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Final report

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Regulatory opportunities for extensive electrification in mobile machinery and equipment, recreational craft, and powered two-wheelers

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Christoph Heidt, Dominik Räder, Hinrich Helms, Esther Kummetz, Institute for Energy and Environmental Research Heidelberg gGmbH (ifeu), Heidelberg

Konstantin Weller, Johann Friedrich Absenger, FVT mbH, Graz

Stephan Schmidt, Hans-Jürgen Schacht, Graz University of Technology, Graz
Eamonn Mulholland, Felipe Rodriguez, Lingzhi Jin, ICCT, Berlin

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Wörlitzer Platz 1
06844 Dessau-Roßlau
Tel: +49 340-2103-0
Fax: +49 340-2103-2285
buergerservice@uba.de
Internet: www.umweltbundesamt.de

Report performed by:
Institute for Energy and Environmental Research Heidelberg gGmbH (ifeu)
Wilckensstr. 3
69120, Heidelberg
Germany

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Abstract: eNRMM – Regulatory opportunities for extensive electrification in mobile machinery and equipment, recreational craft, and two-wheelers

Non-road mobile machinery (NRMM) used in agriculture, construction, and horticulture, as well as recreational boats, remain heavily dependent on fossil fuels. These machines account for approximately 2 Gt CO_2e worldwide—more than global maritime shipping—and represent about 3% of the EU's annual greenhouse gas emissions (90–110 Mt CO_2e). In principle, electrification is often the most energy-efficient and cost-effective path to decarbonization here as well, provided it is technically feasible. However, it requires systemic changes—ranging from the redesign of powertrains to the development of charging infrastructure. The study therefore first analyzes the direct electrification potential of NRMM, motorized two-wheelers, and recreational boats, broken down in detail by sector, machine type, and power class.

In addition, it identifies policy options that would promote the decarbonization of these sectors. Here, the study shows that, in the short term, further development of existing regulatory frameworks—such as Stage V—is recommended to create incentives for early electrification through stricter pollutant limits, operational requirements, and flexible mechanisms (e.g., exemptions in conjunction with the simultaneous market launch of zero-emission machines). At the same time, the groundwork for CO_2-based regulation should be laid, for example through a targeted monitoring and reporting framework for emission-relevant categories (> 19 kW) and, in the long term, through a zero-emission target—the implementation of which, however, requires reliable market data and a harmonized registration system. This can be supplemented by demand-side instruments such as public procurement, environmental zones, and subsidy programs. Accompanying investments in infrastructure, electricity supply, and market transparency are necessary to support the market ramp-up of zero-emission technologies and achieve substantial emissions reductions.

Kurzbeschreibung: eNRMM – Regulatorische Möglichkeiten für eine umfassende Elektrifizierung von mobilen Maschinen und Geräten, Sportbooten und Zweirädern

NRMM, die in der Landwirtschaft, im Bauwesen und im Gartenbau eingesetzt werden, sowie Freizeitboote sind nach wie vor stark von fossilen Brennstoffen abhängig. Diese Maschinen verursachen weltweit etwa 2 Gt CO_{2e} – mehr als die globale Seeschifffahrt – und machen etwa 3 % der jährlichen Treibhausgasemissionen der EU aus (90–110 Mt CO_{2e}). Prinzipiell ist auch hier Elektrifizierung oft der energieeffizienteste und kostengünstigste Weg zur Dekarbonisierung, sofern sie technisch machbar ist. Sie erfordert jedoch systemische Veränderungen – von der Neugestaltung der Antriebsstränge bis hin zur Ladeinfrastruktur. Die Studie analysiert daher zunächst die direkten Elektrifizierungspotenziale von NRMM, motorisierten Zweirädern und Freizeitbooten detailliert aufgeschlüsselt nach Sektoren, Maschinentypen und Leistungsklassen.

Zusätzlich werden politische Handlungsoptionen aufgezeigt, die eine Dekarbonisierung dieser Bereich befördern. Hier zeigt die Studie, dass sich kurzfristig eine Weiterentwicklung bestehender Regelwerke wie Stufe V empfiehlt, um über verschärfte Schadstoffgrenzwerte, Betriebsanforderungen und flexible Mechanismen (z. B. Ausnahmen bei gleichzeitiger Markteinführung emissionsfreier Maschinen) Anreize für eine frühzeitige Elektrifizierung zu schaffen. Parallel sollten die Grundlagen für eine CO_2-basierte Regulierung gelegt werden, etwa durch einen fokussierten Monitoring- und Berichtsrahmen für emissionsrelevante Kategorien (> 19 kW) sowie perspektivisch durch eine Null-Emissions-Vorgabe, deren Umsetzung jedoch verlässliche Marktdaten und ein harmonisiertes Zulassungssystem voraussetzt. Ergänzen können nachfrageseitige Instrumente wie öffentliche Beschaffung, Umweltzonen und Förderprogramme. Flankierend sind Investitionen in Infrastruktur, Stromversorgung und Markttransparenz erforderlich, um den Markthochlauf emissionsfreier Technologien zu unterstützen und substanzielle Emissionsminderungen zu realisieren.

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List of abbreviations

Abbreviation	Explanation
BEM	Battery Electric Machine
BEV	Battery Electric Vehicle
CCNR	Central Commission for the Navigation of the Rhine
CEMA	European Agricultural Machinery Association
CVD	Clean Vehicle Directive
EBI	European Boating Industry
EP	Electrification Potential
EU27	European Union with 27 member states
GHG	Greenhouse Gas
H2	Hydrogen
HC	Hydrocarbon
IWA	Inland waterway auxiliary engine (EU Stage V Category)
IWP	Inland waterway propulsion engine (EU Stage V Category)
kW	Kilowatt
kWh	Kilowatt Hour
LCA	Life Cycle Assessment
NOx	Nitrogen Oxides
NRE	Non-road engines intended and suited to move (EU Stage V Category)
NRG	Non-Road Generator (EU Stage V Category)
NRMM	Non-Road Mobile Machinery
NRS	Spark Ignition nonroad engines (EU Stage V Category)
NRSh	Spark Ignition handheld nonroad engines (EU Stage V Category)
PJ	Petajoule
PM	Particulate Matter
PWC	Personal Watercraft
RLL	Rail Locomotive Engine (EU Stage V Category)
RLR	Rail Railcar Engine (EU Stage V Category)
PTW	Powered Two-Wheeler
SI	Spark ignition
SMB	Snow mobile Engines (EU Stage V Category)
SOC	State of Charge

Abbreviation	Explanation
TCO	Total Cost of Ownership
TREMOD-MM	Transport Emission Model-Mobile Machinery
VDMA	Verband Deutscher Maschinen- und Anlagenbau

Summary

Introduction

The European Union has committed to reducing greenhouse gas (GHG) emissions by 55 % by 2030 (compared to 1990) and achieving climate neutrality by 2050. Germany aims to reach net-zero emissions even earlier, by 2045. While the road transport sector is already transitioning toward electrification – b supported by EU regulations like CO_2 fleet targets and national incentives – non-road mobile machinery (NRMM) lacks a clear pathway for decarbonization. The same applies for powered two-wheelers (PTW) and recreational craft.

NRMM, used in agriculture, construction, and gardening, and recreational craft still rely heavily on fossil fuels. These machines contribute ~2 Gt CO_{2e} globally – more than global maritime shipping – and account for ~3 % of the EU's annual GHG emissions (90-110 Mt CO_{2e}). Beyond GHGs, NRMM also emit significant air pollutants (NOx, PM) and noise, particularly impacting urban air quality and public health.

Electrification is often the most energy-efficient and cost-effective path to decarbonization where technically feasible within the transport sector. However, it requires systemic changes – from powertrain redesigns to charging infrastructure. Regarding NRMM there is still little information on the electrification potential across diverse machine types. To address this knowledge gap, the German Federal Ministry for the Environment (BMUKN) and the German Environment Agency (UBA) commissioned the eNRMM study. Its goal is to assess the electrification potential of NRMM, recreational craft, and powered two-wheelers and to develop policy options to incentivize electrification where it is feasible.

Why focus on electrification?

This study fills public knowledge gaps on the technical potential for electrification – accounting for constraints such as the much lower energy density of batteries versus liquid and gaseous fuels – across the diverse mobile-machinery, two-wheeler, and recreational-craft sectors, and develops targeted regulatory options to facilitate market uptake. The study follows the premise that electrification is—where technically feasible—the most energy-efficient and consequently, in many cases, the most cost-effective pathway to decarbonise vehicles and mobile machinery. At the same time, electrification requires substantial systemic changes down to the individual vehicle/machine level: at minimum, electric vehicles and machines have different powertrain and energy storage systems. Moreover, supporting infrastructure (e.g. charging, grid access) must be adapted to operational contexts.

The study did not focus on decarbonisation via green fuels because it does not require the same systemic and application-specific redesign. There are already many studies on producing and scaling green fuels; by contrast, electrification requires detailed, equipment-level/use-case analyses across diverse machine (and vehicle) types. At the same time, availability of green fuels is constrained, with competing demand from sectors such as aviation, shipping, and industry. Only once the electrification potential in the mobile machinery, two-wheeler, and recreational-craft sectors is quantified can residual demand for alternative solutions such as green fuels be determined.

The study covers the EU27 from 2025 to 2050, analyzing NRMM, powered two-wheelers, and recreational craft in detail – broken down by sectors (e.g., construction, forestry), machine types (e.g., tractors, chainsaws), and power classes (e.g., 0–18 kW). The primary focus is on direct electrification (batteries, grid connection), with alternative powertrains (e.g., hydrogen)

considered only where electrification is infeasible. Emissions assessments prioritize tank-to-wheel (TTW) but include well-to-wheel (WTW) and life-cycle analyses (LCA).

Product Categorization Framework for NRMM, Recreational Craft, and Powered Two-Wheelers

The classification of product categories is foundational, as it structures the analysis of this study, i.e. electrification potential, policy options, and impact assessments. The categories – covering non-road mobile machinery (NRMM), recreational craft, and powered two-wheelers – reflect diverse applications, technical characteristics, operational profiles, and regulatory contexts. To ensure compatibility with existing regulations, the study aligns its categories with the EU Stage V Regulation (2016/1628), see Table 1.

Table 1: NRMM categories as defined for Stage V included in the study

Category	Description
NRE	All other engines for NRMM not falling under categories below (IWP, IWA, RLL, RLR)
NRG	Engines for mobile power generation
NRSh	Spark-ignition (SI) engines for handheld machinery
NRS	SI engines, excluding NRSh
IWP	Engines for inland waterway vessel propulsion
IWA	Auxiliary engines for inland waterway vessels
RLL	Engines for locomotive propulsion
RLR	Engines for railcar propulsion

Note: SMB (snowmobiles) and ATS (all-terrain vehicles) were excluded from the study. In NRG all power classes were addressed, while Stage V only includes engines >560 kW in this category.

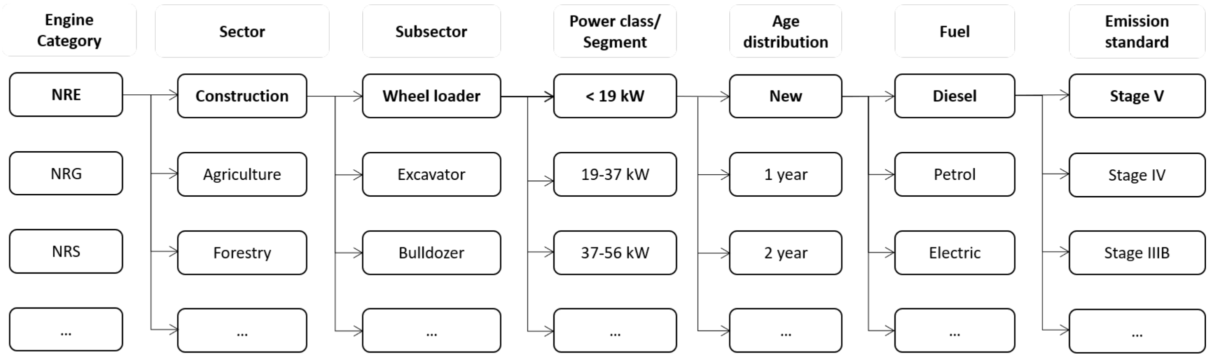
Powered two-wheelers (PTWs) were segmented by power and type (e.g., mopeds, motorcycles) as classified under EU Regulation 168/2013 (L-category vehicles). The categories for recreational craft range from small outboard-powered boats and personal watercraft to larger fishing or sailing vessels.

For a more detailed analysis, the categories were further subdivided by machine category, engine power and fuel type (see next section).

EU27 Emissions Inventory for NRMM and Recreational Craft (2025)

The creation of a bottom-up emissions inventory served as the basis for further analyses. It includes energy consumption, greenhouse gas (GHG) emissions, and air pollutants across all NRMM and recreational craft categories in the EU27 for 2025. Therefore, we used the TREMOD-MM model — a tool with over 20 years of application in Germany — and extended its scope to the EU27 and incorporated new drivetrain types (electric and hydrogen). The model employs a population-based approach multiplying stock, operating hours, power and energy consumption/emissions factors in high differentiation (see Figure 1).

