repair. It provides assurance to consumers and independent repair shops that a new part will function correctly for a reasonable period.
- Long-term software warranty would ensure that vehicles receive critical security patches and bug fixes, protecting against hacking and functional failures. This is a crucial public safety issue.

CONS / Obstacles:

- Longer usage times can delay technological innovation towards more environmentally friendly technologies.
- Feasible in the medium term
- How is the warranty fulfilled if a supplier becomes insolvent?
- The financial risk for OEMs of covering potential failures over such a long period would be immense, leading to a massive increase in vehicle prices to offset the risk.
- The cost of replacing a battery is currently thousands of euros. A 20-year warranty represents a massive financial liability for manufacturers. This would be reflected in a higher initial purchase price for EVs.
- Vehicles are getting more complex, and providing continuous software updates for a wide range of hardware configurations for 15-20 years is a massive technical challenge.

5.5.4 Company car taxation (U2)

Description

An estimated 20 to 25% of newly registered cars in Germany are company cars that are also used privately (UBA 2021). The reason for the attractiveness of the car as a salary component is the low taxation: for employees, the taxable non-cash benefit can be significantly cheaper than the cost of a privately purchased car (on average only 40% of the true benefit). Companies can deduct the purchase of cars for business use as business expenses without a maximum price limit and regardless of the CO_2 emissions of the vehicles.

A CO_2 spread of the non-cash benefit as part of company car taxation can provide an incentive to purchase particularly efficient vehicles. However, if company cars become cheaper as a result of a CO_2 spread, this could make them even more attractive as a salary component and lead to more rather than fewer cars in the long term. The higher taxation of company cars with combustion engines would also have the advantage that the promotion of electric company cars would no longer be borne by all taxpayers, but only by those who drive a - less environmentally friendly - company car themselves. For plug-in hybrids, which currently bring hardly any benefits for the climate as company cars, a short-term abolition of the tax reduction is an option.

In the medium term, a CO_2 spread in company car taxation is no longer necessary or sensible. Instead, such a differentiation should be applied to every vehicle, regardless of whether it is purchased for private or business use - for example in the form of a CO_2 dependent vehicle tax. Otherwise, an additional preference for low-emission company cars would risk continuing to establish company cars as a salary component. This would slow down the modal shift, lead to substantial tax losses and perpetuate socially unbalanced distributions.

How effectively does it guide climate and resource protection?

According to (Fischer et al. 2021) tax breaks for BEVs compared to other drive technologies with direct emissions appear to make sense in principle to support market ramp-up. For PHEVs, however, tax breaks should be linked to the proportion of electric mileage and should not apply if this is low. The resulting subsidy effect for electric cars, which goes beyond the government purchase premiums, should, however, be limited in amount and duration and be designed to be degressive. This is the only way to avoid unbalanced distribution effects compared to those who cannot use a company car.

On the issue of special depreciation allowances for battery-electric vehicles Agora Verkehrswende recommended: „Special depreciation allowances for climate-friendly capital goods generate a steering effect that incurs still low cost for the state under current financing conditions. A special depreciation allowance in the year of purchase, for example amounting to 50 percent of the acquisition costs, can therefore be a fiscally efficient solution to accelerate the switch to purely battery electric vehicles in corporate fleets. Solutions are also conceivable that shorten the depreciation period for climate-compatible vehicles for a transitional period but retain the existing linear character of the "deduction for wear and tear" (AfA). Extending or limiting the general deductibility of vehicle costs depending on the climate impact or other vehicle characteristics, and thus deviating from the objective net principle of German income tax law, could be legally justified on the basis of non-fiscal steering objectives.“ (Agora Verkehrswende 2023)

What are the examples of similar measures already introduced in other countries?

In other European countries, a higher percentage is usually used to calculate the non-cash benefit than in Germany. The consideration of environmentally relevant vehicle characteristics (e.g. CO_2 emissions, fuel consumption, benefits for electric vehicles) for the spread of the calculation is also widespread (FÖS 2018a).

Agora Verkehrswende provides an overview of how company car taxation is structured in various European countries. Various options have already been implemented to favor more environmentally friendly vehicles in company car taxation. In most countries, the list prices of the vehicles are used to calculate the income tax liability for the private use of a company car. The percentage rate is linked to various factors, with lower percentages often being applied depending on CO_2 emissions (e.g. Belgium, Great Britain, Italy, Luxembourg, Austria), 0% is sometimes applied to electric vehicles (e.g. Ireland, Portugal), and in some countries the assessment basis, i.e. the list price applied to electric vehicles, is reduced (e.g. Greece, Ireland, Norway) (Agora Verkehrswende 2022).

For example, Belgium takes CO_2 emissions into account when taxing company cars, with the tax rate increasing linearly with increasing emissions per kilometer. The calculated rate is applied to the list price and an age-related correction factor. Employees also have the option of applying for a mobility allowance/“cash for car” or a mobility budget. These two alternatives are intended to create incentives to give up the company car and switch to more environmentally friendly transport options or to make use of them from the outset. The maximum annual mobility

allowance ("cash for car") when giving up an existing company car is calculated as follows according to a formula.

What is the practical feasibility of the measure, including possible existing obstacles (PROS, CONS)?

PROS:

- Medium potential for reduction of resource consumption and and O_2 emissions
- Significant ecological steering effect on new registrations
- Feasible at the national level
- Feasible in the short term

PROS / Obstacles:

- The company car privilege should be viewed critically from a socio-political perspective, as it benefits a small, generally privileged segment of the population. Only employed persons benefit, and even within this group, company car use correlates with salary level and thus also with gender.

5.5.5 Batteries measures: energey density / capacity (U11)

Description

In this measure minimum specifications for energy density and the maximum capacity would be set. The Battery Regulation defines energy turnover as a functional unit (as a rule, the warranty service life is probably used), which is already an incentive in this direction - with fixed limit values, this could become more important.

A simple and largely reliable criterion for saving battery materials is the use of smaller batteries. Limit values for battery weight per car be achieved by limiting battery capacity as well as through higher energy densities. The maximum permissible battery capacity per utilisation profile is therefore limited. In particular, this approach is more robust in the face of technological developments than, for example, restricting the use of specific materials would be. In the future, it can be expected that the demand for larger batteries will tend to decrease as charging infrastructure improves (especially with fast charging).

In chapter 4 criteria for a resource efficient vihicle are developed and described. There also a proposal for maximum battery capacities is given.

For the three utilisation cases these maximum battery capacities are recommended for all new registred vehicles (minimum ambition level):

- City (2 seats): 22 kWh
- Family (5 seats): 88 kWh
- Transport (9 seats): 130 kWh

There is also a proposal for public procurement, which should be implemeted in the Public Procurement Guidelines.

- City (2 seats): 18 kWh
- Family (5 seats): 70 kWh

- Transport (9 seats): 100 kWh

As a third ambition levele there is a proposal for eco-labelling:

- City (2 seats): 12 kWh
- Family (5 seats): 65 kWh
- Transport (9 seats): 95 kWh

How effectively does it guide climate and resource protection?

As shown in chapter 3.2 a limitation of battery capacity leads to a significant reduction in resource consumption and greenhouse gas emissions.

What economic and administrative costs and effort are incurred with the introduction?

- Reporting via battery passport (OEMs)
- Cost for R&D of batteries with higher energy density (OEM)
- Compliance monitoring (Authorities)

What is the practical feasibility of the measure, including possible existing obstacles (PROS, CONS)?

PROS:

- High potential for reduction of resource consumption and and CO_2 emissions
- Significant ecological steering effect on new registrations
- Feasible at the national level
- Feasible in the short term

PROS / Obstacles:

For public procurement, it may become more difficult to obtain bids if only a few vehicles are put out to tender.ince higher-income households generally have a higher degree of motorization and higher individual mileage, they benefit more from low tax burdens, subsidies, and government benefits in the area of passenger car transportation.

What are the possible anchoring in existing or possible legal acts/ standards/ initiatives etc.

A maximum capacity for all new registered vehicles should be implementedon European level in the 3R type approval regulation.

There are different options for the legal framing of the criteria concerning public procurement: Green public procurement in Germany in general is addressed in the administrative regulations on the procurement of climate-friendly services (Bundesministerium für Wirtschaft und Klimaschutz 2021). However, specifications for vehicles are explicitly referred to in the law and administrative regulation on the procurement of clean vehicles(Bundesministerium für Wirtschaft und Klimaschutz 2022; Bundestag, Bundesrat 2021). Although these do not contain any resource-saving aspects, these laws seem like a logical place to specify such aspects on a federal level. At the EU level, the corresponding anchor legislation is the Revised Clean Vehicles Directive (European Parliament, Council of the European Union 2019) and the Green Public Procurement Criteria for Road Transport (European Commission 2021b).

For eco-labelling, the 'Blauer Engel' eco-label awarded by the German Federal Environment Agency and the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN) is one of the possible standards where the measure could be set.

5.5.6 Obligation on car makers to provide detailed instructions on how to replace and remove parts and components together with the obligation that the design of new vehicles shall allow easy removal and replacement for certain parts and components (D2)

Description

Article 7 of ELV Regulation proposal in a current version indicates that new vehicle types must be designed in a way that allows ATFs to easily remove the parts and components listed in Annex VII, Part C during the vehicle's waste phase. This obligation on OEMs shall be fulfilled by them 72 months after the regulation enters into force. It is intended to facilitate replacement, reuse, recycling, remanufacturing, or refurbishment where technically feasible. This is intended to facilitate replacement, reuse, recycling, remanufacturing, or refurbishment where technically feasible. Manufacturers are explicitly forbidden from using software updates to hinder the removal and replacement of parts and must ensure access to the necessary software documentation and diagnostic tools. (European Parliament, Council of the European Union et al. 2025)

Article 11 complements Article 7 by mandating that manufacturers provide the detailed instructions necessary to perform the removal and replacement of parts, components, and materials. From 36 months after the regulation enters into force, manufacturers must provide unrestricted, standardised, and non-discriminatory access to the information listed in Annex V. This information must enable the safe access, removal, and replacement of specific items, including: electric vehicle batteries and their packs; e-drive motors; parts containing fluids that require depollution; all parts and components listed for mandatory removal in Annex VII, Part C; components containing critical raw materials; digitally coded components whose coding prevents their repair or reuse in another vehicle. The information must be made available to waste management operators, repair and maintenance operators, and emergency services. The information must be provided free of charge, although manufacturers may charge reasonable and proportionate administrative fees for making it accessible through their communication platforms. In the long term (84 months after entry into force), this information will be required to be included in a digital Circularity Vehicle Passport for each vehicle, which will be accessible free of charge. Similar to Article 7, this obligation does not apply to heavy-duty vehicles or trailers. For L-category vehicles, the scope is limited to providing information on the removal of EV/LMT batteries, SLI batteries, catalytic converters, wheels, and tyres. (European Parliament, Council of the European Union et al. 2025)

Climate impact and resource protection

By mandating that vehicles are designed for the easy and non-destructive removal of key components like electric vehicle (EV) batteries and e-drive motors, the regulation ensures that these valuable parts can be recovered for reuse, remanufacturing, refurbishment, or high-quality recycling. Providing detailed instructions ensures that treatment operators can perform these tasks safely and efficiently. This prevents valuable materials from being lost or degraded in shredding processes, thereby maximising resource conservation. By ensuring operators know how to remove a part, where it is, and what it contains, the measures create the necessary conditions for a functioning circular market for parts and materials. (European Parliament, Council of the European Union et al. 2025)

Impact assessment prepared by the Commission provides aggregate estimations for the entire preferred policy package, which clearly link the "design for removal" and "information provision" measures to specific environmental outcomes. The complete preferred policy package is estimated to achieve an annual reduction of 12.3 million tonnes of CO_2 equivalent by 2035. This is largely driven by the better valorisation of materials, which avoids the high GHG emissions associated with primary material production. The monetised value of these CO_2 savings is estimated at EUR 2.8 billion annually in 2035. The package is projected to lead to 5.4 million tonnes of materials being better valorised annually by 2035. This includes materials such as plastics, steel, aluminium, and copper. The JRC estimates that the mandatory removal of e-drive motors (enabled by these design and information measures) will make 350 tonnes of rare earth materials from permanent magnets available for reuse and recycling in 2035, a figure rising to 1,500 tonnes in 2040. (European Commission 2023c)

Economic and administrative efforts

The obligations require vehicle manufacturers to invest in both the physical design of their vehicles and the creation and dissemination of detailed technical information, inter alia:

- Manufacturers will incur costs related to redesigning vehicles to facilitate the easy and non-destructive removal of key components like electric vehicle batteries and e-drive motors.
- To verify compliance, the proposed measures may require OEMs to perform dismantling and shredding tests on prototype vehicles before type-approval. This would involve costs for the vehicle prototype itself, hiring an independent authorised treatment facility (ATF) and a type-approval service provider, and documenting the results. A supporting study estimates that for a scenario including such tests, the cost for OEMs could be around half a million euros annually, assuming 10 OEMs each test five vehicles per year. (Baron et al. 2023)
- While the dismantling information itself must be provided free of charge to waste management operators, manufacturers may incur costs for establishing and maintaining the necessary communication platforms.
- Manufacturers must provide extensive documentation to the type-approval authority to demonstrate compliance, which will increase the administrative workload of the type-approval process. (Baron et al. 2023)

The administration, including Member State authorities and EU bodies like the European Commission, will also incur costs and also face an implementation effort, inter alia:

- Member State authorities will face costs for verifying compliance. The supporting study estimates that market surveillance activities could cost around €190,000 annually across the EU, covering the purchase of vehicles/components and the working time for authorities. (Baron et al. 2023)
- The European Commission will need staff and financial resources to develop the detailed rules and methodologies required by the regulation. This includes, inter alia, specifying the removability requirements for EV batteries and e-drive motors, general removal information for other relevant components and aligning the requirements for the CRM Act with the Batteries Regulation. (European Parliament, Council of the European Union 2023, 2024a)

Feasibility with PROS and CONS

The proposed in EU ELV Regulation proposal new provisions are significant facilitate the transition of the automotive sector to the circular economy, at all vehicle's stages – from design to final treatment at end of life.

PROS:

- The requirement to provide information uses existing industry platforms like the International Dismantling Information System (IDIS) and Repair and Maintenance Information (RMI) systems. While these systems are currently considered insufficient, they provide a foundation that can be enhanced rather than built from scratch. (Baron et al. 2023)
- Designing vehicles for easier dismantling can reduce for OEMs the time and cost required for end-of-life treatment. This is linked to the proposed EPR scheme, were modulated fees privilege design that facilitate easier and more profitable dismantling and recycling. (European Commission 2023a)
- Thanks to the two measures introduced, dismantling high-value components such as EV batteries and e-drive motors, as well as parts containing critical raw materials, shall no longer be hindered. Until now, this was avoided due to economic factors and a lack of specific instructions. (Baron et al. 2023)
- Providing free, standardised, and unrestricted access to dismantling information for all operators removes a significant barrier, especially for SMEs. It enables a level playing field for repair, reuse, and remanufacturing, which in turn reduces the demand for new primary materials.

CONS/Obstracles:

- Redesigning vehicles to facilitate easier removal of components requires investment in R&D.
- Testing and verification costs to prove compliance before type-approval.
- Administrative effort to collect, manage, and standardise the vast amount of technical information required for each vehicle type.
- New administrative workloads for national type-approval authorities. (Baron et al. 2023)
- OEMs concerns that providing detailed technical information, particularly for digitally coded components, could compromise proprietary data and vehicle security. (Baron et al. 2023)
- Trade-offs between designing for circularity and other crucial objectives like vehicle safety, performance, and reducing emissions during the use phase (e.g., through lightweighting with non-recyclable materials). (Baron et al. 2023)

The proposed regulation aims to overcome these obstacles by:

- Introduction of transition periods to give the industry adequate time to adapt their processes and supply chains.
- The regulation allows manufacturers to levy reasonable and proportionate charges to cover the administrative costs of maintaining the communication platforms, balancing access with cost recovery. Otherwise, the information must be provided for free.

- Financial incentives vie EPR, which fees are linked to design choices and rewards manufacturers who overcome the obstracles and invest in more circular designes.

6 Circular Economy Roadmap for passenger cars

In the AutoRess project technical and non-technical options across all vehicle life cycle phases (resource extraction, vehicle design, vehicle production, use and vehicle disposal at end-of-life) were analysed to reduce the impact of the transport sector on climate change and resource consumption. In addition, suitable instruments and measures were developed and evaluated.