Figure 1: Example of the differentiation in the emission inventory TREMOD-MM



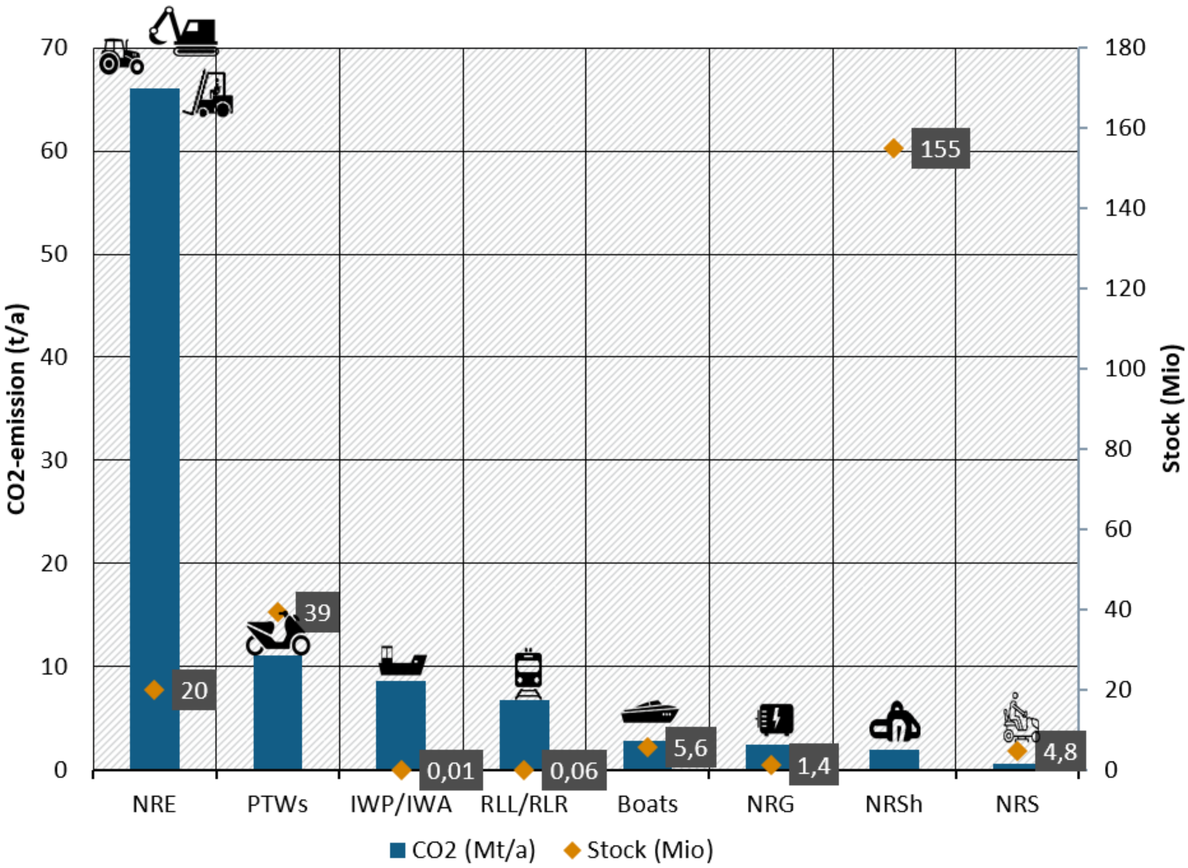
Source: Own illustration by ifeu

A similar approach for the EU was implemented, for example, in analysis for the European Commission by JRC (Krasenbrinck, Dobranskyte-Niskota 2008) and EMISIA (Mellios et al. 2019). However, these data are no longer up to date. Therefore, a key part of the research involved collecting sales and stock figures for all categories across the EU-27 and, where possible, broken down by power class and drive type. The main data sources are:

- Construction machinery: EU PRODCOM database ("PRODuction COMmunautaire or" Community Production Database) and data from the German machinery and equipment manufacturing association ("Verband Deutscher Maschinen und Anlagenbau", VDMA)
- Agriculture machinery: EU PRODCOM database and statistics from the machinery manufacturers' association European Agricultural Machinery Industry Association (CEMA)
- Generators and forklifts: EU PRODCOM database
- Locomotives and railcars: Eurostat
- Chainsaws and garden tools: EU PRODCOM
- Inland waterway vessels: Central Commission for the Navigation of the Rhine (CCNR)
- Recreational boats: International Council of Marine Industry Associations (ICOMIA)
- Motorcycles: Eurostat and European Association of Motorcycle Manufacturers (ACEM)

Figure 2 shows the estimated stock figures and CO_2 emissions for all sectors/categories. In total, CO_2 emissions across all sectors amount to approximately 100 Mt/a, with NRMM – and in particular construction and agricultural machinery – accounting for the largest shares of energy consumption and emissions.

Figure 2: Estimated population and CO_2 emissions per engine/vehicle category in the emission inventory, EU27, 2025



Source: Own illustration by ifeu. Note: The pictograms shown represent examples of applications in the various categories, but do not claim to be exhaustive.

The results of the bottom-up calculation thus align well with the estimates from the UNFCCC reports. However, our model allows for more detailed analyses by machine type, power class, etc., and was therefore used for the policy scenarios (see section impact assessment below).

Electrification potential

Based on the product categorization, the assessment of the technical feasibility of electrification is done by quantifying the Electrification Potential (EP) of the single product categories. It describes the possibility to electrify a machine or a vehicle considering the usage in its standard operating conditions including average and high volume working days. The EP refers to new machines/vehicles (no retrofits) and is based solely on technical feasibility. Factors like production capacity, efforts when switching product portfolio or economic influences are not considered. Therefore, the EP does not reflect sales numbers. Looking at the technical limitations when it comes to the electrification of non-road mobile machinery and the operation of such, three guiding questions summarize the main challenges of electrification:

- Can a suitable battery be installed
- Can the battery be recharged in the non-working periods
- Is sufficient infrastructure at the spot of operation available to build up systems for recharging and operating

To quantify these questions, independent factors have been created: “Battery”, “Charging” and “Infrastructure”. The data basis for determining the factors, and ultimately the EP, has been built in the project on expert judgment through surveys, discussions, workshops with Original Equipment Manufacturer (OEMs), stakeholders and consortium members, detailed data analysis of telemetric data in real-world use cases as well as on expertise gained from previous projects.

The EP is calculated as in Equation 1 and categorized into one of five classes, spanning from very low potential (EP from 0 % to 20 %) to very high potential (EP from 80 % to 100 %). The values for the individual factors are in the range of 0.00 to 1 and are then multiplied for the EP. The factor “Specific” is optional and can be adopted in specific use cases, for example if special power demands exist. The factor “Special solution” integrates individual solutions like catenary or cable operation. The EP was calculated for the years 2030 and 2050 for a variety of applications in the segments from Figure 2 .

Equation 1: Electrification potential (EP)

$$EP = f_{Battery} * f_{Charging} * f_{Infrastructure} (* f_{Specific}) + f_{Special\ solution}$$

EP … Electrification potential [-]

$f_{Battery}$ … Factor Battery [-]

$f_{Charging}$ … Factor Charging [-]

$f_{Infrastructure}$ … Factor Infrastructure [-]

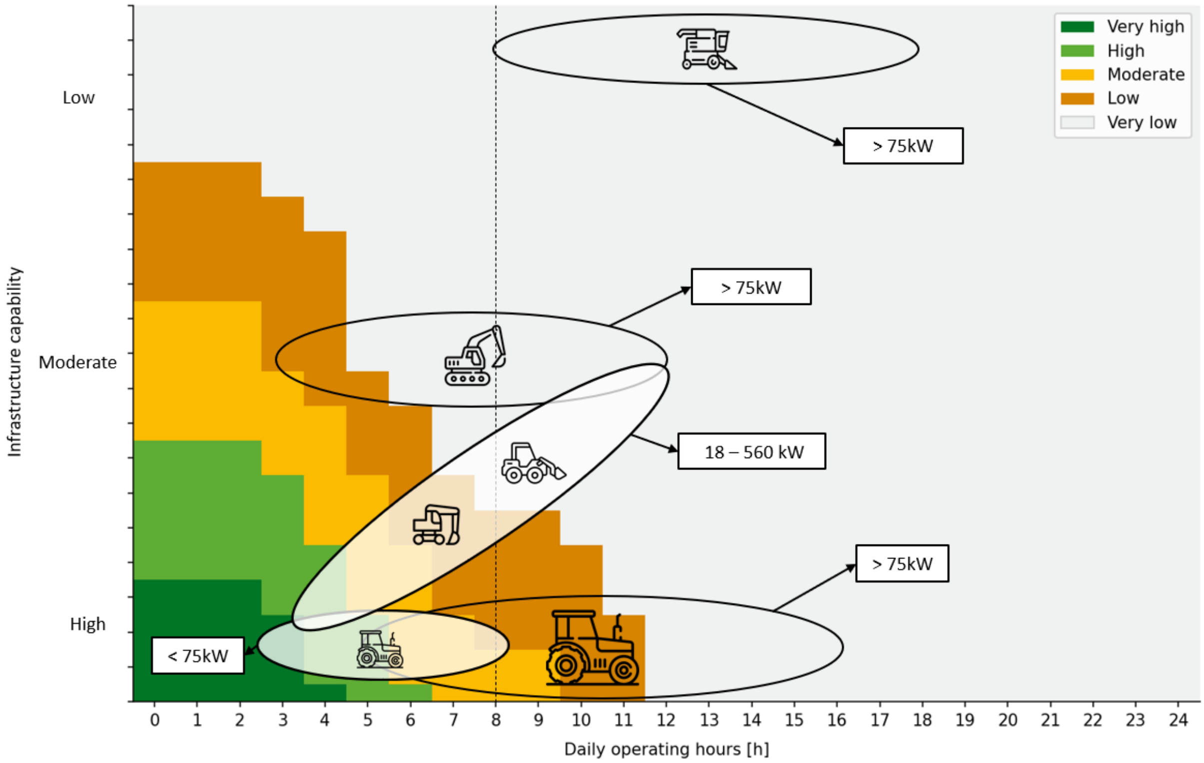
$f_{Specific}$ … Factors Specific [-]

$f_{Special\ solution}$ … Factor Special solution [-]

To gather a deeper understanding of how the specific input parameters (e.g., daily operating hours, load profile or the factor infrastructure) effect the EP, a sensitivity analysis was conducted. The most critical parameters in terms of data availability—particularly for the long-term forecast to 2050 – combined with high influence on the EP are ” Infrastructure” and the possible “Charging” power.

Figure 3 illustrates a representative picture of the EP in the NRMM category NRE in the year 2050 as a function of charging infrastructure availability and daily operating hours, which represent the factors battery and charging. This NRE category covers NRMM mainly in the application fields of construction, agricultural and forestry. The graph highlights the placement of five representative subsectors (including tractors, combine harvesters, and excavators) in this NRE covering illustration. The colour code on the top right side of the graph illustrates the different areas of electrification potential: dark green for “very high” electrification potential in the range of 80–100 %, green for "high" (60–80 %), yellow for “moderate” (40–60 %), orange for “low” (20–40 %) and grey for “very low” (0–20 %). Low daily operating hours combined with good infrastructure favour electrification, whereas high daily operating hours and poor infrastructure hinder it. The ovals indicate the spread of operating hours and thus EP within the same subsector, highlighting the dependency of the EP on the specific mission profiles. In 2030, the electrification potential is slightly lower due to lower charging capabilities or less performant batteries.

Figure 3: Excerpt of NRMM Electrification for the engine category NRE in 2050



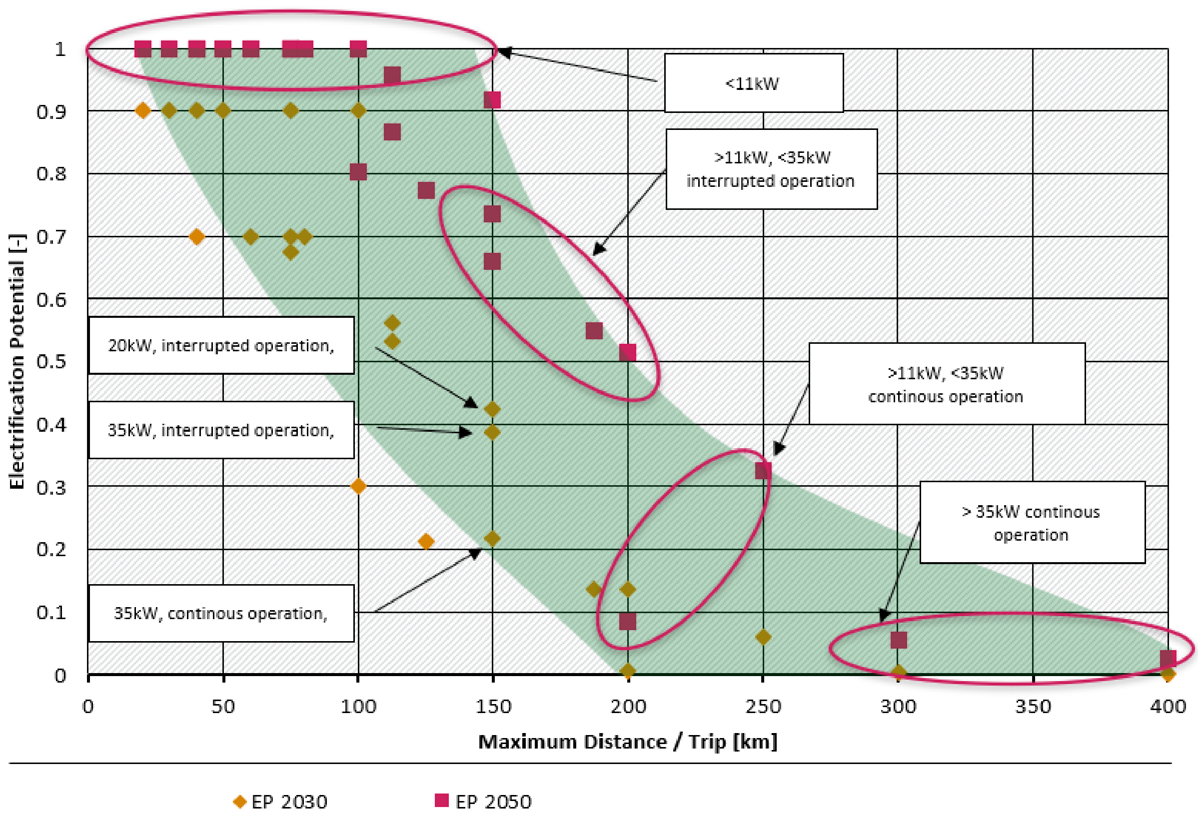
Source: Source: Own illustration by TU Graz

Engine categories IWA and IWP representing inland waterways between 19 and 75 kW show a moderate EP, while higher powered engines in this sector only reach a low or even very low EP. A slight increase in EP from 2030 to 2050 is found for these categories, attributed to improvements in battery technology and higher available charging power.