Key steps to reduce CO_2 emissions and resource consumption from car transport include the following aspects:

- **Downsizing**: Smaller vehicles with smaller engines consume fewer resources in production and also tend to have lower energy consumption during operation.
- **Switch to electric cars**: The switch to electric cars is an important measure for reducing greenhouse gas emissions. At the same time, the size of the batteries has a significant impact on emissions and, above all, on the raw material requirements in vehicle production. Avoiding oversized battery capacities therefore also offers significant potential for conserving resources.
- **Longevity**: Increasing the service life of both the entire vehicle and its individual components (e.g., through reuse, remanufacturing, or other second-life applications) leads to a reduction in the number of vehicles and thus also to a reduction in resource consumption.
- **Circular Economy**: Improved recycling processes with closed loops contribute to a reduction in primary raw material extraction and to reduction of CO_2 emissions.

The aim of this chapter is to develop a strategic roadmap for the circular economy for vehicles as part of the transport and energy transition in the transport sector. Table 84 gives an overview on the roadmap with the recommended measures and instruments from AutoRess classified according to the following questions:

- Which stakeholders are addressed by the measure?
- In which time frame can the measure be implemented (up to 2030, up to 2035, up to 2040)?
- What impact does the measure have on raw material savings and the reduction of greenhouse gas emissions (green: high impact; yellow: medium impact; red: low impact)?
- Which target is addressed by the measure (smaller vehicles, longevity, lower GH emissions, lower consumption of primary resources, lower energy consumption, better recycling)

Table 84: Recommended measures in a strategic roadmap for the circular economy for passenger cars

No.	Adressed stakeholders	up to 2030	up to 2035	up to 2040	Target
O1	Introduction by authorities; purchase decision by car buyers	Bonus-malus system in tax system based on vehicle size (green)			Smaller vehicles

No.	Adressed stakeholders	up to 2030	up to 2035	up to 2040	Target
D2	Introduction by authorities; Obligation on OEM	Obligation on OEMs to provide detailed instructions on how to replace and remove parts and components together with the obligation that the design of new vehicles shall allow easy removal and replacement for certain parts and components (yellow)			Longevity
D7	Introduction by authorities; Obligation on OEM		Establish a statutory lifetime guarantee for the entire vehicle of 20 years (green)		Longevity
D8	Introduction by authorities; Obligation on OEM		Obligation on OEMs to provide a product carbon footprint (PCF) (yellow)	)	GHG emissions
D9	Introduction by authorities; Obligation on OEM			Establishing a resource footprint; Obligation on OEMs to provide a resource footprint (green)	Primary resources
D10	Introduction by authorities; purchase decision by procurers	Promoting sustainable vehicle in public procurement guidelines (red)			Smaller vehicles / Longevity / Energy consumption
P1	Introduction by authorities; Obligation on OEM		Establishment of recycled content target for steel of 25% post-consumer, thereof 15% closed-loop ellow)		Primary resources / GHG emissions
P3	Introduction by **authorities**; Obligation on OEM		Establishment of recycled content target for plastics of 25% post-		Primary resources / GHG emissions

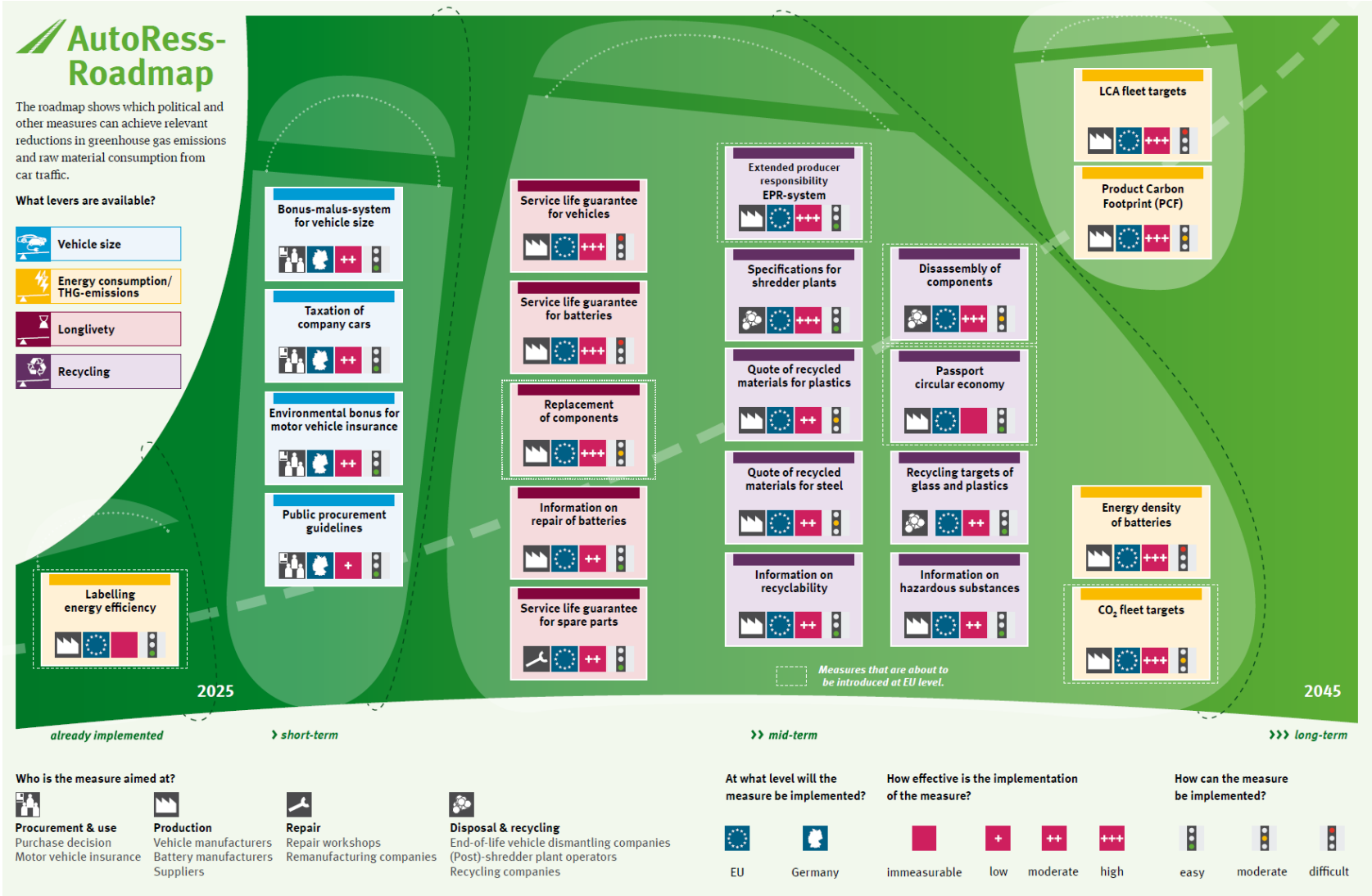
No.	Adressed stakeholders	up to 2030	up to 2035	up to 2040	Target
			consumer, thereof 25% closed loop (yellow)		
U1	Introduction by car insurances; purchase decision by car buyers	Environmental bonus for electric cars and cars with low CO_2 emissions in car insurances (yellow)			GHG emission
U2	Introduction by authorities purchase decision by car buyers / companies	Lower company car taxation for electric cars and cars with low CO_2 emissions (yellow)			GHG emission
U11	Introduction by authorities; Obligation on OEM / battery manufacturers		Set minimal values for energy density of EV batteries (green)		Energy consumption
U12	Introduction by authorities; Obligation on OEM / battery manufacturers		Minimum warranty of 20 years for EV batteries (green)		Longevity
U13	Introduction by authorities; Obligation on OEM / garages / remanufacturers		Minimum warranty of 2 years for spare parts (green)		Longevity
U15	Introduction by authorities; decision by car buyers		Introduction of incentive to encourage the sale of spare parts (yellow)		Longevity
U17	Introduction by authorities; Obligation on OEM / battery manufacturers		Specifications for software update warranties (green)		Longevity
E26	Introduction by authorities; Obligation on OEM		Introduction of EPR scheme to finance proper ELV treatment operations (green)		Recycling

Source: own table Oeko-Institut

Figure 111 shows a graphical representation of the Autoress roadmap “Navigating into the future”. The roadmap shows which political and other measures can achieve relevant reductions in greenhouse gas emissions and raw material consumption from car traffic. Icons are used to provide assessments on the following questions:

- At what level does the measure take effect?
- When will the measure be implemented?
- How effective is the implementation of the measure?
- How easy can the measure be implemented?

Figure 111: Navigating into the future – The AutoRess roadmap for resource-efficient and circular economy-compatible electric vehicles



Source: Own figure Gerda Palmetshofer/Oeko-Institut

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A Appendix

A.1 Scenario analysis

A.1.1 Methodical approach

GHG impacts in the use phase

The core of the scenario analysis was the evaluation of the contributions of individual direct reduction paths to the GHG savings in the scenarios and the assessment of the associated material consumption. Table 85 shows the direct levers in transport that were examined.

Table 85: Direct influencing factors in transport

	Passenger traffic	Freight traffic
Transport demand	Mobility behaviour (number and length of trips per person)	Freight transport demand due to economic development
Shift to other means of transport	Shift to conventional ecomobility (cycling/walking & public transport), multimodality & car/ride sharing	Shifting truck transport services to rail, inland waterway, combined transport
Drive change	Electromobility	Electromobility, fuel cell
Increased efficiency	Drive-specific efficiency increases, across all drives (additional lightweighting)[33]	Efficiency increases for trucks of different size classes

Source: own table Oeko-Institut / ifeu

The analysis of the GHG reduction contributions of these influencing factors with direct effect on transport follows the methodological approach described below:

- Step 1: Differentiated representation of the current initial situation (base year 2021) from the 2023 projection report (Harthan et al. 2023). The traffic volume structure and vehicle fleets with their characteristics (drive types, size classes) are differentiated to such an extent that changes in each individual influencing variable can then be mapped individually compared to this baseline situation.
- Step 2: The GHG reduction contributions of the individual influencing variables in the target years (2030, 2035, 2045) with currently adopted political measures compared to the current situation are derived.
  - From the MMS scenario in the 2023 projection report, the changes in the respective target year compared to the initial situation in 2021 are determined for all parameters (e.g. change in mileage in car kilometers, electric mileage shares in percent).
  - Changes to specific parameters are used individually for each single direct lever for the base year 2021; all other parameters are retained unchanged from 2021. The change in the calculated GHG emissions of national transport (tank-to-wheel, well-to-wheel) compared to the national emissions in 2021 shows the isolated GHG impact of the individual lever. In the comparison between the individual GHG effects, the

33 Downsizing vehicles would also contribute to increasing efficiency across all drives, but is not being investigated in current scenarios.

proportionate contribution of the various direct levers to the overall GHG development in transport can also be weighted.

- **Step 3**: Analogous to the derivation of GHG changes through current political measures in step 2, GHG savings potentials that go beyond the trend are derived from the measure scenarios.
  - For each lever, the differences in the corresponding transport system parameters in the respective target year compared to the MMS scenario are determined.
  - These changes to specific parameters are now used individually for each influencing factor and the associated GHG differences compared to the MMS are calculated. This GHG difference corresponds to the additional GHG savings potential that exists in principle for the respective direct lever according to current scenarios, but which has not yet been realized with political measures adopted to date. By comparing the individual direct levers, the basic GHG savings potentials can be compared with each other.

GHG impacts in vehicle manufacturing

In addition to the GHG emissions in the use phase, the direct levers in the transport sector can also influence upstream and downstream GHG emissions in vehicle production and disposal as well as the material requirements in vehicle production (see chapter 2.1.1). Therefore, changes in the number, size and composition of newly registered vehicles and decommissioned end-of-life vehicles associated with changes in the direct influencing variables were also determined from the scenarios. Based on this, GHG emissions from vehicle production and disposal were calculated.

Vehicle configurations

In the first step, average specific unladen weights of new vehicles were estimated for all vehicle categories on a powertrain-specific basis. Basis for the new registration year 2021 are the average unladen weights of new passenger car registrations in Germany (see chapter 2.1.1) as well as typical unladen weights for trucks in various size classes researched in other projects (Biemann et al. 2024; Dünnebeil et al. 2015; FVV 2021). The average weights for passenger cars also reflect different proportions of new registrations in different purchase segments (diesel cars are on average significantly larger and heavier than petrol cars), and for electric cars also the range of battery capacities. Using the specific vehicle information for selected vehicle classes in (Biemann et al. 2024), the unladen weights were then differentiated according to various GHG and material-relevant vehicle components (body, powertrain and energy storage). For electric vehicles, the assumed battery sizes were also standardized according to (Biemann et al. 2024) as well as typical unladen weights for trucks in various size classes researched in other projects (Biemann et al. 2024; Dünnebeil et al. 2015; FVV 2021). The average weights for passenger cars also reflect different proportions of new registrations in different purchase segments (diesel cars are on average significantly larger and heavier than petrol cars), and for electric cars also the range of battery capacities. Using the specific vehicle information for selected vehicle classes in (Biemann et al. 2024), the unladen weights were then differentiated according to various GHG and material-relevant vehicle components (body, powertrain and energy storage). For electric vehicles, the assumed battery sizes were also standardized according to (Biemann et al. 2024).

In the coming years, average vehicle weights are likely to continue to change as a result of further shifts between purchasing segments, changes in vehicle dimensions etc. (see past developments in chapter 2.1.1). A forecast of these developments is subject to a high degree of uncertainty. In the scenario analysis, the average weights for the vehicle body in the target years were therefore not changed compared to today. However, changes due to powertrain-specific

further developments were taken into account in line with the assumptions in (Biemann et al. 2024).

- Full hybridization is assumed for new passenger cars with combustion engines from 2030.
- In the case of electric vehicles, further developments in battery technologies as well as increasing ranges and thus battery capacities were assumed.
- Fuel cell vehicles do not play a role in the evaluated scenarios for passenger cars, but have a relevant share in light commercial vehicles and trucks and were taken into account accordingly in the analysis for these vehicle categories.

In the GreenSupreme scenario from the RESCUE study(Dittrich et al. 2020a), additional assumptions were made regarding increased lightweighting and a weaker increase in the range and thus battery capacity of electric vehicles. The associated effects were assessed in the scenario analysis as additional sensitivity. Table 86 shows the average vehicle empty weights and battery capacities used in the scenario analysis in the first project phase.

Table 86: Assumptions on average unladen vehicle weights and battery capacities of newly registered cars in the scenario analyses

		Petrol	Diesel	PHEV	BEV
Average unladen weight	2020	1.418	1.962	1.986	1.852
	2030+	1.495	2.038	1.990	1.889
	2030+ GreenSupreme	1.239	1.782	1.734	1.506
Usable battery capacity (kWh)	2020	-	-	12	55
	2030+	2	2	16	80
	2030 + GreenSupreme	2	2	11	53

Source: own table Oeko-Institut / ifeu

Specific GHG emissions

To calculate the GHG emissions in vehicle production and disposal, specific GHG emissions for passenger cars, light commercial vehicles and articulated lorries were taken from (Biemann et al. 2024) and additionally converted to the vehicle configurations shown in Table 86 for passenger cars. These specific GHG values already take into account the increasing decarbonization of electricity and process heat supply for production processes in particular. Solo trucks are not included in (Biemann et al. 2024), and they only account for a small proportion of new truck registrations. Therefore, values for solo trucks up to 12t GVW are taken from (FVV 2021)and scaled up in a simplified manner for trucks >18t.

On this basis, the number of annual new registrations or decommissioning in the scenarios could be extrapolated to the entire vehicle fleet. Analogous to the analysis of the GHG impacts in the use phase, a comparison of the scenarios for the effects of currently adopted policy measures and for additional potentials beyond this could be made.

A.1.2 GHG emissions in the use phase

GHG emissions with currently adopted policy measures

Direct GHG emissions from national transport in Germany will fall from 147 million tons of CO_2e in 2021 to 118 million tons of CO_2e by 2030 with currently adopted policy measures (MMS scenario) in the 2023 projection report. The main factors influencing this development are the increase in electromobility in car and truck transport (around 80% contribution to the GHG savings). Relevant contributions also come from modal shift to ecomobility modes (20%). After 2030, the direct GHG emissions from national transport modelled in the MMS of 2023 projection report decrease further to 87 million tons CO_2e (2035) and 34 million tons CO_2e (2045) [34]. The GHG impacts of individual levers change significantly compared to the development up to 2030.

- **Transport services** continue to increase, especially in freight transport. Without any effects of modal shift and fleet changes compared to 2021, direct GHG emissions would increase as well.
- GHG savings through **modal shift** weaken significantly in passenger transport after 2030 with current policy measures. While passenger car transport performance continues to grow after 2030, transport performance in ecomobility modes decreases after 2030, especially in public transport, and is significantly lower again in 2045 than in 2030. In 2045, the passenger car share of passenger transport performance is 79%, which is only slightly lower than in 2021 (78%). Accordingly, the GHG reduction from modal shifts in passenger transport in 2045 is also very low at 1 million t CO_2e. In freight transport, the GHG impact from modal shifts remains approximately the same as in 2021 in all target years at around 5 million t CO_2e.
- In contrast, the reductions from **improving the car and truck fleet** increase sharply. In 2045, around 85% of cars in the MMS will be electric and therefore have no direct emissions. Compared to the fleet composition of 2021, this corresponds to an emission saving of 97 million t CO_2e. In addition, there is a 54 million t CO_2e GHG reduction from the conversion of the truck fleet to vehicles with alternative powertrains.

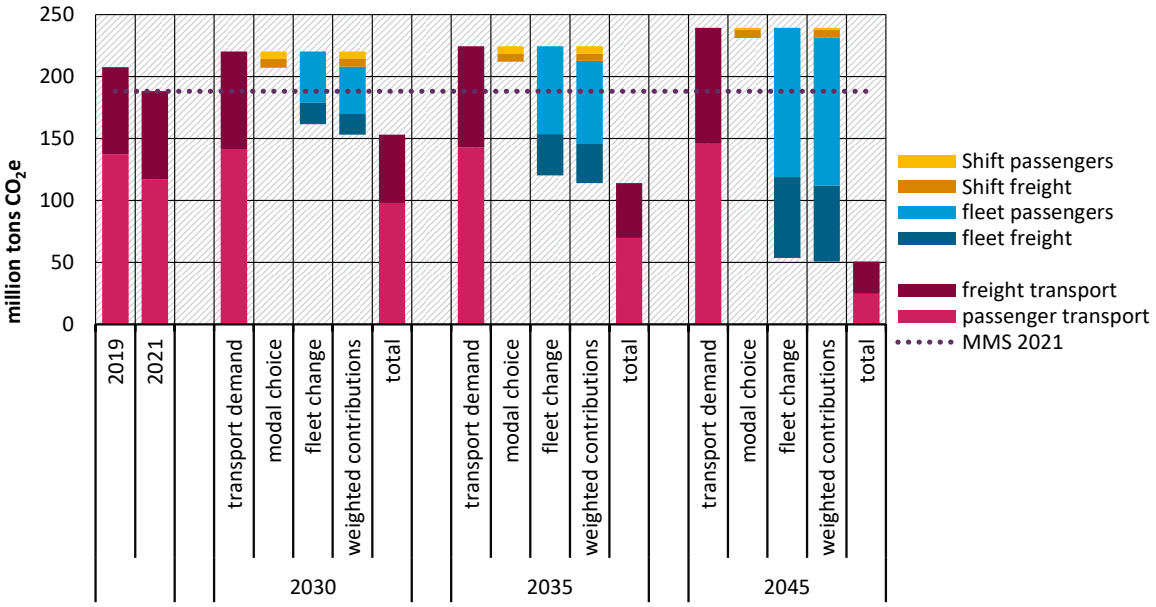
GHG emissions in the use phase are not only generated directly by the vehicles (tailpipe emissions, tank-to-wheel), but also in the provision of fuels and electricity (well-to-tank). As electromobility increases and the proportion of renewable fuels rises, emissions in the use phase shift from the transport sector to energy supply. Figure 112 shows the total energy-related GHG emissions of national transport in the use phase (well-to-wheel). In 2021, these were around 28% higher than direct GHG emissions.

With policy measures in the 2023 MMS scenario, the well-to-wheel GHG emissions in 2035 are 32% higher than the direct GHG emissions from the vehicle. In 2045, the well-to-wheel emissions are 51% higher. Accordingly, future GHG emission reductions in transport in the use phase are somewhat weaker when energy provision is included than when direct GHG emissions alone are considered. From 2021 to 2035, the GHG reduction well-to-wheel is 39% (instead of tank-to-wheel 41%). By 2045, well-to-wheel 73% (instead of tank-to-wheel 77%) of GHG emissions are reduced.

[34] Note: The scenario analyses in AutoRess were carried out in 2023 using the then current 2023 projection report (Harthan et al. 2023). An update to the 2025 projection report (Förster et al. 2025) was available at the end of the AutoRess project. As a result of general development trends and additional measures, a significantly greater reduction in GHG emissions from national transport to 115 million tons CO_2e (2030), 66 million tons CO_2e (2035) or 15 million tons CO_2e (2045) is expected here as a trend.

The basic picture of future GHG developments in transport with current policy measures and the contributions of various influencing factors do not change with the inclusion of energy supply (Figure 112). In 2030, modal shifts in passenger and freight transport will make a relevant contribution to GHG savings, but the majority of GHG reductions will come from the electrification of car and truck fleets, including the effects of an increasing share of renewable energies in electricity production. Even without a strong energy transition at the same time, electromobility would achieve well-to-wheel emission reductions compared to petrol and diesel vehicles, but these would be significantly lower. In the years after 2030, the GHG reduction contributions from modal shift in passenger transport will fall sharply, as a decline in transport services in the ecomobility modes is expected. At the same time, the GHG reduction contributions coming from electromobility will rise sharply due to the increasing electrification of vehicle fleets combined with the simultaneous expansion of renewable electricity generation.

Figure 112: GHG emissions of national transport in the use phase (well-to-wheel) and GHG reduction contributions of different levers as a result of current policy measures



Source: own calculations, based on (Allekotte et al. 2024; Harthan et al. 2023)

Additional GHG reduction potentials of direct levers in national transport

Figure 113 and Figure 114 show additional GHG reduction potentials of direct influencing factors in transport beyond current policy measures that can be derived from the scenario analysis. The direct levers considered in the scenarios are (1) traffic reductions overall, (2) shifts from car and truck traffic to other modes of transport, (3) GHG savings through accelerated electrification of car and truck fleets and (4) cross-drive efficiency improvements.

Measures for dedicated drive-specific efficiency improvements are not considered separately in the scenarios analysed; additional efficiency increases via cost curves in the models include both drive-related and cross-drive technologies. Efficiency increases in new petrol and diesel cars also have little relevance for further GHG reductions if new registrations are completely converted to electric vehicles. A reduction in vehicle size (downsizing: vehicle dimensions, shift to smaller segments) and the associated efficiency potentials are also not included in any of the scenarios analysed. With increasing electrification of vehicle fleets and the use of renewable electricity, the relevance of vehicle size for GHG emissions in the use phase generally decreases.

Nevertheless, smaller, more fuel-efficient vehicles would reduce the overall electricity demand and thus the requirements for the expansion of renewable energies.

The MWMS of the 2023 projection report (Harthan et al. 2023) shows only minor additional GHG savings potentials in passenger as well as freight transport.

Additional GHG savings potentials in passenger transport in GreenSupreme result from avoidance and modal shift as well as in accelerated electric fleet ramp-up and cross-drive efficiency improvements.

- In 2030 and 2035, the additional potential from avoidance and modal shift amounts to around 7-8 million tons of CO_2e each, rising to 9-12 million tons of CO_2e by 2035. An accelerated ramp-up of electromobility will result in additional GHG savings of 12 million t CO_2e (2030) and 16 million t CO_2e (2035). The additional potential from lightweighting is significantly lower at 2-3 million t CO_2e, whereby the share of additional lightweighting in the 2030/35 car population is still low.
- By 2045, the GHG savings potential in all levers will be reduced to less than half compared to 2035, primarily due to the reduced baseline emissions level in 2045 achieved with current policy measures (high proportion of electromobility, high share of renewable electricity).
- In GreenSupreme, the expansion of ridesharing services is being pursued as a central field of action, with the aim of replacing a large proportion of journeys by private car and significantly reducing overall car mileage. Without taking into account the simultaneous modal shift, car mileage will fall by around a quarter in 2045 based on the assumptions made. The additional GHG savings potential in GreenSupreme associated with such a significant reduction in mileage (6 million t CO_2e) is of a similar order of magnitude to that of modal shift (5 million t CO_2e) and additional electromobility (6 million t CO_2e). The additional potential from modal shift is also due to the fact that with current measures in the MMS, transport performance in the ecomobility transport modes will decrease again after an increase up to 2030, while in GreenSupreme the path of action for modal shift will continue to be pursued after 2030.
- An even faster transition to electric passenger cars than in GreenSupreme was considered as an additional sensitivity for electromobility. With current political measures (MMS), the proportion of electric vehicles in the passenger car population will be 79% in 2045. In GreenSupreme, this share rises to 88%. In the scenario study KND45 (Prognos AG et al. 2021), a significantly higher share of 96% is calculated[35]. In this case, the additional GHG savings potential would double from 6 million t CO_2e to 12 million t CO_2e.

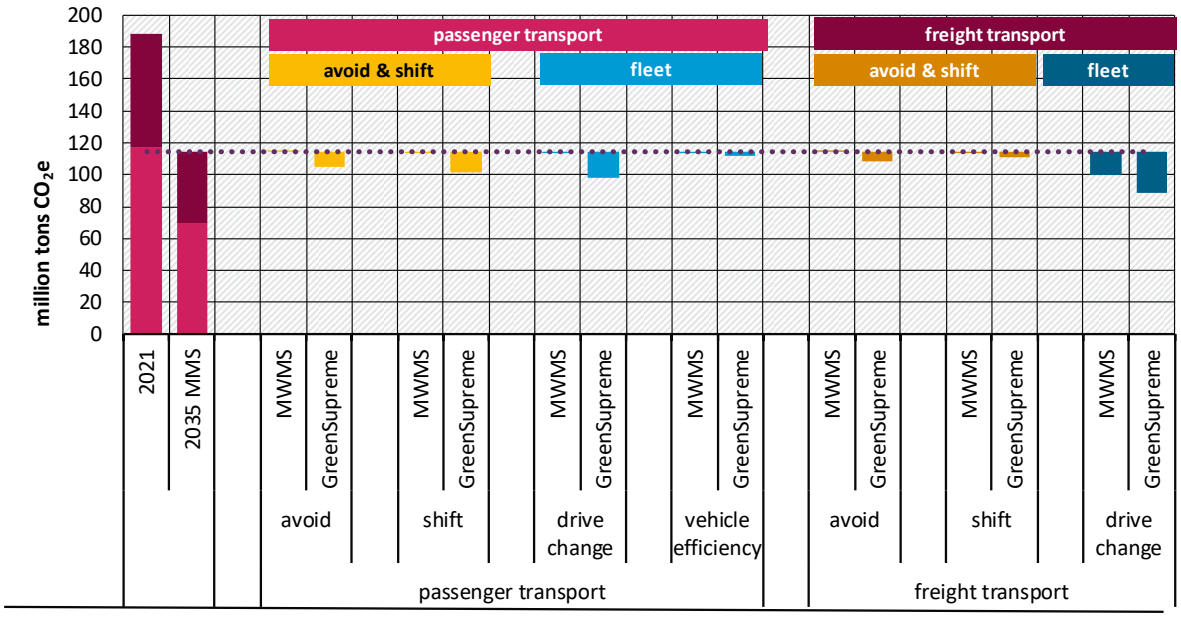
Additional GHG savings potentials in freight transport exist primarily in a lower overall freight transport performance and an accelerated electrification of the truck fleet. Lower transport performance in GreenSupreme is not attributable to transport measures, but results from a weaker economic development and thus transport demand. Additional potential from an accelerated fleet ramp-up of electric trucks in 2030 is similar to passenger transport, but significantly higher in 2035 and 2045 at 26 million t CO_2e (2035) and 19 million t CO_2e (2045).

Conclusion: Significant additional GHG savings potentials in the vehicle use phase are identified in the scenarios primarily in an acceleration of the fleet ramp-up of electric cars and trucks. Additional GHG savings can also come from avoiding and shifting car journeys, but the additional

[35] The electric share of new registrations does not increase any faster in KND45 than in GreenSupreme (in both scenarios, all new registrations will be electric in 2035). This may therefore be due to different assumptions regarding the declining annual mileage of older cars or assumed shorter vehicle lifetimes and the earlier retirement of petrol and diesel cars from the fleet.

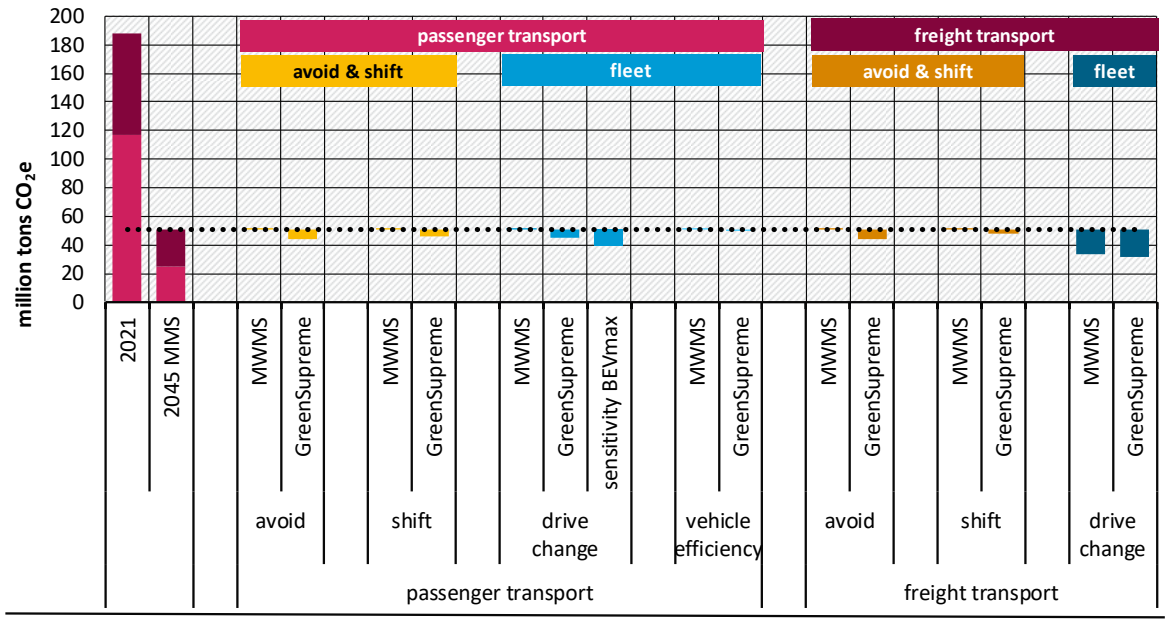
potential is lower than for drive changes. Additional GHG potential estimated in scenarios from the technical lightweighting of passenger cars is low compared to other direct levers. Other increases in efficiency, e.g. through smaller vehicles, are hardly examined in current scenarios and can therefore not be assessed on the basis of the scenario analysis.

Figure 113: Additional GHG reduction potentials (well-to-wheel) through individual direct levers compared to the situation with current policy measures in 2035



Source: own calculations ifeu

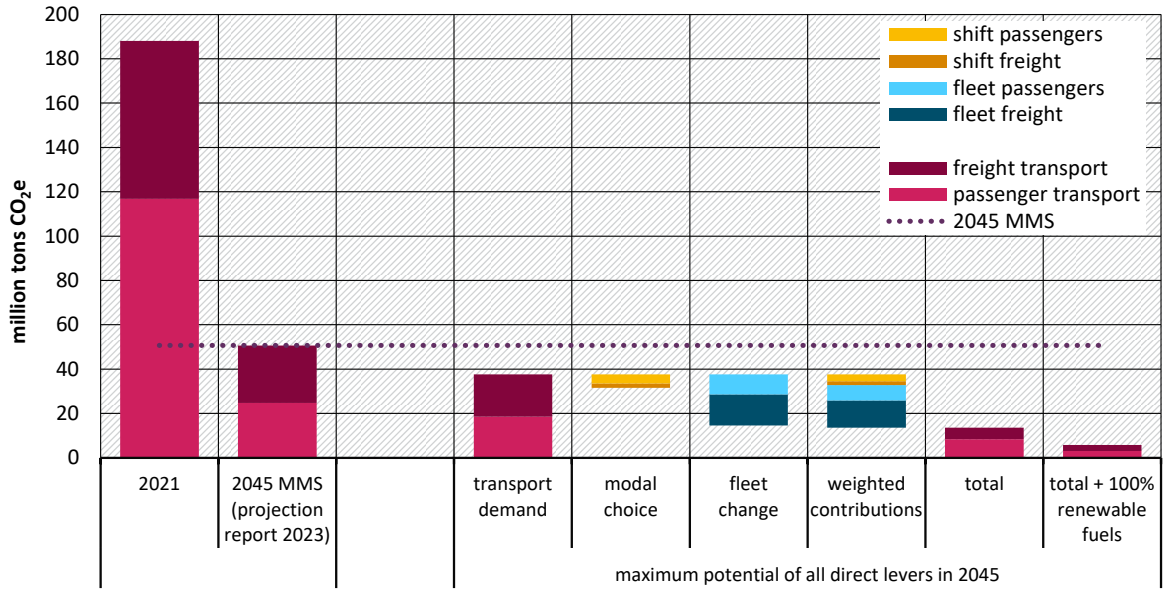
Figure 114: Additional GHG reduction potentials (well-to-wheel) through individual direct levers compared to the situation with current policy measures in 2045



Source: own calculations ifeu

Combined total potential of all direct levers: Figure 115 shows the GHG emissions in national transport in 2045 for the use phase including energy supply with weighted maximum additional potentials of all direct influencing factors in transport considered. If all potentials are exploited, the total well-to-wheel GHG emissions of national transport fall by 93% by 2045 compared to 2021 to 14 million t CO_2e. According to the assumptions in the MMS, 75% of the remaining petrol and diesel vehicles in the fleet run on fossil fuels. If a complete switch to electricity-based fuels (PtL) is also assumed, the GHG emissions well-to-wheel in 2045 will only amount to 6 Mt CO_2e, a reduction of 97% compared to 2021. In a pure tank-to-wheel approach, as in the national GHG inventory, the transport sector will then be completely greenhouse gas neutral.