Small machinery below 19kW in the NRS and NRSh class show a high diversity of EP across different types of application, ranging from low to very high. The main influencing factors are installed power and daily operating hours. The EP of lower power machinery with the operation profile “hobby” range from moderate (riding mower hobby) to high (chainsaw, trimmer hobby) in 2030 which increase in 2050. Machinery with higher installed power, usually in the operation profile “professional”, tend to show lower electrification potential from low (riding mower professional) to moderate (chainsaw professional) in 2030 with significant increase in 2050.

For powered two-wheelers, a similar trend can be observed. The results show a high diversity of EP across different vehicle classes, ranging from low to very high. Main factors are the installed power and maximum trip distance. Those with higher installed power tend to show lower EP. The dependency of the EP on the maximum trip distance is shown in the scatter band in Figure 4. Mopeds with low power demand and low trip distances have a very high EP even in 2030 whereas large motorcycles with power above 35 kW and high trip distances of 250 km have low to very low EP. The high range for similar trip distances shows the influence of other factors like charging possibilities and power demand.

Figure 4: Scatter band for electrification potential of powered two-wheelers



Source: Source: Own illustration by TU Graz

In the sector of recreational craft eleven types of boats have been assessed, from the low powered outboard engine sailing yacht (3 kW) to the higher-powered fishing boat (135 kW) and the highest power day cruiser (260 kW). For very low powered outboard and sailing yacht crafts (3 kW) the EP is very high to high. Although a general correlation higher power leads to lower EP can be identified, other factors like available load and volume capacity influence significantly. For recreational craft in general, the EP in 2030 is low to moderate with some types being high. Looking ahead from 2030 to 2050, an increase in EP is observed across all applications. These increases are rather moderate; therefore, some applications still have an EP of moderate to high in 2050.

Electrification is possible for a wide variety of uses cases and segments, especially in smaller machines and vehicles. However, looking at large and high-powered machines and vehicles, substantial gaps remain.

Policy options

Examples of supply-side regulation directly targeting GHG emissions from NRMM are limited globally. No such regulations currently exist in the EU, and existing regulation focuses primarily on air pollutants through Stage V, which sets limits for CO, HC, NOx, PM and PN from NRMM engines. There are significant challenges in building a framework which would target the GHG emissions from NRMM compared to the on-road sector owing to the heterogeneity of the NRMM sector compared to on-road vehicles, and a lack of harmonized registration and monitoring systems for NRMM across EU Member States.

This study assessed how to address these challenges through two main supply-side policy pathways:

- Scenario 1: Amending Stage V to promote zero-emission NRMM
- Scenario 2: Establishing a tiered zero-emission mandate for NRMM

Scenario 1 involved setting advanced regulation for NRMM including tighter pollutant limits, in-service conformity requirements, stronger durability provisions, low-load and idle emission requirements, and targeted provisions for high-priority categories such as transport refrigeration units. These measures would improve real-world air pollutant performance and could indirectly improve the competitiveness of zero-emission machinery by increasing the compliance costs of combustion engines. A complementary zero-emission crediting mechanism could allow manufacturers to earn credits from placing zero-emission machines on the market, particularly in higher-power categories, and use these credits to provide flexibility for combustion engines in harder-to-electrify applications.

Scenario 2 would establish a separate tiered zero-emission mandate for NRMM, similar to the current EU CO_2-regulations for trucks or buses. Under this approach, machine categories would be grouped according to electrification potential:

- No targets would apply to categories with a low electrification potential, e.g. agricultural vehicles >130 kW
- categories with a medium electrification potential, e.g. non-mobile construction equipment >130 kW would face a 30 % zero-emission target in 2035, rising to 50 % in 2050.
- High-potential categories, e.g. non-mobile construction equipment <130 kW, would face a 70 % target in 2035, rising to 85 % in 2050.

This approach would cover a larger share of NRMM energy consumption than a narrow Stage V amendment, but would require a more robust monitoring framework and careful design of flexibilities such as averaging, banking and trading, exemptions for niche applications, and weighting mechanisms based on expected emissions impact.

Demand-side measures can complement supply-side regulation. Oslo has used public procurement to accelerate zero-emission construction equipment, London has introduced a low-emission zone for construction machinery, the Netherlands combines voluntary targets with substantial public funding, and New York City is testing electric construction machinery through pilot programs. Similar EU measures could include extending clean public procurement rules to NRMM, supporting charging infrastructure, using fuel taxation or CO_2 pricing, and creating incentives through renewable fuel or electricity crediting schemes.

Environmental Impact Assessment

This impact assessment evaluates energy consumption, greenhouse gas (GHG) emissions, and air pollutant reductions across three policy scenarios (BAU, ZEV Mandate, and POT) from 2025 to 2050, using the TREMOD-MM model. Additionally, life cycle assessments (LCA) are conducted to account for upstream emissions from energy supply and battery production.

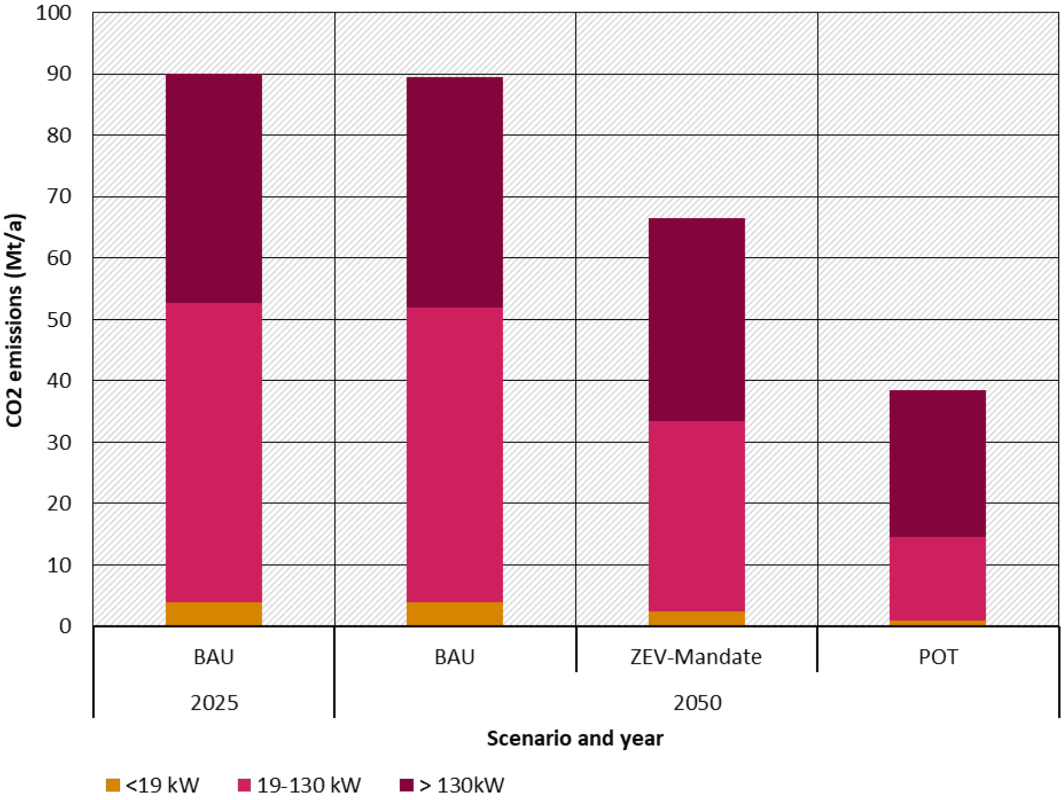
Three scenarios are modelled to assess the impact of electrification and hydrogen adoption:

- Business-as-usual (BAU): Zero-emission vehicle (ZEV) shares remain at 2025 levels.
- ZEV Mandate: Partial electrification is mandated (see scenario 2 in the previous section)

- Technical Potential (POT): Full exploitation of electrification and hydrogen potential per EP group, representing the theoretical maximum ZEV market penetration by 2050. Linear interpolation is used between 2030 and 2050.

Figure 5 shows that CO_2 emissions in BAU remain flat due to stagnant drivetrain changes and fossil fuel dependence. The ZEV Mandate achieves 26 % CO_2-reduction compared to BAU by 2050, driven by electrification of <130 kW machines. The POT-scenario has 57 % CO_2-reduction compared to BAU in 2050, including contributions from >130 kW machines (e.g., excavators, dump trucks) via partial electrification and hydrogen.

Figure 5: Tailpipe CO_2 emissions of NRMM and recreational craft by scenario and fuel type, EU27



Source: Source: Own illustration by ifeu. Note: Exhaust emissions are calculated using 100 % fossil fuels.

In POT, 40 Mt CO_2/year persists by 2050, necessitating renewable fuels (e.g. biofuels, e-fuels) for full decarbonization. While fossil fuel demand plummets in the policy scenarios, a minimum 550 PJ/year of liquid fuels (mostly diesel) persist—equivalent to current EU biofuel use in transport. This is partly due to the limited potential for electrification of new machinery, but also to the long service life of the existing fleet, as 9 % of fossil fuel consumption in 2050 will be accounted for by machinery that is 30 years old or older. Similar trends can be found for PTWs with 24 % CO_2 reduction by 2050 in the ZEV Mandate and 49 % CO_2 reduction in the POT scenario. This is mainly driven by electrification of mopeds and smaller motorcycles, though larger motorcycles (L3A3) see limited gains due to lower electrification potential. 70 PJ/year remains for non-electrifiable vehicles.

All scenarios, including the BAU, also show a decrease in NO_X, PM_{10} and HC emissions until 2050, proving that the current Stage V regulation will lead to significant improvements in air quality.

However, with increasing electrification in a ZEV-Mandate or in the POT-scenario the reduction can be even higher, therefore supporting the path towards zero air pollutant emission in the long run. Certain emission reduction effects could also be expected by amendments in air pollution limits, i.e. Stage VI (Scenario 1), but quantifying these was not part of this study.

As the scenario results above only cover tailpipe emission, a simplified life cycle assessment (LCA) was carried out which also included upstream emissions (fuel extraction/refining vs. electricity generation) and Battery production (additional emissions for electric machines). For electricity generation average 2023 vs. 2030 electricity mixes in the EU 27 were used. Key Findings are that electric machines emit >70 % less CO_2 per operating hour than diesel, despite upstream electricity and battery emissions. High-usage machines (e.g., wheel loaders) yield greater annual GHG savings than low-usage machines, e.g. small tractors, even with similar per-hour reductions. Savings increase from 2023 to 2030 as the EU electricity mix improves.

A sensitivity analysis regarding annual operating hours shows that electric mini excavators offset battery emissions after >50 operating hours/year which is well below typical usage. However, as other studies confirm, electric machines in Low-Usage Applications e.g. recreational craft/emergency generators may negate LCA benefits due to battery emissions. In some cases, renewable fuels (HVO100, PtL) may offer lower LCA emissions than electrification, particularly for low-usage, high-power applications.

Regarding the policy scenarios, a ZEV mandate can be a powerful policy in order to trigger electrification and reduce emissions. A full implementation of the technical potentials would lead to even further emission reductions, but would be difficult to tap with supply side polices only. And even then, a full decarbonization of the sectors with electrification alone is not possible in the current state. Thus, additional technologies, e.g. renewable fuels, and policies will be necessary.

Stakeholder Feedback

In conjunction with the project team's work, individual interviews were conducted with various stakeholders, and an expert workshop was held. OEM representatives emphasized that the industry has already made significant strides in the field of electrification and offers a range of solutions. However, while electrification offers great potential, it also has clear limitations depending on the application. Given the wide variety of use cases, there is no one-size-fits-all solution. Instead of setting requirements for the supply, it is necessary to ensure that there is actually a demand for such machines, which is currently still low.

The stakeholders further emphasized that a successful decarbonization strategy for the NRMM, recreational boat, and PTW sectors must include technology neutrality, lifecycle-based assessment, infrastructure readiness, availability of sustainable energy carriers, and economically viable solutions for users. Equally important are a competitive business environment, fair global competition and policies that support fleet renewal and the decarbonisation of existing machines.

Policy recommendations

NRMM remain one of the few transport sectors whose GHG emissions remain unregulated in the EU. The sector contributes towards 3 % of the Union's annual GHG emissions which poses a challenge for compliance with the European Union's climate law. Given the sector's significant and currently unregulated CO_2 emissions, the European Commission should initiate a structured policy process to integrate NRMM into the EU's broader decarbonisation framework.