Figure 115: GHG emissions from national transport in the use phase (well-to-wheel) in 2045 with additional GHG reduction potentials



Source: own calculation

A.1.3 GHG emissions from vehicle manufacturing

GHG emissions from vehicle manufacturing with current policy measures

Figure 116 shows on the left the number of new vehicle registrations per year in the base year 2021 and in the target years 2030, 2035 and 2045 with currently adopted policy measures (MMS) in the 2023 projection report (Harthan et al. 2023) and on the right the GHG emissions from vehicle production calculated for this.

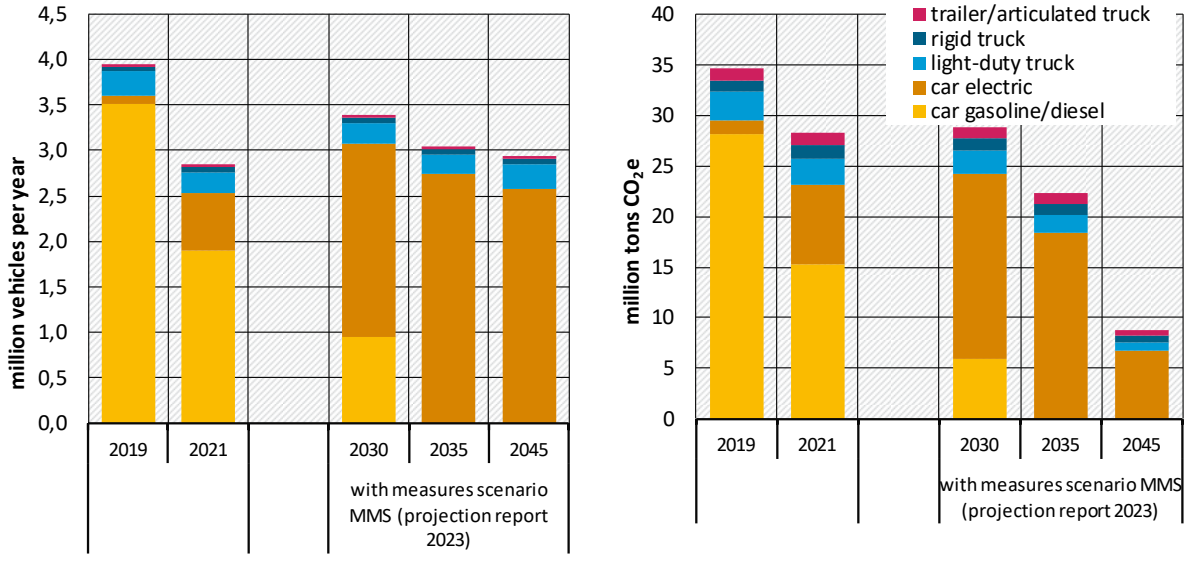
Number of new registrations: 90% of total annual new registrations in Germany are for passenger cars, with a further 7-8% for light commercial vehicles. Trucks >3.5t GVW and articulated lorries account for only 2-3% of total new registrations. The figure also shows the generally wide range of annual new registrations. Compared to 3.6 million new passenger car registrations in 2019, only 2.5 million new passenger cars were registered in 2021. This decline is partly due to the coronavirus pandemic and the associated slump in vehicle mileage in 2020. However, key factors influencing new registrations are independent of (short-term) mileage trends. The general economic situation, individual economic considerations and manufacturers' supply bottlenecks have a strong influence on the number and timing of vehicle purchases (FAZ 2023; ZON 2023), especially as commercial buyers also account for more than half of new car

registrations. Accordingly, increases or decreases in future new registrations modelled in scenarios cannot be attributed solely to the assumed traffic developments.

For the coming years, the MMS of the 2023 projection report (Harthan et al. 2023) initially models a renewed increase in annual new registrations to 3.4 million vehicles in 2030 (of which 3.1 million passenger cars). In 2035 and 2045, only around 3 million new vehicles (2.6-2.7 million passenger cars) will be registered despite a further increase in driving and traffic performance. At the same time, the share of alternative drive systems in new registrations will rise sharply. In 2030, electric cars will account for almost 70% of new registrations; from 2035, only electric cars will be newly registered. In truck traffic, the share of new registrations for alternative drive systems (electric, fuel cell) will rise to 33% by 2030, 54% by 2035 and 67% by 2045.

GHG emissions from vehicle manufacturing: Passenger cars not only dominate the number of new registrations, but also the GHG emissions from vehicle production, accounting for over 80% of total GHG emissions from car and truck production in 2021 (Figure 116, right). In 2030, the modelled greenhouse gas emissions from vehicle production are at a similar level as in 2021, despite a significantly higher number of new registrations and a simultaneous sharp increase in the share of electric vehicles with higher specific GHG emissions from vehicle production (see chapter 2.1.2). In the future, annual emissions from the production of newly registered vehicles could fall sharply. The reason for this lies in the aimed decreasing GHG intensity of production systems in Germany and Europe and a long-term defossilisation of worldwide material supply assumed here, analogous to (Biemann et al. 2024). With slower improvements of GHG intensity in production processes and material supply, manufacturing emissions will be higher in future years.

Figure 116: Number of new registrations in the with-measures scenario of the 2023 projection report and associated GHG emissions from vehicle manufacturing



Source: own calculation

Additional impacts of direct levers on GHG emissions from vehicle manufacturing

Direct levers in the transport sector essentially have the following effects on the annual number of new registrations and the associated greenhouse gas emissions from vehicle manufacturing:

- Number of new registrations per year

- Share of new registrations for various drive concepts
- Technical vehicle characteristics such as range (battery capacities) and efficiency technologies (e.g. lightweighting)

As already described in the previous chapter, the linking of new registration figures to traffic trends is very limited; other factors, in particular economic considerations of vehicle buyers (e.g. total costs of ownership), have a major influence. In addition, these various influencing factors are evaluated in different scenarios using different modelling approaches. Therefore, it is not possible to make reliable estimates of the effects of individual direct influencing factors (traffic avoidance, modal shift) on the number of new registrations by comparing scenarios. For this reason, the assessment of possible effects of direct influencing factors in traffic on vehicle production emissions was simplified. For each target year, 5 different variants of changes in the number or structure of new registrations compared to the reference situation were considered, each based on maximum values from the scenarios analysed. Table 87 describes the different variants.

Table 87: Variants of changes in the number and structure of new registrations in the scenario analyses

Control lever	Maximum expression				V1	V2	V3	V4	V5
		2030	2035	2045					
Number of new car registrations (million cars p.a.)	Reference (MMS)	3.1	2.7	2.6	X				X
	Max. Characteristics (GreenSupreme)	3.0	2.3	1.0					
New registrations of alternative drive systems	Cars: 90% BEVs among new registrations in 2030. From 2035, all new registrations will be BEVs anyway. Trucks: 60% share of new BEV/FCEV registrations in 2030, 100% from 2035.					X		X	X
Additional lightweighting	Aluminium lightweighting. Changes in unladen weight Petrol/diesel/PHEV: -250kg (vehicle body) BEV: -380 kg (vehicle body, reduced battery capacity)						x	x	x

Source: own table Oeko-Institut / ifeu

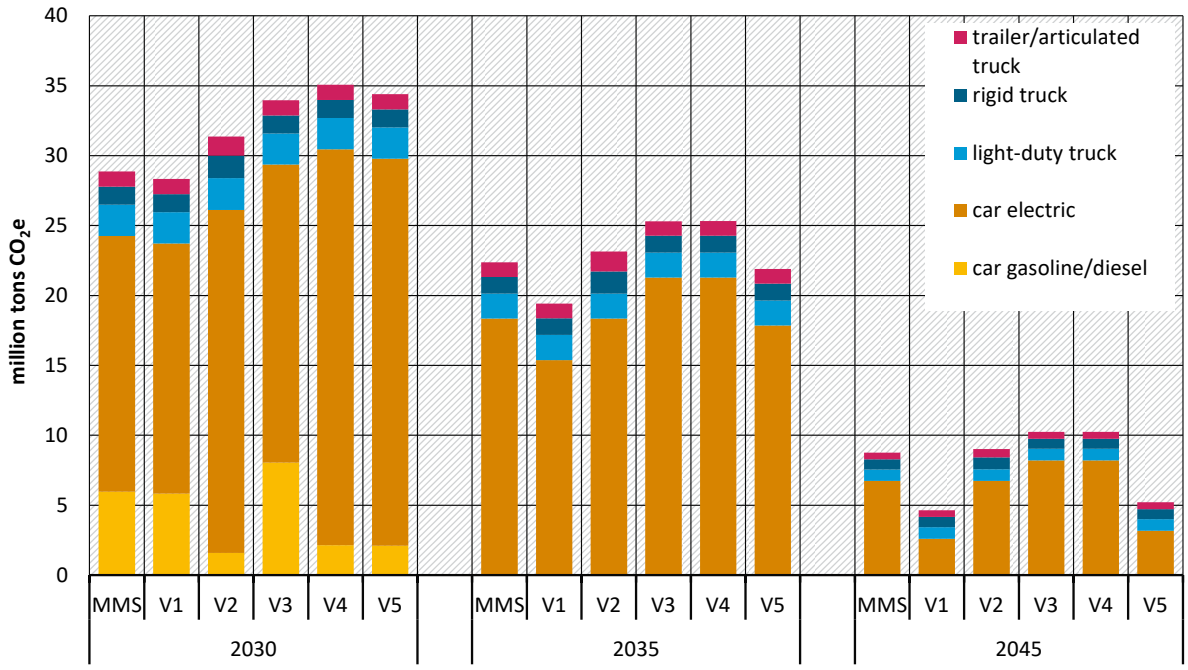
The effects of different new registration figures and structures on GHG emissions from vehicle production are shown in Figure 117. A reduction in new car registrations (V1) with an unchanged new registration structure leads to a reduction in GHG emissions from vehicle production to the same extent. No reduction in the number of new registrations was estimated for trucks.36 An accelerated ramp-up of electromobility for cars and trucks (V2) leads to ~10% higher emissions in 2030 compared to the reference situation. In 2035, all new car registrations are already electric with current policy measures, changes in GHG emissions come only from additional new registrations of electric trucks. In 2045, all new truck registrations are already fully electric or fuel cell vehicles in the reference situation. Additional lightweight aluminium construction (V3) for passenger cars leads to a significant increase in manufacturing emissions of up to 20%. The additional GHG emissions from vehicle production are highest if an accelerated switch to electric drives and additional lightweight aluminium construction are

[36] Since a large proportion of truck mileage in Germany is performed by foreign trucks, it is not possible to simply link mileage to the number of new registrations for trucks either.

assumed together (V4). A reduced number of annual new registrations can partially or fully compensate for the additional emissions in vehicle production as a result of an accelerated change in drive systems and additional lightweight aluminium construction (V5).

The additional effects of direct levers in transport via current measures would thus reduce production emissions slightly in the best case scenario (fewer vehicles) in 2030. However, if the number of new registrations remains the same with additional electric vehicles and lightweight aluminium construction, emissions will increase considerably. Even in 2045, assuming defossilisation of all production processes including worldwide material supply, the direct levers will still have a significant impact on GHG emissions from vehicle production. Additional lightweight aluminium construction leads to a significant increase in GHG emissions. A significant reduction in annual new registrations would also save up to 4 million t CO2e. However, the latter can only occur if, as assumed in the RESCUE study in GreenSupreme, ride sharing becomes the primary means of transport for individual everyday mobility and thus leads to a very sharp decline in private car ownership(Dittrich et al. 2020a). As explained in the scenario selection in chapter A.1.1, such a reduction in car ownership will not be achieved with the policy instruments examined so far in measure scenarios.

Figure 117: GHG emissions from vehicle production for different variants of new registration numbers and structure



Source: own calculation

A.2 Additional information on the AutoRess model

Table 88: Recyled content sources

Material	Process in ecoinvent 3.8	Source / Link
Steel	market for steel, low-alloyed, hot rolled	https://ecoquery.ecoinvent.org/3.8/cutoff/dataset/6862/exchanges
Chromium steel	market for steel, chromium steel 18/8, hot rolled	https://ecoquery.ecoinvent.org/3.8/cutoff/dataset/23886/exchanges
Long steel	-	Öko-Institut, expert knowledge
Flat Steel	-	Öko-Institut, expert knowledge
Cast iron	market for cast iron	https://ecoquery.ecoinvent.org/3.8/cutoff/dataset/3630/exchanges
Wrought aluminium	market for aluminium, wrought alloy	https://ecoquery.ecoinvent.org/3.8/cutoff/dataset/5813/exchanges
Cast aluminium	market for aluminium, cast alloy	https://ecoquery.ecoinvent.org/3.8/cutoff/dataset/7573/exchanges
Copper	market for copper, cathode	https://ecoquery.ecoinvent.org/3.8/cutoff/dataset/23772/exchanges

Source: own table Oeko-Institut / ifeu

A.3 Annual material requirements in the analysed technical and social options

Table 89: Steel & iron: Annual total material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	3,127	3,159	3,285	3,393	3,159	2,881	2,972	3,073	3,174	2,954
Vehicle downsizing	2,959	2,918	2,728	2,640	-	2,767	2,730	2,552	2,469	-
Lightweighting	2,528	2,973	2,986	3,105	3,105	2,364	2,780	2,951	2,904	2,904
Design for circularity	3,146	3,142	3,150	3,150	-	2,872	2,814	2,947	2,947	-
Reuse/remanufacturing EV batteries	3,150	3,146	3,150	-	-	2,947	2,868	2,947	-	-
Reuse/remanufacturing except batteries	3,151	3,046	3,146	-	-	2,946	2,682	2,868	-	-
Recycled content battery materials	3,150	3,150	-	-	-	2,947	2,947	-	-	-
Recycled content non-battery metals	3,150	3,150	3,150	3,150	-	2,947	2,947	2,947	2,947	-
Plastics cycles	3,150	3,150	-	-	-	2,947	2,947	-	-	-
End of life	3,150	3,150	-	-	-	2,947	2,947	-	-	-

Sources: own calculations

Baseline: 2025: 3,452 million kg; 2035: 3,150 million kg; 2045: 2,947 million kg

Table 90: Steel & iron: Annual primary material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	2,703	2,731	2,840	2,934	2,730	2,490	2,569	2,656	2,744	2,554
Vehicle downsizing	2,558	2,523	2,359	2,282	-	2,392	2,360	2,206	2,134	-
Lightweighting	2,184	2,569	2,581	2,684	2,684	2,043	2,403	2,551	2,510	2,510
Design for circularity	2,719	2,716	2,723	2,723	-	2,483	2,433	2,547	2,468	-
Reuse/remanufacturing EV batteries	2,723	2,720	2,723	-	-	2,547	2,479	2,547	-	-
Reuse/remanufacturing except batteries	2,723	2,634	2,720	-	-	2,547	2,319	2,479	-	-
Recycled content battery materials	2,723	2,723	-	-	-	2,547	2,547	-	-	-
Recycled content non-battery metals	2,478	2,233	2,478	2,233	-	2,089	2,089	2,089	2,089	-
Plastics cycles	2,723	2,723	-	-	-	2,547	2,547	-	-	-
End of life	2,723	2,478	-	-	-	2,537	2,089	-	-	-

Sources: own calculations

Baseline: 2025: 2,930 million kg; 2035: 2,723 million kg; 2045: 2,547 million kg

Table 91: Aluminium: Annual total material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	501	540	555	782	424	415	525	519	731	397
Vehicle downsizing	499	490	463	442	-	467	458	433	414	-
Lightweighting	933	678	682	484	484	873	635	674	452	452
Design for circularity	529	528	529	529	-	483	473	495	495	-
Reuse/remanufacturing EV batteries	529	529	529	-	-	495	482	495	-	-
Reuse/remanufacturing except batteries	529	512	529	-	-	495	451	481	-	-
Recycled content battery materials	529	529	-	-	-	495	495	-	-	-
Recycled content non-battery metals	529	529	529	529	-	495	495	495	495	-
Plastics cycles	529	529	-	-	-	495	495	-	-	-
End of life	529	529	-	-	-	495	495	-	-	-

Sources: own calculations

Baseline: 2025: 478 million kg; 2035: 529 million kg; 2045: 495 million kg

Table 92: Aluminium: Annual primary material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	264	277	282	358	238	229	266	264	335	223
Vehicle downsizing	258	253	238	229	-	241	237	223	214	-
Lightweighting	516	312	314	258	258	483	292	310	241	241
Design for circularity	273	273	274	274	-	249	244	256	256	-
Reuse/remanufacturing EV batteries	274	273	274	-	-	256	249	256	-	-
Reuse/remanufacturing except batteries	273	265	273	-	-	256	233	249	-	-
Recycled content battery materials	274	274	-	-	-	256	256	-	-	-
Recycled content non-battery metals	252	238	252	238	-	216	206	216	206	-
Plastics cycles	274	274	-	-	-	256	256	-	-	-
End of life	274	253	-	-	-	256	216	-	-	-

Sources: own calculations

Baseline: 2025: 244 million kg; 2035: 274 million kg; 2045: 256 million kg

Table 93: Copper: Annual total material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	231	260	238	97	155	177	259	222	91	145
Vehicle downsizing	239	233	222	211	-	223	218	208	197	-
Lightweighting	251	252	253	251	251	235	236	250	234	234
Design for circularity	252	252	252	252	-	230	226	236	236	-
Reuse/remanufacturing EV batteries	252	252	252	-	-	236	230	236	-	-
Reuse/remanufacturing except batteries	253	244	252	-	-	236	215	230	-	-
Recycled content battery materials	252	252	-	-	-	236	236	-	-	-
Recycled content non-battery metals	252	252	252	252	-	236	236	236	236	-
Plastics cycles	252	252	-	-	-	236	236	-	-	-
End of life	252	252	-	-	-	236	236	-	-	-

Sources: own calculations

Baseline: 2025: 154 million kg; 2035: 252 million kg; 2045: 236 million kg

Table 94: Copper: Annual primary material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	187	210	192	78	125	143	209	180	73	117
Vehicle downsizing	193	188	179	170	-	180	176	168	159	-
Lightweighting	203	204	205	202	202	189	190	202	189	189
Design for circularity	203	203	204	204	-	186	182	191	191	-
Reuse/remanufacturing EV batteries	204	204	204	-	-	191	186	191	-	-
Reuse/remanufacturing except batteries	203	197	203	-	-	191	174	185	-	-
Recycled content battery materials	204	204	-	-	-	191	191	-	-	-
Recycled content non-battery metals	191	182	191	182	-	167	161	167	161	-
Plastics cycles	204	204	-	-	-	191	191	-	-	-
End of life	204	191	-	-	-	191	167	-	-	-

Sources: own calculations

Baseline: 2025: 124 million kg; 2035: 204 million kg; 2045: 191 million kg

Table 95: Plastics: Annual total material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	841	864	861	981	808	756	819	805	918	756
Vehicle downsizing	806	794	744	718	-	754	743	696	671	-
Lightweighting	857	857	861	825	825	802	802	851	771	771
Design for circularity	856	855	857	857	-	782	766	802	802	-
Reuse/remanufacturing EV batteries	857	856	857	-	-	802	780	802	-	-
Reuse/remanufacturing except batteries	858	829	857	-	-	802	730	781	-	-
Recycled content battery materials	857	857	-	-	-	802	802	-	-	-
Recycled content non-battery metals	857	857	857	857	-	802	802	802	802	-
Plastics cycles	857	857	-	-	-	802	802	-	-	-
End of life	857	857	-	-	-	802	802	-	-	-

Sources: own calculations

Baseline: 2025: 856 million kg; 2035: 857 million kg; 2045: 802 million kg

Table 96: Plastics: Annual primary material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	820	842	839	957	788	734	796	782	892	735
Vehicle downsizing	786	774	726	700	-	732	721	675	651	-
Lightweighting	836	836	840	804	804	779	779	827	749	749
Design for circularity	835	834	834	829	-	759	744	760	733	-
Reuse/remanufacturing EV batteries	836	835	836	-	-	779	758	779	-	-
Reuse/remanufacturing except batteries	835	808	835	-	-	780	709	758	-	-
Recycled content battery materials	836	836	-	-	-	779	779	-	-	-
Recycled content non-battery metals	836	836	836	836	-	779	779	779	779	-
Plastics cycles	600	600	-	-	-	481	481	-	-	-
End of life	836	836	-	-	-	780	780	-	-	-

Sources: own calculations

Baseline: 2025: 835 million kg; 2035: 836 million kg; 2045: 779 million kg

Table 97: Glass: Annual total material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	176	176	176	176	176	165	165	165	165	165
Vehicle downsizing	166	164	153	148	-	155	153	143	138	-
Lightweighting	176	176	177	176	176	165	165	175	165	165
Design for circularity	176	176	176	176	-	161	158	165	165	-
Reuse/remanufacturing EV batteries	176	176	176	-	-	165	161	165	-	-
Reuse/remanufacturing except batteries	176	171	176	-	-	165	150	161	-	-
Recycled content battery materials	176	176	-	-	-	165	165	-	-	-
Recycled content non-battery metals	176	176	176	176	-	165	165	165	165	-
Plastics cycles	176	176	-	-	-	165	165	-	-	-
End of life	176	176	-	-	-	165	165	-	-	-

Sources: own calculations

Baseline: 2025: 180 million kg; 2035: 176 million kg; 2045: 165 million kg

Table 98: Glass: Annual primary material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	176	176	176	176	176	165	165	165	165	165
Vehicle downsizing	166	164	153	148	-	155	153	143	138	-
Lightweighting	176	176	177	176	176	165	165	175	165	165
Design for circularity	176	176	174	171	-	161	158	155	145	-
Reuse/remanufacturing EV batteries	176	176	176	-	-	165	161	165	-	-
Reuse/remanufacturing except batteries	176	171	176	-	-	165	150	161	-	-
Recycled content battery materials	176	176	-	-	-	165	165	-	-	-
Recycled content non-battery metals	176	176	176	176	-	165	165	165	165	-
Plastics cycles	176	176	-	-	-	165	165	-	-	-
End of life	171	155	-	-	-	109	86	-	-	-

Sources: own calculations

Baseline: 2025: 180 million kg; 2035: 176 million kg; 2045: 165 million kg

Table 99: Lithium: Annual total material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	19	23	29	0	108	13	23	28	0	101
Vehicle downsizing	21	20	20	18	-	20	19	18	17	-
Lightweighting	22	22	22	22	22	21	21	22	21	21
Design for circularity	22	22	22	22	-	20	20	21	21	-
Reuse/remanufacturing EV batteries	22	22	22	-	-	21	20	21	-	-
Reuse/remanufacturing except batteries	22	21	22	-	-	21	19	20	-	-
Recycled content battery materials	22	22	-	-	-	21	21	-	-	-
Recycled content non-battery metals	22	22	22	22	-	21	21	21	21	-
Plastics cycles	22	22	-	-	-	21	21	-	-	-
End of life	22	22	-	-	-	21	21	-	-	-

Sources: own calculations

Baseline: 2025: 8 million kg; 2035: 22 million kg; 2045: 21 million kg

Table 100: Lithium: Annual primary material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	17	20	26	0	95	7	16	19	0	81
Vehicle downsizing	18	18	17	16	-	13	13	12	11	-
Lightweighting	19	19	19	19	19	14	14	14	14	11
Design for circularity	19	19	19	19	-	13	13	14	14	-
Reuse/remanufacturing EV batteries	19	19	19	-	-	15	18	18	-	-
Reuse/remanufacturing except batteries	19	19	19	-	-	14	13	13	-	-
Recycled content battery materials	19	19	-	-	-	17	14	-	-	-
Recycled content non-battery metals	19	19	19	19	-	14	14	14	14	-
Plastics cycles	19	19	-	-	-	14	14	-	-	-
End of life	19	19	-	-	-	14	14	-	-	-

Sources: own calculations

Baseline: 2025: 8 million kg; 2035: 19 million kg; 2045: 14 million kg

Table 101: Nickel: Annual total material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	100	118	8	8	102	70	120	7	7	95
Vehicle downsizing	108	105	101	94	-	101	98	94	88	-
Lightweighting	113	114	114	114	114	106	106	113	106	106
Design for circularity	113	113	114	114	-	103	101	106	106	-
Reuse/remanufacturing EV batteries	114	113	114	-	-	106	103	106	-	-
Reuse/remanufacturing except batteries	114	109	114	-	-	106	97	103	-	-
Recycled content battery materials	114	114	-	-	-	106	106	-	-	-
Recycled content non-battery metals	114	114	114	114	-	106	106	106	106	-
Plastics cycles	114	114	-	-	-	106	106	-	-	-
End of life	114	114	-	-	-	106	106	-	-	-

Sources: own calculations

Baseline: 2025: 46 million kg; 2035: 114 million kg; 2045: 106 million kg

Table 102: Nickel: Annual primary material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	87	102	8	8	87	33	80	7	7	59
Vehicle downsizing	93	90	86	81	-	63	61	58	54	-
Lightweighting	98	98	98	98	98	67	67	69	67	50
Design for circularity	97	97	98	98	-	66	65	69	73	-
Reuse/remanufacturing EV batteries	98	97	98	-	-	77	89	91	-	-
Reuse/remanufacturing except batteries	98	94	98	-	-	67	64	66	-	-
Recycled content battery materials	98	98	-	-	-	86	67	-	-	-
Recycled content non-battery metals	97	96	97	96	-	66	66	66	66	-
Plastics cycles	98	98	-	-	-	67	67	-	-	-
End of life	98	97	-	-	-	67	66	-	-	-

Sources: own calculations

Baseline: 2025: 46 million kg; 2035: 98 million kg; 2045: 67 million kg

Table 103: Cobalt: Annual total material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	11.6	13.9	0.0	0.0	6.3	7.8	14.2	0.0	0.0	5.9
Vehicle downsizing	12.6	12.3	11.8	11.0	-	11.8	11.5	11.0	10.3	-
Lightweighting	13.3	13.3	13.3	13.3	13.3	12.4	12.4	13.2	12.4	12.4
Design for circularity	13.3	13.2	13.3	13.3	-	12.1	11.9	12.4	12.4	-
Reuse/remanufacturing EV batteries	13.3	13.3	13.3	-	-	12.4	12.1	12.4	-	-
Reuse/remanufacturing except batteries	13.0	13.0	13.0	-	-	12.0	11.0	12.0	-	-
Recycled content battery materials	13.3	13.3	-	-	-	12.4	12.4	-	-	-
Recycled content non-battery metals	13.3	13.3	13.3	13.3	-	12.4	12.4	12.4	12.4	-
Plastics cycles	13.3	13.3	-	-	-	12.4	12.4	-	-	-
End of life	13.3	13.3	-	-	-	12.4	12.4	-	-	-

Sources: own calculations

Baseline: 2025: 8.4 million kg; 2035: 13.3 million kg; 2045: 12.4 million kg

Table 104: Cobalt: Annual primary material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	8.6	10.3	0.0	0.0	4.5	2.4	8.3	0.0	0.0	2.2
Vehicle downsizing	9.3	9.1	8.7	8.2	-	6.3	6.1	5.8	5.3	-
Lightweighting	9.8	9.8	9.9	9.8	9.8	6.7	6.7	7.0	6.7	4.2
Design for circularity	9.8	9.8	9.8	9.8	-	6.6	6.5	7.0	7.7	-
Reuse/remanufacturing EV batteries	9.8	9.8	9.8	-	-	8.2	8.9	9.2	-	-
Reuse/remanufacturing except batteries	10.0	10.0	10.0	-	-	7.0	6.0	7.0	-	-
Recycled content battery materials	9.8	9.8	-	-	-	9.2	6.7	-	-	-
Recycled content non-battery metals	9.8	9.8	9.8	9.8	-	6.7	6.7	6.7	6.7	-
Plastics cycles	9.8	9.8	-	-	-	6.7	6.7	-	-	-
End of life	9.8	9.8	-	-	-	6.7	6.7	-	-	-

Sources: own calculations

Baseline: 2025: 8.3 million kg; 2035: 9.8 million kg; 2045: 6.7 million kg

Table 105: Graphite: Annual total material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	120	144	223	0	0	81	146	209	0	0
Vehicle downsizing	130	127	122	114	-	122	119	114	107	-
Lightweighting	137	137	138	137	137	128	128	136	128	128
Design for circularity	137	137	137	137	-	125	123	128	128	-
Reuse/remanufacturing EV batteries	137	137	137	-	-	128	125	128	-	-
Reuse/remanufacturing except batteries	137	133	137	-	-	128	117	125	-	-
Recycled content battery materials	137	137	-	-	-	128	128	-	-	-
Recycled content non-battery metals	137	137	137	137	-	128	128	128	128	-
Plastics cycles	137	137	-	-	-	128	128	-	-	-
End of life	137	137	-	-	-	128	128	-	-	-

Sources: own calculations

Baseline: 2025: 48 million kg; 2035: 137 million kg; 2045: 128 million kg

Table 106: Graphite: Annual primary material requirements

	2035					2045				
	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
Alternative powertrains	120	143	223	0	0	79	144	206	0	0
Vehicle downsizing	130	126	121	114	-	120	117	112	105	-
Lightweighting	137	137	137	137	137	126	126	134	126	125
Design for circularity	137	136	137	136	-	123	121	124	122	-
Reuse/remanufacturing EV batteries	137	137	137	-	-	127	124	128	-	-
Reuse/remanufacturing except batteries	137	132	137	-	-	126	115	123	-	-
Recycled content battery materials	137	130	-	-	-	127	94	-	-	-
Recycled content non-battery metals	137	136	136	136	-	126	124	124	124	-
Plastics cycles	137	137	-	-	-	126	126	-	-	-
End of life	137	137	-	-	-	126	126	-	-	-

Sources: own calculations

Baseline: 2025: 48 million kg; 2035: 137 million kg; 2045: 126 million kg

A.4 Models BEV currently available on the German market

The following tables summarizes how the electric vehicle models currently on the market in Germany perform on a selection of criteria. In total, the tables list all 415 BEV models that are included in the Electric Vehicles Database (EV database 2024) and are currently available in Germany.

Table 107: Electric vehicles currently on the market in Germany (Euro Car Segment A mini; KBA: Kleinstwagen)

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Dacia Spring Electric 45	26.8 kWh	230 km *	109 Wh/km *	**1020 kg ***	308 L	4	No
Dacia Spring Electric 65	26.8 kWh	220 km *	114 Wh/km *	**1040 kg ***	308 L	4	No
Leapmotor T03	37.3 kWh	265 km	136 Wh/km	**1175 kg**	210 L	4	No
Hyundai INSTER	42.0 kWh	327 km	119 Wh/km	**1388 kg**	280 L	4	Optional
Hyundai INSTER	49.0 kWh	370 km	124 Wh/km	**1418 kg**	280 L	4	Optional

Source: (EV database 2024)

Table 108: Electric vehicles currently on the market in Germany (Euro Car Segment B small; KBA: Kleinwagen)

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Hyundai INSTER	49.0 kWh	370 km	124 Wh/km	1418 kg	280 L	4	Optional
Fiat 500 Limousine 24kWh	23.8 kWh	190 km	112 Wh/km	1255 kg	185 L	4	No
Fiat 500 Cabrio 24 kWh	23.8 kWh	190 km	112 Wh/km	1281 kg	185 L	4	No
Fiat 500	42.0 kWh	331 km	113 Wh/km	1365 kg	185 L	4	No
Fiat 500 3+1	42.0 kWh	314 km	119 Wh/km	1400 kg	185 L	4	No
Renault 5 E-Tech 40kWh 120ps	43.0 kWh*	312 km	128 Wh/km	1400 kg *	326 L	5	Yes
Fiat 500 Cabrio 42 kWh	42.0 kWh	310 km	120 Wh/km	1405 kg	185 L	4	No