In the short term, policymakers should build on existing frameworks, particularly Stage V, to incentivise early electrification. Targeted tightening of pollutant limits, combined with measures such as in-service conformity requirements, can indirectly accelerate the uptake of zero-emission technologies in small NRMM categories which have a high electrification potential. These measures should be accompanied by flexibility mechanisms, for example by providing limited exemptions to manufacturers to comply with a post-Stage V standard if they may prove that they have placed a number of zero-emission machines on the market instead of diesel fueled machines.

In parallel, preparatory work should begin for a more comprehensive CO_2-focused regulatory approach—for example, through a tailored zero-emission mandate. Due to the heterogeneity of the sector, establishing a CO_2 monitoring mechanism for all NRMM categories is not recommended. Instead focus should be given to categories with a high CO_2 impact, e.g. NRE > 19 kW. Establishing a harmonised monitoring and reporting system across Member States will be a critical prerequisite. This could include enhanced manufacturer reporting, improved data collection through declarations of conformity, or the development of a dedicated EU-wide tracking framework for NRMM. While establishing a zero-emission mandate would prove the most effective means of increasing the supply of zero-emission larger machines into the European market, setting such targets is not possible without tracking the sales volume. A pre-requisite for a ZEV mandate would require a harmonized registration procedure.

Policy design should reflect the heterogeneity of the sector by differentiating between machine types and their electrification potential. A tiered approach—setting more ambitious targets for segments with high electrification potential while allowing flexibility for harder-to-abate categories—could deliver effective emissions reductions while maintaining feasibility. Complementary demand-side measures, such as green public procurement, low-emission zones, and targeted funding programs, can further accelerate market uptake.

Finally, enabling measures will be essential to support the transition. These include expanding charging and energy infrastructure, ensuring access to reliable electricity supply at worksites, and improving transparency in the market. The development of an independent information platform on available zero-emission machinery, including performance data and use cases, could help increase awareness and reduce uncertainty among users. Together, these actions can create the conditions for scaling up zero-emission NRMM and achieving meaningful emissions reductions in the sector.

Zusammenfassung

Einleitung

Die Europäische Union hat sich verpflichtet, die Treibhausgasemissionen bis 2030 um 55 % (im Vergleich zu 1990) zu reduzieren und bis 2050 Klimaneutralität zu erreichen. Deutschland strebt an, die Netto-Null-Emissionen sogar noch früher, nämlich bis 2045, zu erreichen. Während der Straßenverkehrssektor bereits auf Elektrifizierung umstellt – unterstützt durch EU-Vorschriften wie CO_2-Flottenziele und nationale Anreize –, fehlt für die nicht für den Straßenverkehr bestimmten mobilen Maschinen (Non Road Mobile Machinery = NRMM) ein klarer Weg zur Dekarbonisierung. Gleiches gilt für motorisierte Zweiräder (Powered Two-Wheeler = PTW) und Freizeitboote.

NRMM, die in der Landwirtschaft, im Bauwesen und im Gartenbau eingesetzt werden, sowie Freizeitboote sind nach wie vor stark von fossilen Brennstoffen abhängig. Diese Maschinen verursachen weltweit etwa 2 Gt CO_{2e} – mehr als die globale Seeschifffahrt – und machen etwa 3 % der jährlichen Treibhausgasemissionen der EU aus (90–110 Mt CO_{2e}). Über die Treibhausgase hinaus stoßen mobile, nicht straßengebundene Maschinen auch erhebliche Luftschadstoffe (NO_x, PM) und Lärm aus, was sich insbesondere auf die Luftqualität in Städten und die öffentliche Gesundheit auswirkt.

Die Elektrifizierung ist oft der energieeffizienteste und kostengünstigste Weg zur Dekarbonisierung, sofern sie im Verkehrssektor technisch machbar ist. Sie erfordert jedoch systemische Veränderungen – von der Neugestaltung der Antriebsstränge bis hin zur Ladeinfrastruktur. Was NRMM betrifft, gibt es bislang nur wenige Informationen zum Elektrifizierungspotenzial der verschiedenen Maschinentypen. Um diese Wissenslücke zu schließen, haben das Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMUKN) und das Umweltbundesamt (UBA) die eNRMM-Studie in Auftrag gegeben. Ihr Ziel ist es, das Elektrifizierungspotenzial von NRMM, Freizeitbooten und motorisierten Zweirädern zu bewerten und politische Optionen zu entwickeln, um die Elektrifizierung dort zu fördern, wo sie machbar ist.

Warum der Fokus auf Elektrifizierung?

Diese Studie schließt Wissenslücken hinsichtlich des technischen Potenzials für die Elektrifizierung – unter Berücksichtigung von Einschränkungen wie der deutlich geringeren Energiedichte von Batterien im Vergleich zu flüssigen und gasförmigen Kraftstoffen – in den verschiedenen Sektoren der mobilen Maschinen, Zweiräder und Freizeitboote und entwickelt gezielte regulatorische Optionen, um die Marktakzeptanz zu fördern. Die Studie geht von der Prämisse aus, dass die Elektrifizierung – sofern technisch machbar – der energieeffizienteste und folglich in vielen Fällen auch der kostengünstigste Weg zur Dekarbonisierung von Fahrzeugen und mobilen Maschinen ist. Gleichzeitig erfordert die Elektrifizierung erhebliche systemische Veränderungen bis hinunter auf die Ebene einzelner Fahrzeuge und Maschinen: Zumindest verfügen Elektrofahrzeuge und -maschinen über andere Antriebs- und Energiespeichersysteme. Darüber hinaus muss die unterstützende Infrastruktur (z. B. Lademöglichkeiten, Netzzugang) an die jeweiligen Betriebsbedingungen angepasst werden.

Die Studie konzentrierte sich nicht auf die Dekarbonisierung durch grüne Kraftstoffe, da diese keine vergleichbare systemische und anwendungsspezifische Neugestaltung erfordert. Es gibt bereits zahlreiche Studien zur Herstellung und zum Ausbau grüner Kraftstoffe; die Elektrifizierung hingegen erfordert detaillierte Analysen auf Geräteebene und für einzelne Anwendungsfälle über verschiedene Maschinen- (und Fahrzeug-)Typen hinweg. Gleichzeitig ist die Verfügbarkeit grüner Kraftstoffe begrenzt, da konkurrierende Nachfrage aus Sektoren wie Luftfahrt, Schifffahrt und

Industrie besteht. Erst wenn das Elektrifizierungspotenzial in den Bereichen mobile Maschinen, Zweiräder und Freizeitboote quantifiziert ist, lässt sich der verbleibende Bedarf an alternativen Lösungen wie grünen Kraftstoffen ermitteln.

Die Studie deckt den Zeitraum von 2025 bis 2050 in der EU-27 ab und analysiert NRMM, motorisierte Zweiräder und Freizeitboote im Detail – aufgeschlüsselt nach Sektoren (z. B. Bauwesen, Forstwirtschaft), Maschinentypen (z. B. Traktoren, Kettensägen) und Leistungsklassen (z. B. 0–18 kW). Der Schwerpunkt liegt auf der direkten Elektrifizierung (Batterien, Netzanschluss), wobei alternative Antriebssysteme (z. B. Wasserstoff) nur dann berücksichtigt werden, wenn eine Elektrifizierung nicht realisierbar ist. Bei den Emissionsbewertungen steht der „Tank-to-Wheel"-Ansatz (TTW) im Vordergrund, es werden jedoch auch „Well-to-Wheel"-Analysen (WTW) und Lebenszyklusanalysen (LCA) einbezogen.

Rahmenwerk zur Produktkategorisierung für NRMM, Freizeitboote und motorisierte Zweiräder

Die Klassifizierung der Produktkategorien ist von grundlegender Bedeutung, da sie die Analyse dieser Studie strukturiert, d. h. das Elektrifizierungspotenzial, politische Optionen und Folgenabschätzungen. Die Kategorien – die nicht für den Straßenverkehr bestimmte mobile Maschinen (NRMM), Freizeitboote und motorisierte Zweiräder umfassen – spiegeln vielfältige Anwendungsbereiche, technische Merkmale, Betriebsprofile und regulatorische Rahmenbedingungen wider. Um die Kompatibilität mit bestehenden Vorschriften zu gewährleisten, orientiert sich die Studie bei der Einteilung ihrer Kategorien an der EU-Stufe-V-Verordnung (2016/1628), siehe Tabelle 1:

Tabelle 1: In die Studie einbezogene NRMM-Kategorien gemäß der Definition für Stufe V

Kategorie	Beschreibung
NRE	Alle anderen Motoren für NRMM, die nicht unter die unten aufgeführten Kategorien fallen (IWP, IWA, RLL, RLR)
NRG	Motoren für die mobile Stromerzeugung
NRSh	Ottomotoren (SI) für handgeführte Maschinen
NRS	Ottomotoren, ausgenommen NRSh
IWP	Motoren für den Antrieb von Binnenschiffen
IWA	Hilfsmotoren für Binnenschiffe
RLL	Motoren für den Antrieb von Lokomotiven
RLR	Motoren für den Antrieb von Triebwagen

Anmerkung: SMB (Schneemobile) und ATS (Geländefahrzeuge) wurden aus der Studie ausgeschlossen. Bei NRG wurden alle Leistungsklassen berücksichtigt, während Stufe V in dieser Kategorie nur Motoren >560 kW umfasst.

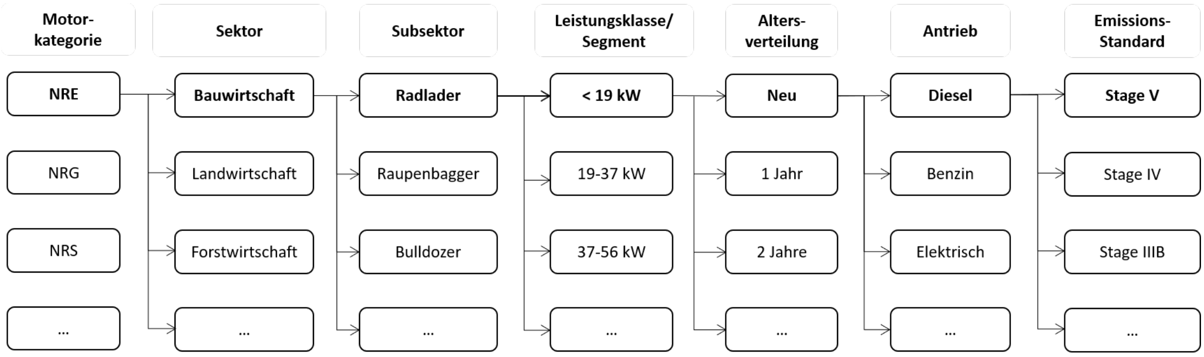
Motorisierte Zweiräder (PTWs) wurden nach Leistung und Typ (z. B. Mopeds, Motorräder) gemäß der EU-Verordnung 168/2013 (Fahrzeuge der Klasse L) unterteilt. Die Kategorien für Freizeitboote reichen von kleinen Booten mit Außenbordmotor und Jetskis bis hin zu größeren Fischerei- oder Segelbooten.

Für eine detailliertere Analyse wurden die Kategorien weiter nach Maschinenkategorie, Motorleistung und Kraftstoffart unterteilt (siehe nächster Abschnitt).

EU-27-Emissionsinventar für mobile Maschinen und Geräte (NRMM) und Freizeitboote (2025)

Die Erstellung eines Bottom-up-Emissionsinventars diente als Grundlage für weitere Analysen. Es umfasst den Energieverbrauch, die Treibhausgasemissionen (THG) und die Luftschadstoffe für alle Kategorien von NRMM und Freizeitbooten in der EU-27 für das Jahr 2025. Daher haben wir das TREMOD-MM-Modell verwendet – ein Tool, das in Deutschland seit über 20 Jahren eingesetzt wird –, dessen Anwendungsbereich auf die EU-27 erweitert und in das neue Antriebsarten (Elektro- und Wasserstoffantrieb) einbezogen wurden. Das Modell verfolgt einen bestandsbasierten Ansatz, bei dem Bestand, Betriebsstunden, Leistung sowie Energieverbrauch und Emissionsfaktoren in hoher Differenzierung miteinander multipliziert werden (siehe Abbildung 1).