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Abarth 500e Limousine	42.2 kWh	265 km	143 Wh/km	1410 kg	185 L	4	No
Abarth 500e Cabrio	42.2 kWh	255 km	148 Wh/km	1435 kg	185 L	4	No
Citroen e-C3	45.0 kWh*	326 km	135 Wh/km	1491 kg	310 L	5	No
Citroen e-C3 Aircross	45.0 kWh*	306 km	144 Wh/km	1504 kg	460 L	5	No
Fiat Grande Panda	44.0 kWh	320 km	137 Wh/km	1511 kg	361 L	5	No
Opel Frontera	45.0 kWh*	305 km	144 Wh/km	1514 kg	460 L	5	No
Renault 5	55.0 kWh*	410 km	127 Wh/km	1524 kg	326 L	5	Yes
Opel Corsa Electric	50.0 kWh	354 km	131 Wh/km	1530 kg	267 L	5	Yes
Peugeot e-208 50 kWh 136	50.0 kWh	362 km	128 Wh/km	1530 kg *	265 L	5	Yes
Opel Corsa Electric 51 kWh	51.0 kWh	406 km	118 Wh/km	1544 kg	267 L	5	Yes
Peugeot e-208 51 kWh 156	51.0 kWh	400 km	120 Wh/km	1550 kg *	265 L	5	Yes
Ford Puma Gen-E	46.0 kWh*	376 km	116 Wh/km	1563 kg	523 L	5	No
Alpine A290 Elektro 180	55.0 kWh*	380 km	137 Wh/km	1579 kg	326 L	5	Yes
Alpine A290 Elektro 220	55.0 kWh*	364 km	143 Wh/km	1579 kg	326 L	5	Yes
Fiat 600e	54.0 kWh	409 km	124 Wh/km	1595 kg	360 L	5	Yes
Jeep Avenger Elektro	54.0 kWh	404 km	126 Wh/km	1595 kg	355 L	5	Yes
Mini Cooper E	40.7 kWh	305 km	120 Wh/km	1615 kg	200 L	4	Yes
Opel Mokka Electric	54.0 kWh	403 km	126 Wh/km	1615 kg	310 L	5	Yes
Alfa Romeo Junior Elettrica 54 kWh	54.0 kWh	410 km	124 Wh/km	1620 kg	400 L	5	Yes
Peugeot e-2008 54 kWh	54.0 kWh	406 km	125 Wh/km	1623 kg	434 L	5	Optional

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Peugeot e-2008 50 kWh	50.0 kWh	340 km	136 Wh/km	1623 kg	434 L	5	Optional
DS 3 E-Tense	54.0 kWh	402 km	126 Wh/km	1625 kg	350 L	5	Yes
Alfa Romeo Junior Elettrica 54 kWh Veloce	54.0 kWh	n.a.	n.a.	1635 kg	400 L	5	No
MG ZS EV Standard	51.1 kWh	320 km	153 Wh/km	1645 kg	448 L	5	n.a.
Mini Cooper	54.2 kWh	402 km	122 Wh/km	1680 kg	200 L	4	Yes
Hyundai Kona Elektro 48 kWh	51.0 kWh*	377 km	128 Wh/km	1690 kg	466 L	5	No
MG ZS EV	72.6 kWh	440 km	155 Wh/km	1695 kg	448 L	5	n.a.
Abarth 600e Scorpionissima	54.0 kWh	321 km	158 Wh/km	1700 kg	360 L	5	n.a.
Abarth 600e Turismo	54.0 kWh	322 km	158 Wh/km	1700 kg	360 L	5	n.a.
Mini Aceman E	42.5 kWh	310 km	124 Wh/km	1720 kg	300 L	5	Yes
Honda e:Ny1	68.8 kWh	412 km	150 Wh/km	1730 kg	361 L	5	n.a.
Mini Cooper SE	54.2 kWh	371 km	133 Wh/km	1730 kg	200 L	4	Yes
Kia e-Soul 64 kWh	67.5 kWh*	452 km	142 Wh/km	1757 kg	315 L	5	Optional
Hyundai Kona	68.5 kWh*	514 km	127 Wh/km	1773 kg	466 L	5	Optional
Mini Aceman SE	54.2 kWh	406 km	121 Wh/km	1785 kg	300 L	5	Yes
Kia EV3	58.3 kWh	436 km	126 Wh/km	1800 kg	460 L	5	Optional
Mini Aceman SE	54.2 kWh	355 km	139 Wh/km	1825 kg	300 L	5	Yes
Volvo EX30 Single Motor	51.0 kWh	337 km	145 Wh/km	1840 kg	318 L	5	No
Smart #1 Pro	49.0 kWh	310 km	152 Wh/km	1855 kg	323 L	5	Optional
Smart #1 Pure	49.0 kWh	310 km	152 Wh/km	1855 kg	323 L	5	Optional
Smart #3 Pro+	66.0 kWh	435 km	143 Wh/km	1855 kg	370 L	5	Optional
Smart #3 Pro	49.0 kWh	325 km	145 Wh/km	1855 kg *	370 L	5	Optional
Smart #1 Pro+	66.0 kWh	420 km	148 Wh/km	1863 kg	323 L	5	Optional

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Smart #1 Pure+	66.0 kWh	420 km	148 Wh/km	1863 kg	323 L	5	Optional
Smart #1 Premium	66.0 kWh	440 km	141 Wh/km	1875 kg	323 L	5	Yes
Kia EV3	81.4 kWh	605 km	129 Wh/km	1885 kg	460 L	5	Optional
Smart #3 Premium	66.0 kWh	455 km	136 Wh/km	1885 kg	370 L	5	Yes
Zeekr X Long Range RWD	69.0 kWh	440 km	145 Wh/km	1930 kg	362 L	5	Yes
Volvo EX30 Twin Motor Performance	69.0 kWh	450 km	142 Wh/km	1960 kg	318 L	5	Yes
Smart #1 Brabus	66.0 kWh	400 km	155 Wh/km	1975 kg	313 L	5	Yes
Smart #1 Pulse	66.0 kWh	400 km	155 Wh/km	1975 kg	313 L	5	Yes
Volvo EX30 Cross Country	69.0 kWh	427 km	150 Wh/km	1983 kg	318 L	5	Yes
Smart #3 Brabus	66.0 kWh	415 km	149 Wh/km	1985 kg	370 L	5	Yes
Zeekr X Privilege AWD	69.0 kWh	400 km	160 Wh/km	2035 kg	362 L	5	Yes

Source: (EV database 2024)

Table 109: Electric vehicles currently on the market in Germany (Euro Car Segment C medium; KBA: Kompaktklasse)

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Citroen e-C4 54 kWh	54.0 kWh	418 km	122 Wh/km	1536 kg	380 L	5	Yes
Citroen e-C4	50.0 kWh	354 km	131 Wh/km	1536 kg	380 L	5	Yes
Citroen e-C4 X 54 kWh	54.0 kWh	427 km	119 Wh/km	1552 kg	510 L	5	Yes
Citroen e-C4 X	50.0 kWh	352 km	132 Wh/km	1559 kg	510 L	5	Yes
Nissan Leaf	40.0 kWh	285 km	137 Wh/km	1580 kg	435 L	5	Optional
Renault Megane E-Tech EV40 130PS	43.3 kWh	300 km	133 Wh/km	1588 kg	440 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
GWM ORA 03 400 Pro	63.1 kWh	420 km	141 Wh/km	1615 kg	228 L	5	Optional
GWM ORA 03 300	47.8 kWh	310 km	146 Wh/km	1615 kg	228 L	5	Optional
MG MG5 Electric Maximal	61.1 kWh	400 km	144 Wh/km	1637 kg	479 L	5	Yes
MG MG5 Electric Standard	50.3 kWh	320 km	144 Wh/km	1637 kg	479 L	5	n.a.
GWM ORA 03 GT	63.1 kWh	400 km	148 Wh/km	1655 kg	228 L	5	Yes
Renault Megane E-Tech EV60 130PS	65.0 kWh	470 km	128 Wh/km	1699 kg	440 L	5	Yes
MG MG4	51.0 kWh	350 km	145 Wh/km	1710 kg	363 L	5	No
Renault Megane	65.0 kWh	450 km	133 Wh/km	1711 kg	440 L	5	Yes
Mazda MX-30	35.5 kWh	200 km	150 Wh/km	1720 kg	366 L	5	n.a.
MG MG4	64.0 kWh	450 km	137 Wh/km	1726 kg	363 L	5	Yes
BYD DOLPHIN 60.4 kWh	62.0 kWh*	427 km	142 Wh/km	1733 kg	345 L	5	Yes
Opel Astra	54.0 kWh	418 km	122 Wh/km	1736 kg	352 L	5	Yes
Nissan Leaf e+	62.0 kWh	398 km	148 Wh/km	1756 kg	420 L	5	Optional
Kia Niro EV	68.0 kWh*	463 km	140 Wh/km	1757 kg	475 L	5	Yes
Peugeot e-308	54.0 kWh	410 km	124 Wh/km	1759 kg	412 L	5	Yes
Opel Astra Sports Tourer Electric	54.0 kWh	413 km	123 Wh/km	1760 kg	516 L	5	Yes
Volkswagen ID.3	55.0 kWh	388 km	134 Wh/km	1787 kg	385 L	5	Optional
Aiways U6	63.0 kWh*	400 km	150 Wh/km	1790 kg	472 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Peugeot e-308 SW	54.0 kWh	400 km *	127 Wh/km *	1791 kg *	608 L	5	Yes
Aiways U5	63.0 kWh*	410 km	146 Wh/km	1795 kg	496 L	5	No
Volkswagen ID.3	63.0 kWh	434 km	136 Wh/km	1815 kg	385 L	5	Optional
Lynk&Co 02	69.0 kWh*	445 km	148 Wh/km	1820 kg	410 L	5	n.a.
Renault Scenic E-Tech EV60 170ps	65.0 kWh*	430 km	140 Wh/km	1822 kg	545 L	5	Yes
BYD ATTO 3	62.0 kWh*	420 km	144 Wh/km	1825 kg	440 L	5	Yes
MG MG4 Electric 77 kWh	77.0 kWh	520 km	143 Wh/km	1826 kg	363 L	5	Yes
SsangYong Korando e-Motion	61.5 kWh	339 km	165 Wh/km	1840 kg	551 L	5	Yes
CUPRA Born 170 kW - 59 kWh	63.0 kWh	427 km	138 Wh/km	1841 kg	385 L	5	Optional
Kia EV6 63 kWh RWD	63.0 kWh	428 km	140 Wh/km	1855 kg	490 L	5	Optional
MG MG4 Electric XPOWER	64.0 kWh	385 km	160 Wh/km	1878 kg	363 L	5	Yes
MG Marvel R	75.0 kWh*	402 km	174 Wh/km	1885 kg	357 L	5	Yes
Renault Scenic	92.0 kWh*	625 km	139 Wh/km	1917 kg	545 L	5	Yes
BMW iX1	66.5 kWh	475 km	136 Wh/km	1940 kg	490 L	5	Yes
Mini Countryman E	66.5 kWh	462 km	140 Wh/km	1940 kg	460 L	5	Yes
Skoda Elroq	55.0 kWh	374 km	139 Wh/km	1949 kg	470 L	5	No
Kia EV6	84.0 kWh	582 km	137 Wh/km	1950 kg	490 L	5	Optional

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
BMW iX2 eDrive20	66.5 kWh	478 km	135 Wh/km	1960 kg	525 L	5	Yes
Volkswagen ID.3	82.0 kWh	559 km	138 Wh/km	1962 kg	385 L	5	Optional
Hyundai IONIQ 5	63.0 kWh	440 km	136 Wh/km	1965 kg	520 L	5	Optional
CUPRA Born 170 kW - 77 kWh	82.0 kWh	555 km	139 Wh/km	1969 kg	385 L	5	Optional
Toyota bZ4X	71.4 kWh	516 km	124 Wh/km	1970 kg	452 L	5	Yes
Volkswagen ID.5 Pure	55.0 kWh	370 km	141 Wh/km	1970 kg	549 L	5	Optional
SsangYong Torres EVX	73.4 kWh	462 km	156 Wh/km	1979 kg	839 L	5	Optional
Leapmotor C10	74.0 kWh*	420 km	166 Wh/km	1980 kg	435 L	5	Yes
Nissan Ariya 63 kWh	66.0 kWh	404 km	156 Wh/km	1980 kg	468 L	5	Yes
Volkswagen ID.3	84.0 kWh	604 km	131 Wh/km	1985 kg	385 L	5	Optional
Audi Q4 e-tron 35	55.0 kWh	355 km	146 Wh/km	1990 kg	520 L	5	Optional
Audi Q4 Sportback e-tron 35	55.0 kWh	365 km	142 Wh/km	1990 kg	535 L	5	Optional
Volkswagen ID.4 Pure	55.0 kWh	364 km	143 Wh/km	1991 kg	543 L	5	Optional
MG Marvel R Performance	75.0 kWh*	370 km	189 Wh/km	1995 kg	357 L	5	Yes
Volkswagen ID.3 GTX Performance	84.0 kWh	601 km *	131 Wh/km *	2000 kg	385 L	5	Optional
Skoda Elroq	63.0 kWh	449 km	131 Wh/km	2000 kg *	470 L	5	Optional
Skoda Enyaq 60	63.0 kWh	437 km	135 Wh/km	2002 kg	585 L	5	Yes
Skoda Enyaq Coupe 60	63.0 kWh	446 km	132 Wh/km	2006 kg	570 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Ford Explorer Standard Range RWD	55.0 kWh	380 km	137 Wh/km	2008 kg	536 L	5	Optional
Lexus RZ 300e	71.4 kWh	480 km	133 Wh/km	2030 kg	522 L	5	n.a.
Volvo EX40 Single Motor	70.0 kWh	479 km	140 Wh/km	2040 kg	410 L	5	Optional
Mercedes-Benz EQA	69.7 kWh	528 km	126 Wh/km	2045 kg	340 L	5	Yes
Mercedes-Benz EQA	73.9 kWh	560 km	126 Wh/km	2055 kg	340 L	5	Yes
Volvo EC40 Single Motor	70.0 kWh	487 km	138 Wh/km	2057 kg	404 L	5	Yes
Hyundai IONIQ 5	84.0 kWh	570 km	140 Wh/km	2060 kg	520 L	5	Yes
Kia EV6 84 kWh AWD	84.0 kWh	546 km	147 Wh/km	2060 kg	490 L	5	Optional
Volvo EX40 Single Motor ER	82.0 kWh	576 km	137 Wh/km	2075 kg	410 L	5	Yes
Toyota bZ4X X-Mode	71.4 kWh	461 km	139 Wh/km	2075 kg	452 L	5	Yes
Mini Countryman SE ALL4	66.5 kWh	433 km	149 Wh/km	2075 kg *	460 L	5	Yes
BMW iX1	66.5 kWh	440 km	147 Wh/km	2085 kg	490 L	5	Yes
Subaru Solterra AWD	71.4 kWh	466 km	137 Wh/km	2085 kg	441 L	5	n.a.
BMW iX2	66.5 kWh	449 km	144 Wh/km	2095 kg	525 L	5	Yes
Genesis GV60 Sport	77.4 kWh	470 km	157 Wh/km	2095 kg	432 L	5	n.a.
Volvo EC40 Single Motor ER	82.0 kWh	583 km	136 Wh/km	2095 kg	404 L	5	Yes
Mercedes-Benz EQB	73.9 kWh	536 km	132 Wh/km	2105 kg	495 L	7	Yes
Mercedes-Benz EQA 300 4MATIC	69.7 kWh	459 km	145 Wh/km	2110 kg	340 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Mercedes-Benz EQA 350 4MATIC	69.7 kWh	459 km	145 Wh/km	2110 kg	340 L	5	Yes
Skoda Elroq	82.0 kWh	579 km	133 Wh/km	2119 kg	470 L	5	Optional
Nissan Ariya 87 kWh	91.0 kWh	536 km	162 Wh/km	2121 kg	468 L	5	Yes
Skoda Enyaq	82.0 kWh	586 km	131 Wh/km	2141 kg	585 L	5	Yes
Volkswagen ID.5	82.0 kWh	556 km	138 Wh/km	2143 kg	549 L	5	Optional
Volkswagen ID.5	82.0 kWh	556 km	138 Wh/km	2143 kg	549 L	5	Optional
Audi Q4 e-tron	82.0 kWh	563 km	137 Wh/km	2145 kg	520 L	5	Optional
Skoda Enyaq Coupe 85	82.0 kWh	596 km	129 Wh/km	2145 kg	570 L	5	Yes
Audi Q4 Sportback e-tron 45	82.0 kWh	579 km	133 Wh/km	2145 kg	535 L	5	Optional
Genesis GV60 Sport Plus	77.4 kWh	465 km	159 Wh/km	2145 kg	432 L	5	n.a.
Volkswagen ID.4	82.0 kWh	550 km	140 Wh/km	2156 kg	543 L	5	Optional
Mercedes-Benz EQB 300 4MATIC	69.7 kWh	448 km	148 Wh/km	2165 kg	495 L	7	Yes
Mercedes-Benz EQB 350 4MATIC	69.7 kWh	448 km	148 Wh/km	2165 kg	495 L	7	Yes
Volvo EX40 Twin Motor	82.0 kWh	539 km	147 Wh/km	2170 kg	410 L	5	Yes
Hyundai IONIQ 5 84 kWh Allrad	84.0 kWh	546 km	147 Wh/km	2175 kg	520 L	5	Yes
CUPRA Tavascan	82.0 kWh	568 km	136 Wh/km	2178 kg	540 L	5	Optional
Peugeot e-3008 73 kWh	77.0 kWh*	527 km	139 Wh/km	2183 kg	588 L	5	Optional

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Volvo EX40 Twin Motor Performance	82.0 kWh	537 km	147 Wh/km	2184 kg	410 L	5	Yes
Volvo EC40 Twin Motor	82.0 kWh	553 km	143 Wh/km	2185 kg	404 L	5	Yes
Ford Explorer Extended Range RWD	82.0 kWh	602 km	128 Wh/km	2190 kg	536 L	5	Optional
Volvo EC40 Twin Motor Performance	82.0 kWh	552 km	143 Wh/km	2191 kg	404 L	5	Yes
Kia EV6	84.0 kWh	450 km	178 Wh/km	2220 kg	480 L	5	Yes
Opel Grandland	86.0 kWh*	583 km	141 Wh/km	2220 kg	550 L	5	Yes
Hyundai IONIQ 5	84.0 kWh	448 km	179 Wh/km	2225 kg	480 L	5	Yes
Skoda Enyaq	82.0 kWh	549 km	140 Wh/km	2230 kg	585 L	5	Yes
Opel Grandland 73 kWh	77.0 kWh*	525 km	139 Wh/km	2232 kg	550 L	5	Yes
Skoda Enyaq Coupe 85x	82.0 kWh	558 km	138 Wh/km	2234 kg	570 L	5	Yes
Audi Q4 e-tron	82.0 kWh	525 km	147 Wh/km	2235 kg	520 L	5	Optional
Audi Q4 e-tron 45 quattro	82.0 kWh	526 km	146 Wh/km	2235 kg	520 L	5	Optional
Audi Q4 Sportback e-tron 55 quattro	82.0 kWh	539 km	143 Wh/km	2235 kg	535 L	5	Optional
Audi Q4 Sportback e-tron 45 quattro	82.0 kWh	541 km	142 Wh/km	2235 kg	535 L	5	Optional
Volkswagen ID.4 Pro 4MOTION	82.0 kWh	530 km	145 Wh/km	2237 kg	543 L	5	Optional
Peugeot e-3008	101.0 kWh*	701 km	138 Wh/km	2241 kg	588 L	5	Optional

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Volkswagen ID.5 GTX	82.0 kWh	533 km	144 Wh/km	2242 kg	549 L	5	Optional
Volkswagen ID.4	82.0 kWh	515 km	150 Wh/km	2256 kg	543 L	5	Optional
Nissan Ariya e-4ORCE 87 kWh - 225 kW	91.0 kWh	515 km	169 Wh/km	2259 kg	415 L	5	Yes
Ford Explorer	84.0 kWh	566 km	140 Wh/km	2267 kg	536 L	5	Optional
CUPRA Tavascan	82.0 kWh	521 km	148 Wh/km	2273 kg	540 L	5	Optional
Nissan Ariya e-4ORCE 87 kWh - 320 kW Nismo	91.0 kWh	417 km	209 Wh/km	2300 kg *	415 L	5	Yes

Source: (EV database 2024)

Table 110: Electric vehicles currently on the market in Germany (Euro Car Segment D large; KBA: Mittelklasse)

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Peugeot e-408 58 kWh	62.0 kWh*	453 km	128 Wh/km	1804 kg	471 L	5	Yes
Tesla Model 3	78.1 kWh	702 km	107 Wh/km	1825 kg *	594 L	5	Yes
Tesla Model 3	60.0 kWh*	554 km	104 Wh/km	1836 kg	594 L	5	Yes
Hyundai IONIQ 6 53 kWh	53.0 kWh	429 km	117 Wh/km	1850 kg	401 L	5	Optional
Tesla Model 3	78.1 kWh	678 km	111 Wh/km	1899 kg	594 L	5	Yes
Ford Capri Standard Range RWD	55.0 kWh		Keine Daten	1914 kg	572 L	5	Optional
Tesla Model 3	78.1 kWh	528 km	142 Wh/km	1929 kg	594 L	5	Yes
Elaris BEO 86 kWh	86.0 kWh	489 km	166 Wh/km	1955 kg	467 L	5	n.a.

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Tesla Model Y	78.1 kWh	600 km	125 Wh/km	1959 kg	854 L	5	Yes
Hyundai IONIQ 6	77.4 kWh	614 km	121 Wh/km	1985 kg	401 L	5	Yes
Polestar 2 Standard Range Single Motor	70.0 kWh	554 km	123 Wh/km	2020 kg	407 L	5	Optional
Tesla Model Y	78.1 kWh	542 km	138 Wh/km	2054 kg	854 L	7	Yes
GWM ORA 07 Pro	67.0 kWh	440 km	146 Wh/km	2065 kg	333 L	5	Yes
GWM ORA 07 Pure	67.0 kWh	440 km	146 Wh/km	2065 kg	333 L	5	Optional
Tesla Model Y	78.1 kWh	514 km	146 Wh/km	2072 kg	854 L	5	Yes
Tesla Model Y Maximale Reichweite AWD Launch	78.1 kWh	568 km	132 Wh/km	2072 kg	854 L	5	Yes
BMW i4 eDrive35	70.3 kWh	500 km	134 Wh/km	2075 kg	470 L	5	Yes
Polestar 2 Long Range Single Motor	82.0 kWh	659 km	120 Wh/km	2075 kg *	407 L	5	Optional
Hyundai IONIQ 6 77.4 kWh Allrad	77.4 kWh	583 km	127 Wh/km	2095 kg	401 L	5	Yes
BYD SEAL U 71.8 kWh Comfort	73.0 kWh*	420 km	171 Wh/km	2095 kg	552 L	5	Yes
Ford Capri Extended Range RWD	82.0 kWh	627 km	123 Wh/km	2098 kg	572 L	5	Optional
XPENG G6	92.0 kWh*	570 km	154 Wh/km	2100 kg	571 L	5	Yes
XPENG G6 RWD Standard Range	69.0 kWh*	435 km	152 Wh/km	2100 kg	571 L	5	Yes
BMW i4	83.9 kWh	600 km	136 Wh/km	2125 kg	470 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
BYD SEAL 82.5 kWh Design	84.0 kWh*	570 km	145 Wh/km	2130 kg	400 L	5	Yes
Lexus RZ 450e	71.4 kWh	440 km	145 Wh/km	2130 kg	522 L	5	n.a.
DS N°8 FWD	77.0 kWh*	572 km	129 Wh/km	2132 kg	620 L	5	Yes
Ford Mustang Mach-E Extended Range	98.7 kWh	600 km	152 Wh/km	2150 kg	322 L	5	No
Ford Mustang Mach-E Standard Range	75.0 kWh*	470 km	154 Wh/km	2166 kg	322 L	5	No
Ford Capri	84.0 kWh	592 km	133 Wh/km	2174 kg	572 L	5	Optional
Polestar 2 Long Range Dual Motor	82.0 kWh	596 km	133 Wh/km	2175 kg *	407 L	5	Optional
Polestar 2 Long Range Performance	82.0 kWh	568 km	139 Wh/km	2175 kg *	407 L	5	Optional
DS N°8 FWD Long Range	101.0 kWh*	750 km	130 Wh/km	2180 kg	620 L	5	Yes
XPENG G6 AWD Performance	92.0 kWh*	550 km	159 Wh/km	2195 kg	571 L	5	Yes
Audi Q6 e-tron	83.0 kWh	533 km	142 Wh/km	2200 kg	526 L	5	Yes
BYD SEALION 7 82.5 kWh RWD Comfort	84.0 kWh*	482 km	171 Wh/km	2200 kg	520 L	5	Yes
Audi Q6 e-tron Sportback	83.0 kWh	545 km	139 Wh/km	2200 kg *	511 L	5	Yes
GWM ORA 07 GT	86.0 kWh	520 km	161 Wh/km	2210 kg	333 L	5	Yes
Peugeot e-5008 73 kWh	77.0 kWh*	502 km	145 Wh/km	2218 kg	348 L	7	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
BYD SEAL U 87 kWh Design	89.0 kWh*	500 km	174 Wh/km	2222 kg	552 L	5	Yes
Jaguar I-Pace EV400	90.0 kWh	470 km	180 Wh/km	2226 kg	505 L	5	Yes
Audi Q6 e-tron Sportback performance	100.0 kWh	656 km	145 Wh/km	2250 kg *	511 L	5	Yes
Ford Mustang Mach-E AWD Extended Range	98.7 kWh	550 km	165 Wh/km	2257 kg	322 L	5	No
BMW i4	83.9 kWh	548 km	148 Wh/km	2260 kg	470 L	5	Yes
BYD SEAL	84.0 kWh*	520 km	159 Wh/km	2260 kg	400 L	5	Yes
Audi Q6 e-tron performance	100.0 kWh	641 km	148 Wh/km	2275 kg	526 L	5	Yes
DS N°8 AWD Long Range	101.0 kWh*	686 km	142 Wh/km	2289 kg	620 L	5	Yes
BMW i4 M50	83.9 kWh	522 km	156 Wh/km	2290 kg	470 L	5	Yes
Porsche Macan Electric	100.0 kWh	641 km	148 Wh/km	2295 kg	540 L	5	Yes
Ford Mustang Mach-E AWD Standard Range	75.0 kWh*	470 km	154 Wh/km	2300 kg	322 L	5	No
Genesis GV70 Electrified Sport	77.4 kWh	455 km	163 Wh/km	2310 kg	503 L	5	n.a.
BYD SEALION 7 82.5 kWh AWD Design	84.0 kWh*	456 km	181 Wh/km	2315 kg	520 L	5	Yes
Peugeot e-5008	101.0 kWh*	668 km	145 Wh/km	2316 kg	348 L	7	Yes
Ford Mustang Mach-E GT	98.7 kWh	515 km	177 Wh/km	2348 kg	322 L	5	No

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Ford Mustang Mach-E Rally	98.7 kWh	510 km	178 Wh/km	2348 kg	322 L	5	No
Audi Q6 e-tron	100.0 kWh	625 km	152 Wh/km	2400 kg	526 L	5	Yes
Audi Q6 e-tron Sportback quattro	100.0 kWh	636 km	149 Wh/km	2400 kg *	511 L	5	Yes
Audi SQ6 e-tron Sportback	100.0 kWh	607 km	156 Wh/km	2400 kg *	511 L	5	Yes
Porsche Macan	100.0 kWh	613 km	155 Wh/km	2405 kg	540 L	5	Yes
Porsche Macan	100.0 kWh	613 km	155 Wh/km	2405 kg	540 L	5	Yes
BYD SEALION 7	93.0 kWh*	502 km	182 Wh/km	2410 kg	520 L	5	Yes
Porsche Macan 4S Electric	100.0 kWh	606 km	157 Wh/km	2420 kg	540 L	5	Yes
Audi SQ6 e-tron	100.0 kWh	598 km	159 Wh/km	2425 kg	514 L	5	Yes
Porsche Macan Turbo Electric	100.0 kWh	591 km	161 Wh/km	2480 kg	480 L	5	Yes
VinFast VF 8 Eco Vergrößerte Reichweite	90.0 kWh*	471 km	186 Wh/km	2530 kg	376 L	5	Yes
VinFast VF 8 Plus Vergrößerte Reichweite	90.0 kWh*	447 km	196 Wh/km	2595 kg	376 L	5	Yes

Source: (EV database 2024)

Table 111: Electric vehicles currently on the market in Germany (Euro Car Segment E executive; KBA: Kleinstwagen)

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
XPENG P7 RWD Long Range	86.2 kWh	576 km	144 Wh/km	2095 kg	440 L	5	Yes
Volkswagen ID.7	82.0 kWh	621 km	124 Wh/km	2172 kg	532 L	5	Optional
Audi A6 Sportback e-tron	83.0 kWh	627 km	121 Wh/km	2175 kg	502 L	5	Optional
Audi A6 Avant e-tron	83.0 kWh	598 km	127 Wh/km	2185 kg	502 L	5	Optional
Volkswagen ID.7 Tourer	82.0 kWh	607 km	127 Wh/km	2193 kg	605 L	5	Optional
BMW i5 eDrive40 Limousine	84.4 kWh	627 km	130 Wh/km	2195 kg	490 L	5	Yes
XPENG P7 AWD Performance	86.2 kWh	505 km	164 Wh/km	2215 kg	440 L	5	Yes
NIO ET5 Standard Range	75.0 kWh	456 km	161 Wh/km	2215 kg	386 L	5	Yes
Volkswagen ID.7	91.0 kWh	709 km	121 Wh/km	2230 kg	532 L	5	Optional
NIO ET5 Long Range	100.0 kWh	590 km	153 Wh/km	2235 kg	386 L	5	Yes
Volkswagen ID.7 Tourer	91.0 kWh	690 km	125 Wh/km	2239 kg	605 L	5	Optional
Audi A6 Sportback e-tron	100.0 kWh	756 km	126 Wh/km	2250 kg	502 L	5	Optional
BMW i5 eDrive40 Touring	84.4 kWh	602 km	135 Wh/km	2255 kg	570 L	5	Yes
XPENG P7 Wing Edition	86.2 kWh	505 km	164 Wh/km	2255 kg	440 L	5	Yes
Audi A6 Avant e-tron	100.0 kWh	720 km	132 Wh/km	2260 kg	502 L	5	Optional
NIO ET5 Touring	75.0 kWh	435 km	169 Wh/km	2265 kg	450 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Standard Range							
Zeekr 001 Long Range RWD	100.0 kWh	620 km	152 Wh/km	2275 kg	539 L	5	Yes
XPENG G9 RWD Long Range	98.0 kWh	570 km	163 Wh/km	2285 kg	660 L	5	Yes
NIO ET5 Touring Long Range	100.0 kWh	560 km	161 Wh/km	2285 kg	450 L	5	Yes
Polestar 4 Long Range Single Motor	100.0 kWh	610 km *	154 Wh/km *	2305 kg	526 L	5	Yes
XPENG G9 RWD Standard Range	78.2 kWh	460 km	165 Wh/km	2310 kg	660 L	5	Yes
BYD HAN	88.0 kWh*	521 km	164 Wh/km	2325 kg	410 L	5	Yes
Volkswagen ID.7 GTX	91.0 kWh	595 km	145 Wh/km	2328 kg	532 L	5	Optional
Volkswagen ID.7 Tourer	91.0 kWh	584 km	147 Wh/km	2339 kg	605 L	5	Optional
BMW i5 xDrive40 Limousine	84.4 kWh	580 km	140 Wh/km	2345 kg	490 L	5	Yes
Audi A6 Sportback e-tron quattro	100.0 kWh	716 km	133 Wh/km	2360 kg	502 L	5	Optional
Audi A6 Avant e-tron quattro	100.0 kWh	685 km	139 Wh/km	2370 kg	502 L	5	Optional
BMW i5 M60 xDrive Limousine	84.4 kWh	540 km	150 Wh/km	2370 kg	490 L	5	Yes
NIO EL6 Standard Range	75.0 kWh	406 km	181 Wh/km	2378 kg	579 L	5	Yes
NIO EL6 Long Range	100.0 kWh	529 km	170 Wh/km	2398 kg	579 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Audi S6 Sportback e-tron	100.0 kWh	675 km	141 Wh/km	2400 kg	502 L	5	Yes
Mercedes-Benz EQE 300	98.0 kWh*	651 km	137 Wh/km	2405 kg	430 L	5	Yes
BMW i5 xDrive40 Touring	84.4 kWh	561 km	145 Wh/km	2405 kg	570 L	5	Yes
Audi S6 Avant e-tron	100.0 kWh	647 km	147 Wh/km	2410 kg	502 L	5	Yes
Zeekr 001 Privilege AWD	100.0 kWh	580 km	162 Wh/km	2410 kg	539 L	5	Yes
Zeekr 001 Performance AWD	100.0 kWh	590 km	159 Wh/km	2410 kg	539 L	5	Yes
Mercedes-Benz EQE 350+	105.0 kWh*	693 km	139 Wh/km	2415 kg	430 L	5	Yes
XPENG G9 AWD Performance	98.0 kWh	520 km	179 Wh/km	2415 kg	660 L	5	Yes
BMW i5 M60 xDrive Touring	84.4 kWh	522 km	156 Wh/km	2425 kg	570 L	5	Yes
Polestar 4	100.0 kWh	580 km *	162 Wh/km *	2430 kg	526 L	5	Yes
Mercedes-Benz EQE SUV 300	100.0 kWh*	587 km	154 Wh/km	2440 kg	520 L	5	Yes
Mercedes-Benz EQE 350 4MATIC	100.0 kWh*	627 km	144 Wh/km	2475 kg	430 L	5	Yes
Mercedes-Benz EQE SUV 350+	105.0 kWh*	628 km	153 Wh/km	2490 kg	520 L	5	Yes
Mercedes-Benz EQE 500 4MATIC	100.0 kWh*	623 km	145 Wh/km	2490 kg	430 L	5	Yes
BMW iX	100.0 kWh*	602 km	157 Wh/km	2525 kg	500 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Mercedes-Benz EQE AMG 43 4MATIC	100.0 kWh*	506 km	179 Wh/km	2535 kg	430 L	5	Yes
Mercedes-Benz EQE AMG 53 4MATIC+	100.0 kWh*	504 km	180 Wh/km	2540 kg	430 L	5	Yes
Maserati Grecale Folgore	105.0 kWh	501 km	190 Wh/km	2555 kg	535 L	5	n.a.
Mercedes-Benz EQE SUV 350 4MATIC	100.0 kWh*	566 km	160 Wh/km	2560 kg	520 L	5	Yes
Polestar 3 Long Range Single motor	111.0 kWh	650 km *	165 Wh/km *	2575 kg *	484 L	5	Yes
BMW iX xDrive 60	115.0 kWh*	701 km	156 Wh/km	2580 kg	500 L	5	Yes
Mercedes-Benz EQE SUV AMG 43 4MATIC	100.0 kWh*	488 km	186 Wh/km	2600 kg	520 L	5	Yes
Mercedes-Benz EQE SUV 500 4MATIC	105.0 kWh*	604 km	159 Wh/km	2610 kg	520 L	5	Yes
BMW iX M70 xDrive	115.0 kWh*	600 km	182 Wh/km	2655 kg	500 L	5	Yes
Polestar 3 Long Range Dual motor	111.0 kWh	631 km *	170 Wh/km *	2660 kg	484 L	5	Yes
Polestar 3 Long Range Performance	111.0 kWh	561 km *	191 Wh/km *	2660 kg	484 L	5	Yes
Mercedes-Benz EQE SUV AMG 53 4MATIC+	100.0 kWh*	470 km	193 Wh/km	2690 kg	520 L	5	Yes
BYD TANG Flagship	111.0 kWh*	530 km	205 Wh/km	2705 kg	235 L	7	Yes