Abbildung 1: Beispielhafte Differenzierung im Emissionsinventar mit TREMOD-MM



Quelle: Eigene Darstellung von ifeu

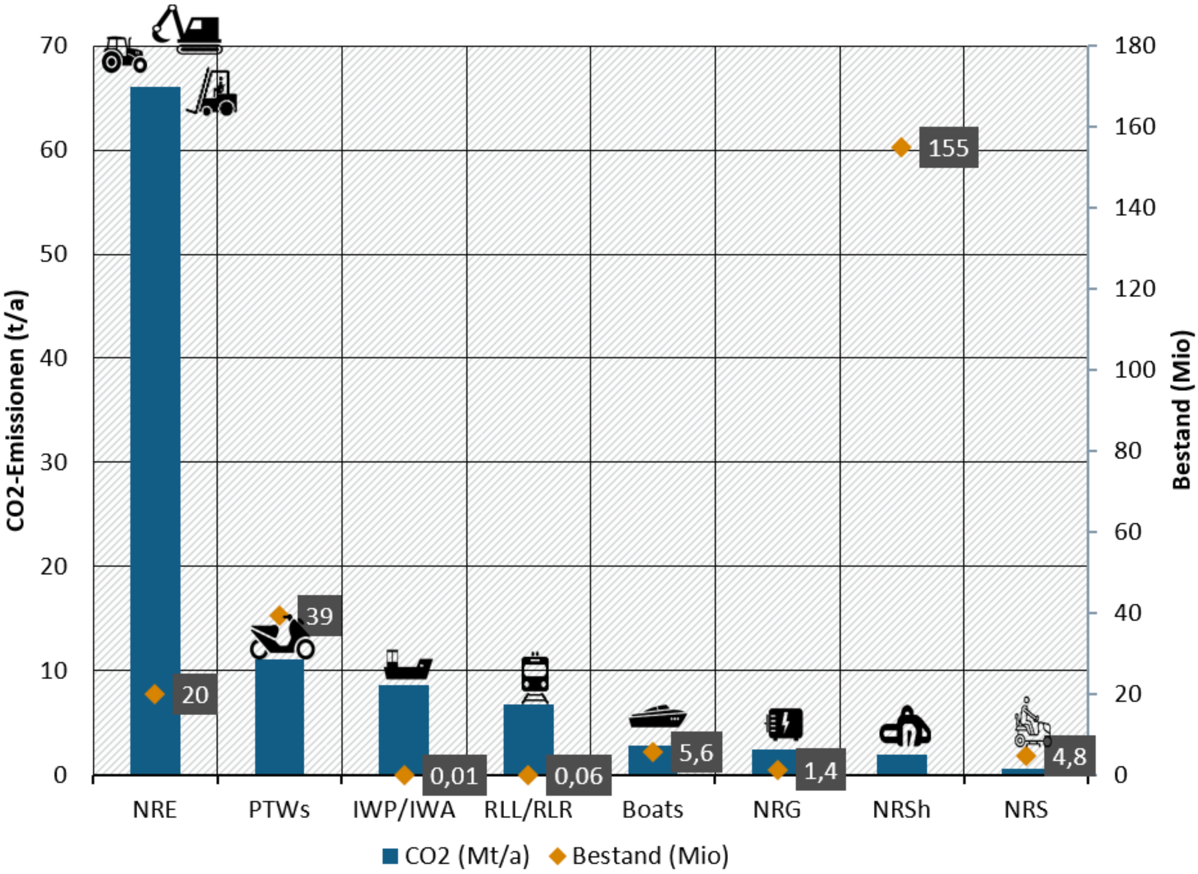
Ein ähnlicher Ansatz für die EU wurde beispielsweise in Analyse für die EU-Kommission von JRC (Krasenbrinck, Dobranskyte-Niskota 2008) und EMISIA (Mellios et al. 2019), umgesetzt. Diese Daten sind jedoch nicht mehr aktuell. Daher bestand ein wesentlicher Teil der Arbeit darin, Absatz- und Bestandszahlen für alle Kategorien in der EU-27 zu erheben und diese, soweit möglich, nach Leistungsklassen und Antriebsarten aufzuschlüsseln. Die wichtigsten Datenquellen sind:

- Baumaschinen: EU-PRODCOM-Datenbank („PRODuction COMmunautaire“ oder „Community Production Database“) und Daten des Verbands Deutscher Maschinen- und Anlagenbau (VDMA)
- Landwirtschaftliche Maschinen: EU-PRODCOM-Datenbank und Statistiken des Maschinenherstellerverbands European Agricultural Machinery Industry Association (CEMA)
- Generatoren und Gabelstapler: EU-PRODCOM-Datenbank
- Lokomotiven und Triebwagen: Eurostat
- Kettensägen und Gartengeräte: EU PRODCOM-Datenbank
- Binnenschiffe: Zentralkommission für die Rheinschifffahrt (ZKR)
- Freizeitboote: Internationaler Rat der Verbände der maritimen Industrie (ICOMIA)
- Motorräder: Eurostat und Europäischer Verband der Motorradhersteller (ACEM)

Abbildung 2 zeigt die geschätzten Bestandszahlen und CO_2-Emissionen für alle Sektoren/Kategorien. Insgesamt belaufen sich die CO_2-Emissionen aller Sektoren auf etwa 100

Mt/a, wobei mobile Maschinen und Geräte (NRMM) – insbesondere Bau- und Landmaschinen – den größten Anteil am Energieverbrauch und an den Emissionen haben.

Abbildung 2: Geschätzter Bestand und CO2-Emissionen pro Motor-/Fahrzeugkategorie im Emissionsinventar, EU27, 2025



Quelle: Eigene Darstellung von ifeu. Hinweis: Die abgebildeten Piktogramme stellen Beispiele für Anwendungen in den verschiedenen Kategorien dar, erheben jedoch keinen Anspruch auf Vollständigkeit.

Die Ergebnisse der Bottom-up-Berechnung stimmen somit gut mit den Schätzungen aus den UNFCCC-Berichten überein. Unser Modell ermöglicht jedoch detailliertere Analysen nach Fahrzeugtyp, Leistungsklasse usw. und wurde daher für die politischen Szenarien verwendet (siehe Abschnitt „Folgenabschätzung“ weiter unten).

Elektrifizierungspotenzial

Auf der Grundlage der Produktkategorisierung erfolgt die Bewertung der technischen Machbarkeit der Elektrifizierung durch die Quantifizierung des Elektrifizierungspotenzials (EP) der einzelnen Produktkategorien. Es beschreibt die Möglichkeit, eine Maschine oder ein Fahrzeug unter Berücksichtigung des Einsatzes unter Standardbetriebsbedingungen – einschließlich Arbeitstagen mit durchschnittlichem und hohem Arbeitsaufkommen – zu elektrifizieren. Das EP bezieht sich auf neue Maschinen/Fahrzeuge (keine Nachrüstungen) und basiert ausschließlich auf der technischen Machbarkeit. Faktoren wie Produktionskapazität, Aufwand bei der Umstellung des Produktportfolios oder wirtschaftliche Einflüsse werden nicht berücksichtigt. Daher spiegelt das EP keine Absatzzahlen wider. Betrachtet man die technischen Einschränkungen bei der Elektrifizierung von mobilen Maschinen und Geräten sowie deren Betrieb, lassen sich die Hauptherausforderungen der Elektrifizierung anhand von drei Leitfragen zusammenfassen:

- Kann eine geeignete Batterie eingebaut werden?
- Kann die Batterie in den Betriebspausen wieder aufgeladen werden?
- Ist am Einsatzort eine ausreichende Infrastruktur vorhanden, um Systeme zum Aufladen und Betrieb aufzubauen?

Um diese Fragen zu quantifizieren, wurden unabhängige Faktoren definiert: „Batterie", „Laden" und „Infrastruktur". Die Datengrundlage für die Ermittlung der Faktoren und letztlich des EP wurde im Rahmen des Projekts auf der Grundlage von Expertenmeinungen durch Umfragen, Diskussionen und Workshops mit Maschinenherstellern (OEMs), Interessengruppen und Konsortiumsmitgliedern, einer detaillierten Analyse von Telemetriedaten aus realen Anwendungsfällen sowie auf der Grundlage von Fachkenntnissen aus früheren Projekten erstellt.

Der EP wird gemäß Formel 1 berechnet und in eine von fünf Klassen eingestuft, die von sehr geringem Potenzial (EP von 0 % bis 20 %) bis zu sehr hohem Potenzial (EP von 80 % bis 100 %) reichen. Die Werte für die einzelnen Faktoren liegen im Bereich von 0,00 bis 1 und werden anschließend zur Ermittlung des EP multipliziert. Der Faktor „Spezifisch" ist optional und kann in bestimmten Anwendungsfällen herangezogen werden, beispielsweise wenn besondere Leistungsanforderungen bestehen. Der Faktor „Sonderlösung" berücksichtigt individuelle Lösungen wie Oberleitungs- oder Kabelbetrieb. Das EP wurde für die Jahre 2030 und 2050 für eine Vielzahl von Anwendungen in den Segmenten aus Abbildung 1 berechnet.

Formel 1: Elektrifizierungspotenzial (EP)

$$EP = f_{Battery} * f_{Charging} * f_{Infrastructure} \, (* f_{Specific}) + f_{Special\ solution}$$

EP ... Elektrifizierungspotenzial [-]

$f_{Batterie}$ ... Faktor Batterie [-]

f_{Laden} ... Faktor Laden [-]

$f_{Infrastruktur}$ ... Faktor Infrastruktur [-]

$f_{Spezifisch}$ ... Spezifische Faktoren [-]

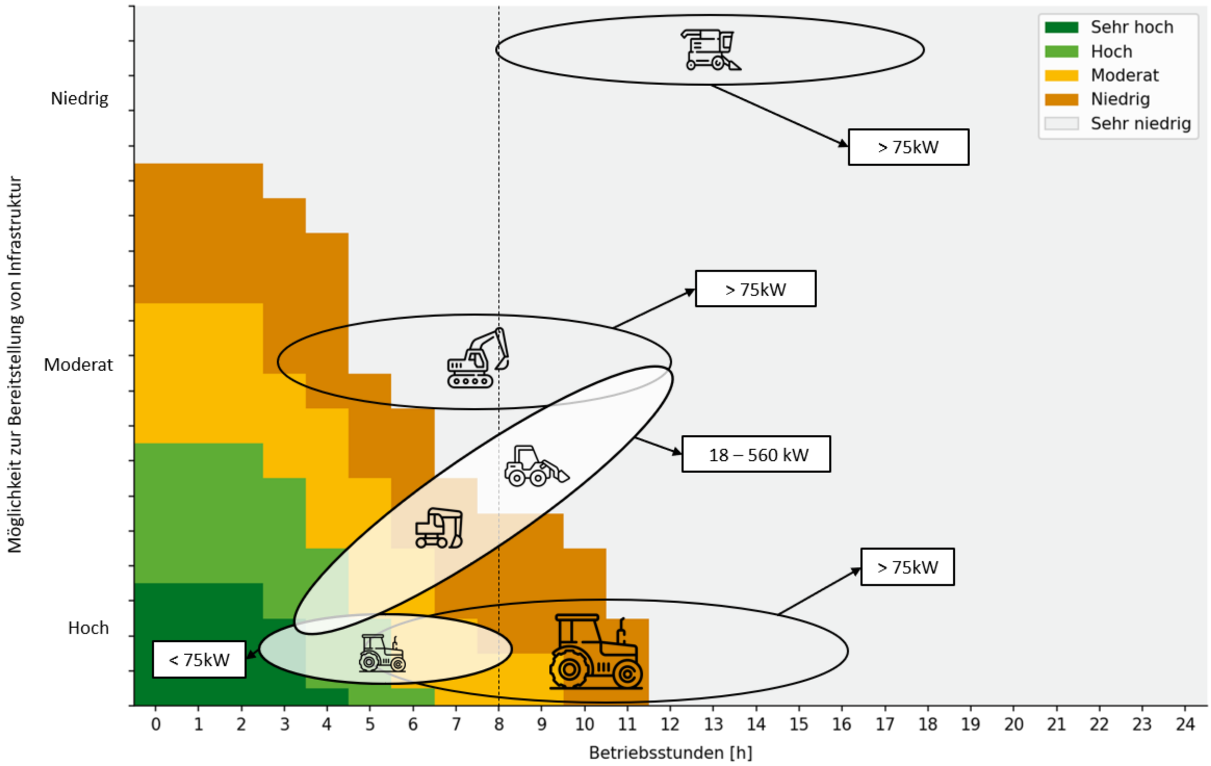
$f_{Sonderlösung}$ ... Faktor Sonderlösung [-]

Um ein tieferes Verständnis dafür zu gewinnen, wie sich die spezifischen Eingabeparameter (z. B. tägliche Betriebsstunden, Lastprofil oder der Faktor Infrastruktur) auf den EP auswirken, wurde eine Sensitivitätsanalyse durchgeführt. Die hinsichtlich der Datenverfügbarkeit kritischsten Parameter – insbesondere für die Langzeitprognose bis 2050 – in Verbindung mit einem hohen Einfluss auf den EP sind „Infrastruktur" und die mögliche „Ladeleistung".

Abbildung 3 veranschaulicht ein repräsentatives Bild des Elektrifizierungspotenzials (EP) in der NRMM-Kategorie NRE im Jahr 2050 in Abhängigkeit von der Verfügbarkeit der Ladeinfrastruktur und den täglichen Betriebsstunden, die die Faktoren Batterie und Laden repräsentieren. Diese NRE-Kategorie umfasst NRMM vor allem in den Anwendungsbereichen Bauwesen, Landwirtschaft und Forstwirtschaft. Die Grafik hebt die Einordnung von fünf repräsentativen Teilsektoren (darunter Traktoren, Mähdrescher und Bagger) in dieser NRE-Übersicht hervor. Die Farbcodierung oben rechts in der Grafik veranschaulicht die verschiedenen Bereiche des Elektrifizierungspotenzials: Dunkelgrün steht für ein „sehr hohes" Elektrifizierungspotenzial im Bereich von 80–100 %, Grün für „hoch" (60–80 %), Gelb für

„mäßig“ (40–60 %), Orange für „niedrig“ (20–40 %) und Grau für „sehr gering“ (0–20 %). Geringe tägliche Betriebsstunden in Verbindung mit einer guten Infrastruktur begünstigen die Elektrifizierung, während hohe tägliche Betriebsstunden und eine schlechte Infrastruktur diese behindern. Die Ovale zeigen die Streuung der Betriebsstunden und damit des EP innerhalb desselben Teilsektors an und verdeutlichen die Abhängigkeit des EP von den spezifischen Einsatzprofilen. Im Jahr 2030 ist das Elektrifizierungspotenzial aufgrund geringerer Ladekapazitäten oder weniger leistungsfähiger Batterien etwas niedriger.

Abbildung 3: Auszug aus „NRMM Electrification“ für die Motorkategorie NRE im Jahr 2050



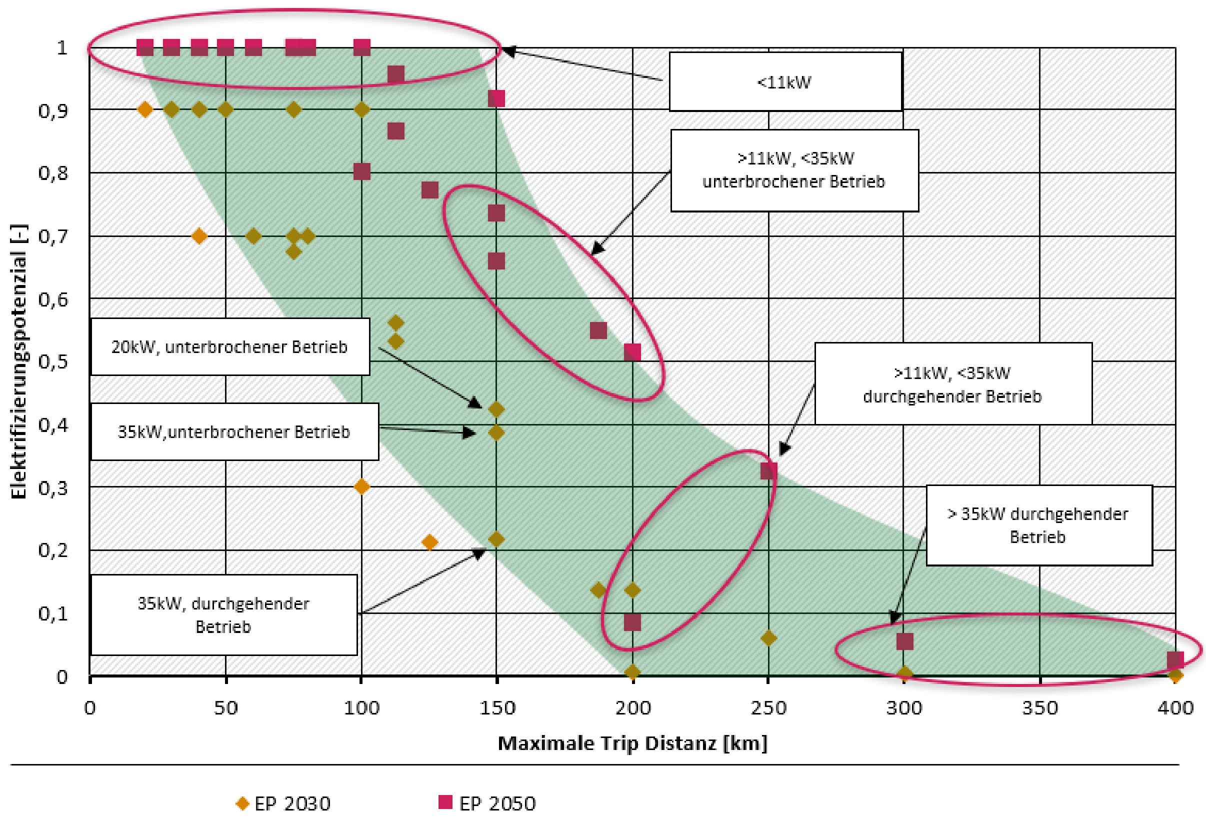
Quelle: Eigene Darstellung von TU Graz

Die Motorkategorien IWA und IWP, die Binnenschifffahrtsmotoren zwischen 19 und 75 kW repräsentieren, weisen ein moderates EP auf, während leistungsstärkere Motoren in diesem Sektor nur ein niedriges oder sogar sehr niedriges EP erreichen. Für diese Kategorien ist von 2030 bis 2050 ein leichter Anstieg des EP zu verzeichnen, der auf Verbesserungen in der Batterietechnologie und eine höhere verfügbare Ladeleistung zurückzuführen ist.

Kleine Maschinen unter 19 kW in den Klassen NRS und NRSh weisen je nach Anwendungsart eine große Bandbreite an EP auf, die von niedrig bis sehr hoch reicht. Die wichtigsten Einflussfaktoren sind die installierte Leistung und die täglichen Betriebsstunden. Das EP von Maschinen mit geringerer Leistung und dem Betriebsprofil „Hobby“ reicht im Jahr 2030 von moderat (Aufsitzmäher Hobby) bis hoch (Kettensäge, Trimmer Hobby) und steigt bis 2050 an. Maschinen mit höherer installierter Leistung, die in der Regel dem Betriebsprofil „professionell“ zugeordnet sind, weisen im Jahr 2030 tendenziell ein geringeres Elektrifizierungspotenzial auf – von niedrig (Aufsitzmäher, professionell) bis mäßig (Kettensäge, professionell) –, das bis 2050 deutlich ansteigt.

Bei motorisierten Zweirädern lässt sich ein ähnlicher Trend beobachten. Die Ergebnisse zeigen eine große Bandbreite des Elektrifizierungspotenzials (EP) über verschiedene Fahrzeugklassen hinweg, die von niedrig bis sehr hoch reicht. Hauptfaktoren sind die installierte Leistung und die maximale Fahrstrecke. Fahrzeuge mit höherer installierter Leistung weisen tendenziell ein geringeres EP auf. Die Abhängigkeit des EP von der maximalen Fahrstrecke ist im Streudiagramm in Abbildung 4 dargestellt. Mopeds mit geringem Leistungsbedarf und kurzen Fahrstrecken weisen selbst im Jahr 2030 ein sehr hohes EP auf, während große Motorräder mit einer Leistung über 35 kW und hohen Fahrstrecken von 250 km ein niedriges bis sehr niedriges EP aufweisen. Die große Bandbreite bei ähnlichen Fahrstrecken verdeutlicht den Einfluss anderer Faktoren wie Lademöglichkeiten und Leistungsbedarf.

Abbildung 4: Streuungsband für das Elektrifizierungspotenzial von motorisierten Zweirädern



Quelle: Eigene Darstellung von TU Graz

Im Bereich der Freizeitboote wurden elf Bootstypen bewertet, von der Segelyacht mit Außenbordmotor geringer Leistung (3 kW) über das leistungsstärkere Fischerboot (135 kW) bis hin zum Tageskreuzer mit der höchsten Leistung (260 kW). Bei Booten mit sehr geringer Leistung (3 kW), wie Außenbordbooten und Segelyachten, ist der EP sehr hoch bis hoch. Zwar lässt sich ein allgemeiner Zusammenhang feststellen, wonach eine höhere Leistung zu einem niedrigeren EP führt, doch beeinflussen andere Faktoren wie die verfügbare Ladekapazität und das Ladevolumen den EP erheblich. Für Freizeitboote im Allgemeinen ist der EP im Jahr 2030 niedrig bis mäßig, wobei er bei einigen Typen hoch ist. Mit Blick auf den Zeitraum von 2030 bis 2050 ist ein Anstieg des EP in allen Anwendungsbereichen zu beobachten. Diese Anstiege sind eher moderat; daher weisen einige Anwendungsbereiche im Jahr 2050 weiterhin einen mäßigen bis hohen EP auf.

Eine Elektrifizierung ist für eine Vielzahl von Anwendungsfällen und Segmenten möglich, insbesondere bei kleineren Maschinen und Fahrzeugen. Bei großen und leistungsstarken Maschinen und Fahrzeugen bestehen jedoch weiterhin erhebliche Lücken.

Politische Optionen

Beispiele für angebotsseitige Vorschriften, die direkt auf die Treibhausgasemissionen von NRMM abzielen, sind weltweit begrenzt. In der EU gibt es derzeit keine derartigen Vorschriften, und die bestehenden Regelungen konzentrieren sich in erster Linie auf Luftschadstoffe im Rahmen der Stufe V, die Grenzwerte für CO, HC, NOx, PM und PN aus NRMM-Motoren festlegt. Der Aufbau eines Rahmens, der auf die Treibhausgasemissionen von NRMM abzielt, stellt im Vergleich zum Straßenverkehrssektor erhebliche Herausforderungen dar, da der NRMM-Sektor im Vergleich zu Straßenfahrzeugen heterogener ist und es in den EU-Mitgliedstaaten an harmonisierten Registrierungs- und Überwachungssystemen für NRMM mangelt.

In dieser Studie wurde untersucht, wie diese Herausforderungen durch zwei wesentliche politische Ansätze auf der Angebotsseite bewältigt werden können:

- Szenario 1: Änderung der Stufe V zur Förderung emissionsfreier NRMM
- Szenario 2: Einführung einer gestaffelten Null-Emissions-Vorgabe für NRMM

Szenario 1 umfasste die Festlegung fortschrittlicher Vorschriften für NRMM, darunter strengere Schadstoffgrenzwerte, Anforderungen an die Konformität im Betrieb, strengere Bestimmungen zur Haltbarkeit, Emissionsanforderungen bei geringer Last und im Leerlauf sowie gezielte Bestimmungen für Kategorien mit hoher Priorität wie Transportkühlaggregate. Diese Maßnahmen würden die Luftschadstoffbilanz unter realen Betriebsbedingungen verbessern und könnten indirekt die Wettbewerbsfähigkeit emissionsfreier Maschinen steigern, indem sie die Konformitätskosten für Verbrennungsmotoren erhöhen. Ein ergänzender Mechanismus zur Vergabe von Emissionsgutschriften könnte es Herstellern ermöglichen, durch das Inverkehrbringen emissionsfreier Maschinen – insbesondere in Leistungsklassen mit höherer Leistung – Gutschriften zu erwerben und diese zu nutzen, um Flexibilität für Verbrennungsmotoren in Anwendungen zu schaffen, die sich nur schwer elektrifizieren lassen.

Szenario 2 würde eine separate, gestaffelte Null-Emissions-Vorgabe für NRMM festlegen, ähnlich den aktuellen EU-CO_2-Vorschriften für Lkw oder Busse. Bei diesem Ansatz würden die Maschinenkategorien entsprechend ihrem Elektrifizierungspotenzial gruppiert:

- Für Kategorien mit geringem Elektrifizierungspotenzial, z. B. landwirtschaftliche Fahrzeuge > 130 kW, würden keine Ziele gelten
- Kategorien mit mittlerem Elektrifizierungspotenzial, z. B. ortsfeste Baumaschinen > 130 kW, müssten bis 2035 ein Null-Emissions-Ziel von 30 % erreichen, das bis 2050 auf 50 % ansteigen würde.
- Kategorien mit hohem Potenzial, z. B. ortsfeste Baumaschinen < 130 kW, müssten bis 2035 ein Ziel von 70 % erreichen, das bis 2050 auf 85 % ansteigen würde.

Dieser Ansatz würde einen größeren Anteil des Energieverbrauchs von nicht straßengebundenen mobilen Maschinen und Geräten (NRMM) abdecken als eine eng gefasste Stage-V-Novelle, würde jedoch einen robusteren Überwachungsrahmen und eine sorgfältige Ausgestaltung von Flexibilitätsmechanismen erfordern, wie z. B. Mittelwertbildung, Anrechnungs- und Handelsmechanismen, Ausnahmen für Nischenanwendungen sowie Gewichtungsmechanismen auf der Grundlage der erwarteten Auswirkungen auf die Emissionen.

Maßnahmen auf der Nachfrageseite können die Regulierung auf der Angebotsseite ergänzen. Oslo hat die öffentliche Beschaffung genutzt, um den Einsatz emissionsfreier Baumaschinen zu beschleunigen, London hat eine Umweltzone für Baumaschinen eingeführt, die Niederlande kombinieren freiwillige Ziele mit erheblichen öffentlichen Fördermitteln, und New York City testet elektrische Baumaschinen im Rahmen von Pilotprogrammen. Ähnliche EU-Maßnahmen könnten die Ausweitung der Regeln für eine umweltfreundliche öffentliche Beschaffung auf NRMM, die Förderung der Ladeinfrastruktur, die Nutzung von Kraftstoffsteuern oder CO_2-Bepreisung sowie die Schaffung von Anreizen durch Gutschriftsysteme für erneuerbare Kraftstoffe oder Strom umfassen.