Source: (EV database 2024)

Table 112: Electric vehicles currently on the market in Germany (Euro Car Segment F luxury; KBA: Oberklasse)

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Lucid Air Touring	94.0 kWh*	725 km	127 Wh/km	2150 kg *	456 L	5	n.a.
Porsche Taycan	89.0 kWh	590 km	139 Wh/km	2165 kg	407 L	5	Yes
Tesla Model S	100.0 kWh*	649 km	146 Wh/km	2170 kg	709 L	5	Yes
Porsche Taycan Sport Turismo	89.0 kWh	565 km	146 Wh/km	2190 kg	446 L	5	Yes
Porsche Taycan Plus	105.0 kWh	678 km	143 Wh/km	2245 kg	407 L	5	Yes
Porsche Taycan 4S	89.0 kWh	557 km	148 Wh/km	2245 kg	407 L	5	Yes
Porsche Taycan 4	89.0 kWh	559 km	147 Wh/km	2245 kg	407 L	5	Yes
Porsche Taycan Plus Sport Turismo	105.0 kWh	650 km	149 Wh/km	2270 kg	446 L	5	Yes
Porsche Taycan 4S Sport Turismo	89.0 kWh	534 km	154 Wh/km	2270 kg	446 L	5	Yes
Porsche Taycan Turbo GT Weissach	105.0 kWh	555 km	175 Wh/km	2295 kg	367 L	2	Yes
Lucid Air Pure RWD	94.0 kWh*	747 km	123 Wh/km	2300 kg *	456 L	5	n.a.
Genesis G80 Electrified Luxury	87.2 kWh	520 km	159 Wh/km	2325 kg	354 L	5	Yes
Porsche Taycan 4S Plus	105.0 kWh	642 km	151 Wh/km	2325 kg	407 L	5	Yes
Porsche Taycan 4 Plus	105.0 kWh	643 km	151 Wh/km	2325 kg	407 L	5	Yes
Maserati GranTurismo Folgore	92.5 kWh	455 km	182 Wh/km	2335 kg	270 L	4	n.a.
Porsche Taycan 4S	105.0 kWh	616 km	157 Wh/km	2350 kg	446 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Plus Sport Turismo							
Porsche Taycan 4 Cross Turismo	105.0 kWh	613 km	158 Wh/km	2355 kg	446 L	5	Yes
Porsche Taycan 4S Cross Turismo	105.0 kWh	610 km	159 Wh/km	2355 kg	446 L	5	Yes
Porsche Taycan GTS	105.0 kWh	628 km	154 Wh/km	2360 kg	366 L	5	Yes
Porsche Taycan Turbo GT	105.0 kWh	554 km	175 Wh/km	2365 kg	326 L	5	Yes
Porsche Taycan Turbo	105.0 kWh	630 km	154 Wh/km	2365 kg	366 L	5	Yes
Porsche Taycan Turbo S	105.0 kWh	630 km	154 Wh/km	2370 kg	366 L	5	Yes
Porsche Taycan GTS Sport Turismo	105.0 kWh	601 km	161 Wh/km	2385 kg	405 L	5	Yes
Audi e-tron GT S	105.0 kWh	609 km	159 Wh/km	2385 kg *	405 L	4	Yes
Porsche Taycan Turbo Sport Turismo	105.0 kWh	606 km	160 Wh/km	2390 kg	405 L	5	Yes
Porsche Taycan Turbo Cross Turismo	105.0 kWh	597 km	162 Wh/km	2395 kg	405 L	5	Yes
Porsche Taycan Turbo S Sport Turismo	105.0 kWh	604 km	161 Wh/km	2395 kg	405 L	5	Yes
Audi e-tron GT RS performance	105.0 kWh	592 km	164 Wh/km	2395 kg *	350 L	4	Yes
Audi e-tron GT RS	105.0 kWh	598 km	162 Wh/km	2395 kg *	350 L	4	Yes
Porsche Taycan Turbo S Cross Turismo	105.0 kWh	596 km	163 Wh/km	2400 kg	405 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Tesla Model X Dualmotor	100.0 kWh*	576 km	165 Wh/km	2415 kg	425 L	7	Yes
Maserati GranCabrio Folgore	92.5 kWh	447 km	186 Wh/km	2415 kg	151 L	4	n.a.
NIO EL7 Standard Range	75.0 kWh	394 km	187 Wh/km	2421 kg	570 L	5	Yes
NIO ET7 Standard Range	75.0 kWh	445 km	165 Wh/km	2434 kg	363 L	5	Yes
Lucid Air Grand Touring	114.0 kWh*	839 km	133 Wh/km	2435 kg	456 L	5	n.a.
NIO EL7 Long Range	100.0 kWh	513 km	175 Wh/km	2441 kg	570 L	5	Yes
NIO ET7 Long Range	100.0 kWh	580 km	155 Wh/km	2454 kg	363 L	5	Yes
Kia EV9 99.8 kWh RWD	99.8 kWh	563 km	171 Wh/km	2501 kg	333 L	7	Yes
Mercedes-Benz EQS	125.0 kWh*	822 km	144 Wh/km	2515 kg	620 L	5	Yes
NIO EL8 Standard Range	75.0 kWh	390 km	188 Wh/km	2538 kg	265 L	6	Yes
Tesla Model X Plaid	100.0 kWh*	543 km	175 Wh/km	2539 kg	425 L	7	Yes
Lotus Emeya	102.0 kWh	610 km	162 Wh/km	2550 kg	509 L	5	Yes
Lotus Emeya S	102.0 kWh	610 km	162 Wh/km	2550 kg	509 L	5	Yes
Lotus Eletre	111.9 kWh	600 km	182 Wh/km	2565 kg	611 L	5	Yes
BMW i7 eDrive50	105.7 kWh	611 km	166 Wh/km	2595 kg	500 L	5	Yes
Lotus Eletre S	111.9 kWh	530 km	206 Wh/km	2595 kg	611 L	5	Yes
Kia EV9 99.8 kWh AWD	99.8 kWh	512 km	188 Wh/km	2625 kg	333 L	7	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Mercedes-Benz EQS 450 4MATIC	125.0 kWh*	798 km	148 Wh/km	2630 kg	620 L	5	Yes
Mercedes-Benz EQS 500 4MATIC	125.0 kWh*	798 km	148 Wh/km	2630 kg	620 L	5	Yes
NIO EL8 Long Range	100.0 kWh	510 km	176 Wh/km	2633 kg	265 L	6	Yes
Mercedes-Benz EQS 580 4MATIC	125.0 kWh*	798 km	148 Wh/km	2635 kg	620 L	5	Yes
Volvo EX90 Single Motor	104.0 kWh	580 km	174 Wh/km	2637 kg	310 L	7	Yes
Lotus Emeya R	102.0 kWh	485 km	204 Wh/km	2650 kg	509 L	5	Yes
Kia EV9 99.8 kWh AWD GT-Line	99.8 kWh	505 km	190 Wh/km	2664 kg	333 L	7	Yes
Mercedes-Benz EQS AMG 53 4MATIC	125.0 kWh*	626 km	188 Wh/km	2700 kg	620 L	5	Yes
BMW i7	105.7 kWh	625 km	163 Wh/km	2715 kg	500 L	5	Yes
Lotus Eletre R	111.9 kWh	450 km	242 Wh/km	2725 kg	611 L	5	Yes
Mercedes-Benz EQS SUV 450+	125.0 kWh*	720 km	164 Wh/km	2730 kg	645 L	7	Yes
BMW i7 M70 xDrive	105.7 kWh	560 km	182 Wh/km	2770 kg	500 L	5	Yes
Cadillac Lyriq 600 E4	106.8 kWh	530 km	192 Wh/km	2774 kg	793 L	5	Yes
Volvo EX90 Twin Motor	111.0 kWh	585 km	183 Wh/km	2811 kg	310 L	7	Yes
Volvo EX90 Twin Motor Performance	111.0 kWh	580 km	184 Wh/km	2811 kg	310 L	7	Yes
Mercedes-Benz EQS SUV 450 4MATIC	125.0 kWh*	673 km	175 Wh/km	2840 kg	645 L	7	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Mercedes-Benz EQS SUV 500 4MATIC	125.0 kWh*	673 km	175 Wh/km	2840 kg	645 L	7	Yes
Mercedes-Benz EQS SUV 580 4MATIC	125.0 kWh*	673 km	175 Wh/km	2845 kg	645 L	7	Yes
Rolls-Royce Spectre	107.0 kWh*	530 km	192 Wh/km	2965 kg	380 L	4	Yes
Mercedes-Benz EQS SUV Maybach 680	125.0 kWh*	612 km	193 Wh/km	3075 kg	440 L	4	Yes
Mercedes-Benz G 580	124.0 kWh*	473 km	245 Wh/km	3085 kg	555 L	5	n.a.

Source: (EV database 2024)

Table 113: Electric vehicles currently on the market in Germany (Euro Car Segment S sports; KBA: Sportwagen)

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
MG Cyberster	77.0 kWh	509 km	146 Wh/km	1900 kg *	249 L	2	n.a.
MG Cyberster XPOWER	77.0 kWh	444 km	168 Wh/km	2000 kg *	249 L	2	n.a.

Source: (EV database 2024)

Table 114: Electric vehicles currently on the market in Germany (Euro Car Segment M multi-purpose; KBA: Nutzfahrzeuge)

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Citroen e-Berlingo M	52.0 kWh	345 km	145 Wh/km	1811 kg	775 L	5	Yes
Toyota Proace City Verso Electric L1 50 kWh	52.0 kWh	345 km	145 Wh/km	1811 kg	775 L	5	Yes
Opel Combo-e Life 50 kWh	52.0 kWh	345 km	145 Wh/km	1811 kg	775 L	5	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Peugeot e-Rifter M 50 kWh	52.0 kWh	345 km	145 Wh/km	1830 kg	775 L	5	Yes
Renault Kangoo E-Tech Electric	48.0 kWh*	285 km	158 Wh/km	1871 kg	950 L	5	Yes
Nissan Townstar EV Kombi	48.0 kWh*	285 km	158 Wh/km	1872 kg	819 L	5	Optional
Mercedes-Benz EQT 200 Standard	48.0 kWh*	282 km	160 Wh/km	1874 kg	551 L	5	Yes
Citroen e-Berlingo XL	52.0 kWh	339 km	147 Wh/km	1881 kg	1050 L	7	Yes
Opel Combo-e Life XL 50 kWh	52.0 kWh	339 km	147 Wh/km	1881 kg	1050 L	7	Yes
Toyota Proace City Verso Electric L2 50 kWh	52.0 kWh	343 km	146 Wh/km	1881 kg	1050 L	7	Yes
Peugeot e-Rifter XL 50 kWh	52.0 kWh	334 km	150 Wh/km	1901 kg	1050 L	7	Yes
Mercedes-Benz EQT 200 Lang	48.0 kWh*	266 km	169 Wh/km	1944 kg	828 L	7	Yes
Renault Kangoo Grand E-Tech Electric	48.0 kWh*	278 km	162 Wh/km	1992 kg	500 L	7	Yes
Peugeot e-Traveller L2 50 kWh	50.0 kWh	223 km	208 Wh/km	2027 kg	603 L	9	Yes
Citroen e-SpaceTourer M 50 kWh	50.0 kWh	223 km	208 Wh/km	2027 kg	603 L	9	Yes
Opel Zafira-e Life L2 50 kWh	50.0 kWh	223 km	208 Wh/km	2027 kg	603 L	9	Yes

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Toyota PROACE Verso L1 50 kWh	50.0 kWh	223 km	208 Wh/km	2027 kg	603 L	9	Yes
Opel Zafira-e Life L3 50 kWh	50.0 kWh	220 km	210 Wh/km	2056 kg	989 L	9	Yes
Citroen e-SpaceTourer XL 50 kWh	50.0 kWh	220 km	210 Wh/km	2056 kg	989 L	9	Yes
Peugeot e-Traveller L3 50 kWh	50.0 kWh	220 km	210 Wh/km	2056 kg	989 L	9	Yes
Opel Zafira-e Life L2 75 kWh	75.0 kWh*	351 km	194 Wh/km	2211 kg	603 L	9	Yes
Citroen e-SpaceTourer M 75 kWh	75.0 kWh*	351 km	194 Wh/km	2211 kg	603 L	9	Yes
Peugeot e-Traveller L2 75 kWh	75.0 kWh*	351 km	194 Wh/km	2211 kg	603 L	9	Yes
Toyota PROACE Verso L2 75 kWh	75.0 kWh*	348 km	195 Wh/km	2240 kg	989 L	9	Yes
Opel Zafira-e Life L3 75 kWh	75.0 kWh*	348 km	195 Wh/km	2240 kg	989 L	9	Yes
Peugeot e-Traveller L3 75 kWh	75.0 kWh*	348 km	195 Wh/km	2240 kg	989 L	9	Yes
Citroen e-SpaceTourer XL 75 kWh	75.0 kWh*	348 km	195 Wh/km	2240 kg	989 L	9	Yes
Maxus MIFA 9	90.0 kWh*	440 km	191 Wh/km	2385 kg	466 L	7	Yes
Volkswagen ID. Buzz KR Pure	63.0 kWh	331 km	178 Wh/km	2400 kg	1121 L	5	Optional
Mercedes-Benz eVito	66.0 kWh	256 km	234 Wh/km	2483 kg	990 L	8	n.a.

Model	Battery capacity	Electric range	Energy consumption in use (WLTP)	Kerb weight	Transport capacity	Seats	Heat pump
Tourer Lang 60 kWh							
Volkswagen ID. Buzz KR GTX	84.0 kWh	400 km *	198 Wh/km *	2500 kg *	1121 L	5	Optional
Volkswagen ID. Buzz KR Pro	84.0 kWh	461 km	171 Wh/km	2510 kg	1121 L	5	Optional
Mercedes-Benz eVito Tourer Extralang 60 kWh	66.0 kWh	254 km	236 Wh/km	2517 kg	1390 L	8	n.a.
Mercedes-Benz EQV 250 Lang	66.0 kWh	236 km	254 Wh/km	2594 kg	1030 L	7	n.a.
Mercedes-Benz eVito Tourer Lang 90 kWh	100.0 kWh	381 km	236 Wh/km	2630 kg	990 L	8	n.a.
Volkswagen ID. Buzz LR Pro	91.0 kWh	487 km	177 Wh/km	2636 kg	1340 L	7	Optional
Mercedes-Benz EQV 250 Extralang	66.0 kWh	236 km	254 Wh/km	2641 kg	1410 L	7	n.a.
Volkswagen ID. Buzz LR GTX	91.0 kWh	450 km *	191 Wh/km *	2700 kg *	1340 L	7	Optional
Mercedes-Benz EQV 300 Lang	100.0 kWh	363 km	248 Wh/km	2741 kg	1030 L	7	n.a.
Mercedes-Benz EQV 300 Extralang	100.0 kWh	361 km	249 Wh/km	2788 kg	1410 L	7	n.a.

Source: (EV database 2024)