Umweltverträglichkeitsprüfung

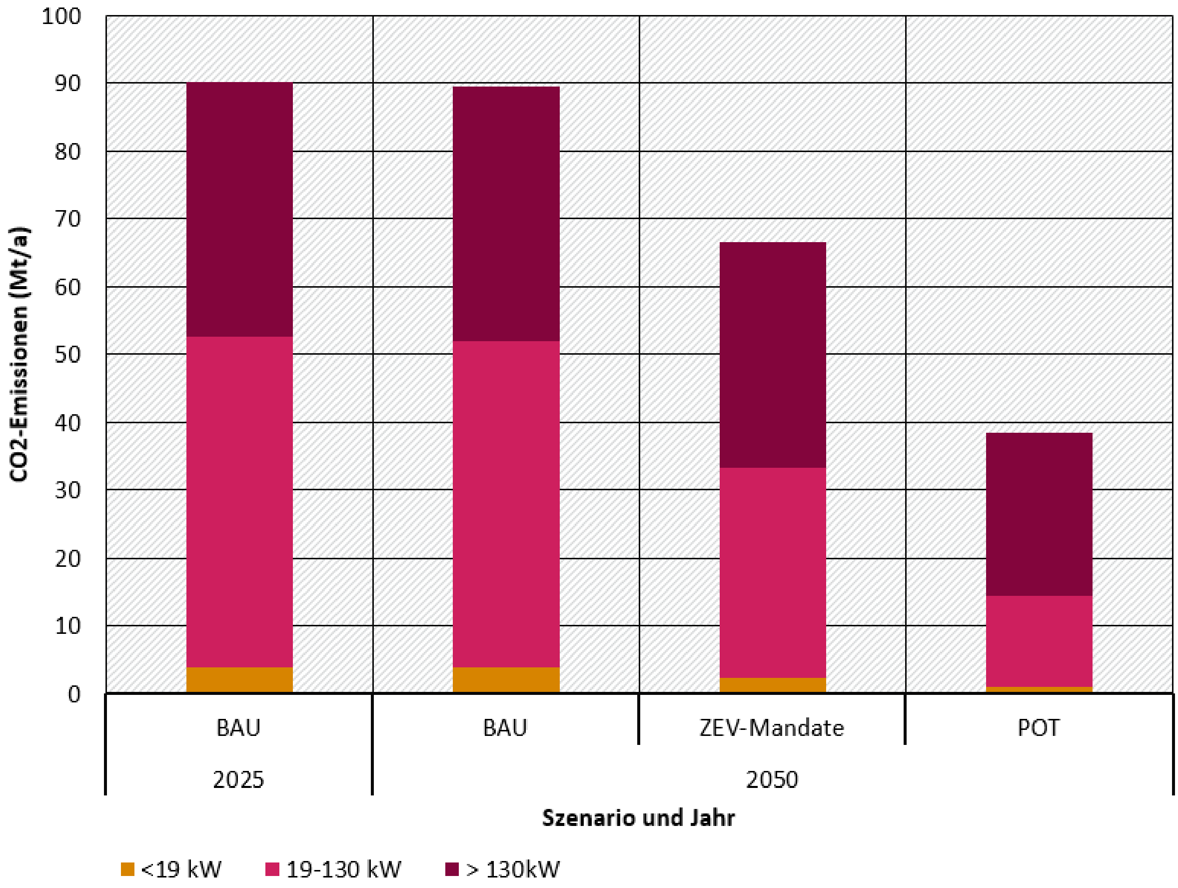
Diese Folgenabschätzung bewertet den Energieverbrauch, die Treibhausgasemissionen sowie die Reduzierung von Luftschadstoffen in drei politischen Szenarien (BAU, ZEV-Vorgabe und POT) im Zeitraum von 2025 bis 2050 unter Verwendung des TREMOD-MM-Modells. Zusätzlich werden Lebenszyklusanalysen (LCA) durchgeführt, um vorgelagerte Emissionen aus der Energieversorgung und der Batterieproduktion zu berücksichtigen.

Zur Bewertung der Auswirkungen der Elektrifizierung und der Einführung von Wasserstoff werden drei Szenarien modelliert:

- Business-as-usual (BAU): Der Anteil emissionsfreier Fahrzeuge (ZEV) bleibt auf dem Niveau von 2025.
- ZEV-Vorgabe: Eine teilweise Elektrifizierung ist vorgeschrieben (siehe Szenario 2 im vorigen Abschnitt).
- Technisches Potenzial (POT): Vollständige Ausschöpfung des Elektrifizierungs- und Wasserstoffpotenzials pro EP-Gruppe, was die theoretisch maximale Marktdurchdringung von ZEV bis 2050 darstellt. Zwischen 2030 und 2050 wird eine lineare Interpolation verwendet.

Abbildung 5 zeigt, dass die CO_2-Emissionen im BAU-Szenario aufgrund stagnierender Antriebsumstellungen und der Abhängigkeit von fossilen Brennstoffen unverändert bleiben. Das ZEV-Mandat erzielt bis 2050 eine CO_2-Reduzierung von 26 % im Vergleich zum BAU-Szenario, angetrieben durch die Elektrifizierung von Maschinen mit einer Leistung von <130 kW. Das POT-Szenario weist im Jahr 2050 eine CO_2-Reduzierung von 57 % im Vergleich zum BAU-Szenario auf, einschließlich der Beiträge von Maschinen mit einer Leistung von >130 kW (z. B. Bagger, Muldenkipper) durch teilweise Elektrifizierung und Wasserstoff.

Abbildung 5: CO_2-Emissionen (direkt) von mobilen Maschinen und Geräten sowie Freizeitbooten nach Szenario und Antriebsart, EU-27



Quelle: Eigene Darstellung von ifeu. Hinweis: Abgasemissionen mit 100 % fossilem Kraftstoff berechnet. „ZEV-Mandate" steht für eine Nullemissionsquote

Im POT-Szenario verbleiben bis 2050 40 Mt CO_2/Jahr, was für eine vollständige Dekarbonisierung den Einsatz erneuerbarer Kraftstoffe (z. B. Biokraftstoffe, E-Kraftstoffe) erforderlich macht. Während der Bedarf an fossilen Brennstoffen in den politischen Szenarien stark zurückgeht, verbleiben mindestens 550 PJ/Jahr an flüssigen Kraftstoffen (hauptsächlich Diesel) – was dem aktuellen Biokraftstoffverbrauch der EU im Verkehrssektor entspricht. Dies ist zum Teil auf das begrenzte Potenzial für die Elektrifizierung neuer Maschinen zurückzuführen, aber auch auf die lange Lebensdauer der bestehenden Flotte, da 9 % des Verbrauchs an fossilen Brennstoffen im Jahr 2050 auf Maschinen entfallen werden, die 30 Jahre oder älter sind. Ähnliche Trends lassen sich bei Zweirädern beobachten, bei denen im ZEV-Mandat bis 2050 eine CO_2-Reduzierung von 24 % und im POT-Szenario eine CO_2-Reduzierung von 49 % erreicht wird. Dies ist hauptsächlich auf die Elektrifizierung von Mopeds und kleineren Motorrädern zurückzuführen, während bei größeren Motorrädern (L3A3) aufgrund des geringeren Elektrifizierungspotenzials nur begrenzte Einsparungen erzielt werden. Für nicht elektrifizierbare Fahrzeuge verbleiben 70 PJ/Jahr.

Alle Szenarien, einschließlich des BAU-Szenarios, zeigen zudem bis 2050 einen Rückgang der NO_X-, PM_{10}- und HC-Emissionen, was belegt, dass die derzeitige Stufe-V-Verordnung zu erheblichen Verbesserungen der Luftqualität führen wird. Mit zunehmender Elektrifizierung im Rahmen eines ZEV-Mandats oder im POT-Szenario kann die Reduktion jedoch noch höher ausfallen, was langfristig den Weg hin zu null Luftschadstoffemissionen unterstützt. Bestimmte

Emissionsminderungseffekte wären auch durch Änderungen der Luftverschmutzungsgrenzwerte zu erwarten, z. B. durch die Stufe VI (Szenario 1), deren Quantifizierung war jedoch nicht Gegenstand dieser Studie.

Da die oben genannten Szenarioergebnisse nur die Abgasemissionen abdecken, wurde eine vereinfachte Ökobilanz (LCA) durchgeführt, die auch vorgelagerte Emissionen (Kraftstoffgewinnung/Raffination im Vergleich zur Stromerzeugung) und die Batterieproduktion (zusätzliche Emissionen bei elektrischen Maschinen) berücksichtigte. Für die Stromerzeugung wurden die durchschnittlichen Strommixe der EU-27 für die Jahre 2023 und 2030 herangezogen. Die wichtigsten Ergebnisse zeigen, dass elektrische Maschinen trotz der vorgelagerten Emissionen aus Stromerzeugung und Batterieproduktion pro Betriebsstunde mehr als 70 % weniger CO_2 ausstoßen als Dieselmaschinen. Maschinen mit hoher Nutzungsintensität (z. B. Radlader) erzielen größere jährliche Treibhausgaseinsparungen als Maschinen mit geringer Nutzungsintensität, z. B. Kleintraktoren, selbst bei ähnlichen Reduktionen pro Stunde. Die Einsparungen steigen von 2023 bis 2030, da sich der Strommix der EU verbessert.

Eine Sensitivitätsanalyse hinsichtlich der jährlichen Betriebsstunden zeigt, dass elektrische Minibagger die Batterieemissionen bereits nach mehr als 50 Betriebsstunden pro Jahr ausgleichen, was deutlich unter der typischen Nutzung liegt. Wie jedoch auch andere Studien bestätigen, können elektrische Maschinen in Anwendungen mit geringer Nutzung, z. B. Freizeitboote oder Notstromaggregate, die Vorteile der Ökobilanz aufgrund der Batterieemissionen zunichte machen. In einigen Fällen können erneuerbare Kraftstoffe (HVO100, PtL) geringere Ökobilanz-Emissionen bieten als die Elektrifizierung, insbesondere bei Anwendungen mit geringer Nutzungshäufigkeit und hoher Leistung.

Was die politischen Szenarien betrifft, kann eine ZEV-Vorgabe eine wirksame Maßnahme sein, um die Elektrifizierung voranzutreiben und Emissionen zu reduzieren. Eine vollständige Ausschöpfung der technischen Potenziale würde zu noch weiteren Emissionsminderungen führen, wäre jedoch allein mit angebotsseitigen Maßnahmen nur schwer zu erreichen. Und selbst dann ist eine vollständige Dekarbonisierung der Sektoren allein durch Elektrifizierung beim derzeitigen Stand der Technik nicht möglich. Daher werden zusätzliche Technologien, z. B. erneuerbare Kraftstoffe, und politische Maßnahmen erforderlich sein.

Feedback der Interessengruppen

Im Rahmen der Arbeit des Projektteams wurden Einzelinterviews mit verschiedenen Interessengruppen geführt und ein Expertenworkshop abgehalten. Vertreter der Erstausrüster (OEM) betonten, dass die Branche im Bereich der Elektrifizierung bereits erhebliche Fortschritte erzielt habe und eine Reihe von Lösungen anbiete. Die Elektrifizierung biete zwar großes Potenzial, habe jedoch je nach Anwendungsfall auch klare Grenzen. Angesichts der großen Vielfalt an Anwendungsfällen gibt es keine Einheitslösung. Anstatt Anforderungen an das Angebot zu stellen, muss sichergestellt werden, dass tatsächlich eine Nachfrage nach solchen Maschinen besteht, die derzeit noch gering ist.

Die Interessengruppen betonten ferner, dass eine erfolgreiche Dekarbonisierungsstrategie für die Sektoren NRMM, Freizeitboote und motorisierteZweiräder Technologieneutralität, eine lebenszyklusbasierte Bewertung, eine ausreichende Infrastruktur, die Verfügbarkeit nachhaltiger Energieträger sowie wirtschaftlich tragfähige Lösungen für die Nutzer umfassen muss. Ebenso wichtig sind ein wettbewerbsfähiges Geschäftsumfeld, fairer globaler Wettbewerb und politische Maßnahmen, die die Erneuerung der Flotten und die Dekarbonisierung bestehender Maschinen unterstützen.

Politische Empfehlungen

NRMM gehören nach wie vor zu den wenigen Verkehrssektoren, deren Treibhausgasemissionen in der EU noch nicht reguliert sind. Der Sektor trägt zu 3 % der jährlichen Treibhausgasemissionen der Union bei, was eine Herausforderung für die Einhaltung des Klimagesetzes der Europäischen Union darstellt. Angesichts der erheblichen und derzeit unregulierten CO_2-Emissionen des Sektors sollte die Europäische Kommission einen strukturierten politischen Prozess einleiten, um NRMM in den umfassenderen Dekarbonisierungsrahmen der EU zu integrieren.

Kurzfristig sollten die politischen Entscheidungsträger auf bestehenden Rahmenwerken, insbesondere der Stufe V, aufbauen, um Anreize für eine frühzeitige Elektrifizierung zu schaffen. Eine gezielte Verschärfung der Schadstoffgrenzwerte in Verbindung mit Maßnahmen wie Konformitätsanforderungen während des Betriebs kann indirekt die Einführung emissionsfreier Technologien in kleinen NRMM-Kategorien mit hohem Elektrifizierungspotenzial beschleunigen. Diese Maßnahmen sollten von Flexibilitätsmechanismen begleitet werden, beispielsweise durch die Gewährung begrenzter Ausnahmeregelungen für Hersteller zur Einhaltung einer Norm nach Stufe V, sofern sie nachweisen können, dass sie eine bestimmte Anzahl emissionsfreier Maschinen anstelle von dieselbetriebenen Maschinen auf den Markt gebracht haben.

Parallel dazu sollten Vorbereitungsarbeiten für einen umfassenderen, auf CO_2 ausgerichteten Regulierungsansatz beginnen – beispielsweise durch eine maßgeschneiderte Null-Emissions-Vorgabe. Aufgrund der Heterogenität des Sektors wird die Einrichtung eines CO_2-Überwachungsmechanismus für alle NRMM-Kategorien nicht empfohlen. Stattdessen sollte der Schwerpunkt auf Kategorien mit hoher CO_2-Belastung liegen, z. B. NRE > 19 kW. Die Einrichtung eines harmonisierten Überwachungs- und Berichtssystems in allen Mitgliedstaaten wird eine entscheidende Voraussetzung sein. Dies könnte eine verstärkte Berichterstattung durch die Hersteller, eine verbesserte Datenerhebung durch Konformitätserklärungen oder die Entwicklung eines speziellen EU-weiten Nachverfolgungsrahmens für NRMM umfassen. Zwar wäre die Einführung einer Null-Emissions-Vorgabe das wirksamste Mittel, um das Angebot an emissionsfreien größeren Maschinen auf dem europäischen Markt zu erhöhen, doch ist die Festlegung solcher Ziele ohne die Erfassung der Verkaufszahlen nicht möglich. Eine Voraussetzung für eine Null-Emissions-Vorgabe wäre ein harmonisiertes Zulassungsverfahren.

Die Gestaltung der Politik sollte der Heterogenität des Sektors Rechnung tragen, indem zwischen Maschinentypen und ihrem Elektrifizierungspotenzial unterschieden wird. Ein abgestufter Ansatz – bei dem für Segmente mit hohem Elektrifizierungspotenzial ehrgeizigere Ziele festgelegt werden, während für Kategorien, bei denen eine Emissionsminderung schwieriger ist, Flexibilität gewährt wird – könnte zu wirksamen Emissionsminderungen führen und gleichzeitig die Machbarkeit gewährleisten. Ergänzende Maßnahmen auf der Nachfrageseite, wie umweltorientierte öffentliche Beschaffung, Umweltzonen und gezielte Förderprogramme, können die Marktakzeptanz weiter beschleunigen.

Schließlich werden unterstützende Maßnahmen unerlässlich sein, um den Übergang zu fördern. Dazu gehören der Ausbau der Lade- und Energieinfrastruktur, die Gewährleistung des Zugangs zu einer zuverlässigen Stromversorgung an den Einsatzorten sowie die Verbesserung der Markttransparenz. Die Entwicklung einer unabhängigen Informationsplattform zu verfügbaren emissionsfreien Maschinen, einschließlich Leistungsdaten und Anwendungsbeispielen, könnte dazu beitragen, das Bewusstsein zu schärfen und Unsicherheiten bei den Anwendern abzubauen. Zusammen können diese Maßnahmen die Voraussetzungen für eine verstärkte

Verbreitung emissionsfreier NRMM und für die Erzielung bedeutender Emissionsminderungen in diesem Sektor schaffen.

1 Introduction and aim of the study

1.1 Background

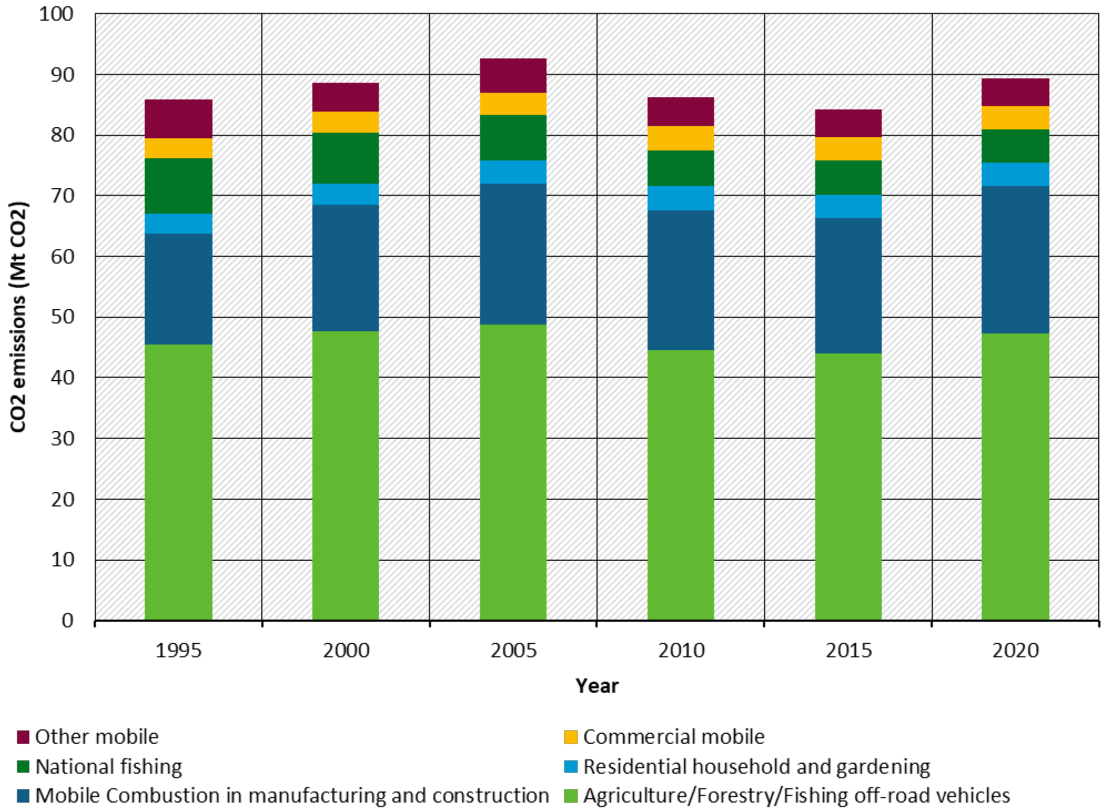
In the course of implementing the ParisClimate Agreement, the European Union has set the goal of reducing greenhouse gas (GHG) emissions by 55 % by 2030 compared to 1990 levels and becoming net zero by 2050. Germany has set the target of reaching GHG neutrality by 2045 in its Climate Action Act. Achieving this will only be possible through the phase-out of fossil fuel combustion and the transition to renewable energy sources.

For road transport, the EU has therefore implemented various regulations to support this objective, such as the European CO_2 fleet targets for passenger cars and heavy-duty vehicles or the Clean Vehicles Directive (CVD). In addition, a wide range of national regulations and incentive schemes exist, such as CO_2-differentiated truck tolls or bonus-malus systems, which have already been implemented or are planned. As a result, recent years have seen a growing increase in the number of electric vehicles in the EU, particularly passenger cars.

For non-road mobile machinery and equipment (NRMM) this transition pathway is not yet paved, and currently fossil fuels and internal combustion engines are used for most applications. Whilst zero emission drives have proven to be an applicable solution for most use cases in the on-road sector, applications in the off-road sector are more diverse. NRMM include a wide range of applications (e.g. in agriculture, construction, gardening) and type of machinery (e.g. tractors, dumpers, chain saws), which are used in both cities and in rural areas. This wide range of applications might bring challenges for direct electrification, due to e.g. battery weight, size or infrastructure limitations.

Since NRMM are a significant contributor to GHG emissions, actions are needed to reduce these emissions and to become net zero by 2050. Currently, NRMM account for estimated GHG-emissions of about 2 Gt CO_2e globally, exceeding the annual GHG-emissions of global maritime shipping (Rodríguez 2025). In Europe, NRMM were responsible for around 3 % of annual greenhouse gas (GHG) emissions, amounting to approximately 90-110 Mt CO_2e according to a recent study (Unterlohner 2024) and own estimations (see Figure 6). This is approximately the equivalent of 55 million cars or more than half of truck emissions in Europe. In Germany, the share of NRMM GHG emissions on all mobile sources is around 8 %. With regard to the individual sectors within NRMM, agriculture and construction account for the highest emissions.

Figure 6: CO_2 emissions in the NRMM sector (EU27)



Source: Own illustration by ifeu[1], based on UNFCCC National Inventory Submissions (United Nations 2024).

In addition to GHG emissions, NRMM also emit a high number of air pollutants (e.g. NOx, PM) and generate noise from their fossil-powered combustion engines. Regarding the total PM and NO_x emissions from the on-road and non-road sector, non-road vehicles and machinery are estimated to have a high share of 44 % on PM and 18 % on NO_x emissions (Rodríguez 2025). Especially in urban areas, these emissions can contribute to health issues for residents and can significantly reduce quality of life.

Another group of mobile sources are recreational craft, such as small passenger boats or other personal watercraft, as well as powered two-wheelers, i.e. mopeds and motorcycles. NRMM, recreational craft, and powered two-wheelers all have in common that there are currently no dedicated regulations facilitating the transition to zero-emission powertrains. Most existing guidelines for these categories[2] mainly focus on air pollutants.

The current regulatory framework therefore poses the risk that NRMM GHG emissions will not significantly be reduced by 2050 and the goal of net zero by 2050 will not be achieved. In addition, currently there is limited information on the feasibility and actual electrification potential for NRMM, recreational craft, and powered two-wheelers. Consequently, there is a lack

[1] Country datasets from the National Inventory Submissions were largely complete for some major sectors but lacked data for some other sectors. For sectors with missing information, a log-linear regression was applied using gross value added (GVA) from the corresponding sectors with available data to fill the gaps.

[2] Regulation (EU) 2016/1628: Requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery; Regulation (EU) 168/2013: Establishes uniform standards for the type approval of two- and three-wheel vehicles and quadricycles in Europe; Directive (EU) 2013/53: On recreational craft and personal watercraft

of knowledge regarding which segments can be electrified as well as which regulatory measures could be suitable to make use of existing electrification potentials.

1.2 Aim of the study

To fill this knowledge gap, the German Federal Ministry for Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN) and the German Environment Agency (UBA) have commissioned this eNRMM study. The aim of the study is to examine the electrification potential and policy options of NRMM, recreational craft, and powered two-wheelers. To achieve this, the technical electrification potential for various types of machinery was assessed, regulatory options for electrification were developed, and policy recommendations were derived. The report is structured along the work packages of the project:

- Definition of product categories (chapter 2): Suitable product categories for NRMM, powered two-wheelers, and recreational boats are derived. These categories form the basis for the analyses in the subsequent work packages.
- Estimation of total energy consumption and electrification potentials per product category in the EU (chapter 3+4): EU-wide energy consumption and CO_2 emissions for non-road mobile machinery (NRMM), powered two-wheelers, and recreational boats by product category were calculated for the year 2025 and in a scenario until 2050. In addition, the electrification potential of each individual type of machine was assessed.
- Assessment of policy options (chapter 5: Elaboration of three regulatory options and derivation of an ambitious level of electrification.
- Assessment of environmental and other impacts of the policy options (chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**): Estimation of greenhouse gas (GHG) emission reductions resulting from the various regulatory options. Assessment of environmental co-benefits (air pollutants), as well as economic and social impacts.
- Expert workshop (chapter 7): Conducting a half-day expert workshop in Brussels to discuss preliminary results and get feedback from external experts (e.g. associations, OEM, research institutes, EU commission).
- Overall comparison of the policy options (chapter 8): Comparison of the advantages and disadvantages of the different regulatory options, and derivation of regulatory recommendations, as well as, where applicable, policy recommendations.

1.3 Scope of the study

The following scope and limitations apply to the study:

- **Geographical and temporal scope:** The study focuses on electrification potential and regulatory options in the European Union (EU27) for the time period 2025 to 2050.
- **Sectors and categories:** The analysis covers non-road mobile machinery and equipment (NRMM) and additionally includes powered two-wheelers and recreational crafts. These are analysed in a highly disaggregated manner, differentiated by engine types, sectors (e.g. construction, forestry), subsectors/machine types (e.g. harvesters, chain saws), and segments/power classes (e.g. 0–18 kW, 18–37 kW), see chapter 2.
- **Technologies/fuels:** With regard to technologies and fuels, the study places a clear emphasis on direct electrification, either through direct grid connection or via intermediate

energy storage in batteries. Where direct electrification is technically not feasible or practical, other alternative powertrain options are considered[3], such as hydrogen use in internal combustion engines and fuel cells, insofar as they may contribute to meeting future regulatory requirements.

- **Emissions:** The assessment of emissions primarily addresses tailpipe emissions (TTW), but additional calculations are made for well-to-wheel (WTW) and life-cycle assessment (LCA) emissions in less detail.
- **Regulations:** The policy perspective of the study primarily focuses on supply-side regulatory instruments, reflecting the primary levers available at EU level to influence technology deployment and emissions savings. Other types of policies are analyzed in less detail.
- **Limitations:** The study focuses on the technical electrification potential and derives regulatory options on that basis. It is not a comprehensive impact assessment and therefore does not cover all relevant aspects such as market-related, economic or social aspects. Therefore, it does not include detailed analysis such as total cost of ownership (TCO), market dynamics, consumer behaviour, or broader industrial production capacities and impacts.

Why focus on electrification?

This study fills public knowledge gaps on the technical potential for electrification—accounting for constraints such as the much lower energy density of batteries versus liquid and gaseous fuels—across the diverse mobile-machinery, two-wheeler, and recreational-craft sectors, and develops targeted regulatory options to facilitate market uptake. The study follows the premise that electrification is—where technically feasible—the most energy-efficient and consequently, in many cases, the most cost-effective pathway to decarbonise vehicles and mobile machinery. At the same time, electrification requires substantial systemic changes down to the individual vehicle/machine level: at minimum, electric vehicles and machines have different powertrain and energy storage systems. Moreover, supporting infrastructure (e.g. charging, grid access) must be adapted to operational contexts.

The study did not focus on decarbonisation via green fuels because it does not require the same systemic and application-specific redesign. There are already many studies on producing and scaling green fuels; by contrast, electrification requires detailed, equipment-level/use-case analyses across diverse machine (and vehicle) types. At the same time, availability of green fuels is constrained, with competing demand from sectors such as aviation, shipping, and industry. Only once the electrification potential in the mobile machinery, two-wheeler, and recreational-craft sectors is quantified can residual demand for alternative solutions such as green fuels be determined.

[3] Hydrogen solutions were analyzed in a simplified method compared to electric solutions

2 Product categories

The classification into product categories provides the framework for the project. The product categories in the scope of the project – NRMM, recreational craft, and powered two-wheelers – cover a wide range of different applications, which differ in terms of their technical characteristics, operational profile, and regulatory framework. Therefore, product categories are defined as a basis for the emissions inventory, electrification potential, policy options and impact assessment.

Care was taken to ensure that the selected categories are compatible with existing regulations as far as possible. For NRMM, the categories were therefore assigned to the engine categories and performance classes of the EU Stage V Regulation (EU) 2016/1628[4]. However, as these are too broad for the purposes of this study, subcategories were defined, which are listed below.

2.1 Overview of nomenclature

As the scope of this study entails a variety of different machinery and vehicles, a clear nomenclature is necessary to convey information correctly. All machines are assigned to the following engine categories according to Regulation (EU) 2016/1628 which defines NRMM as "*any mobile machine, transportable equipment or vehicle with or without bodywork or wheels, not intended for the transport of passengers or goods on roads, and includes machinery installed on the chassis of vehicles intended for the transport of passengers or goods on roads.*" .

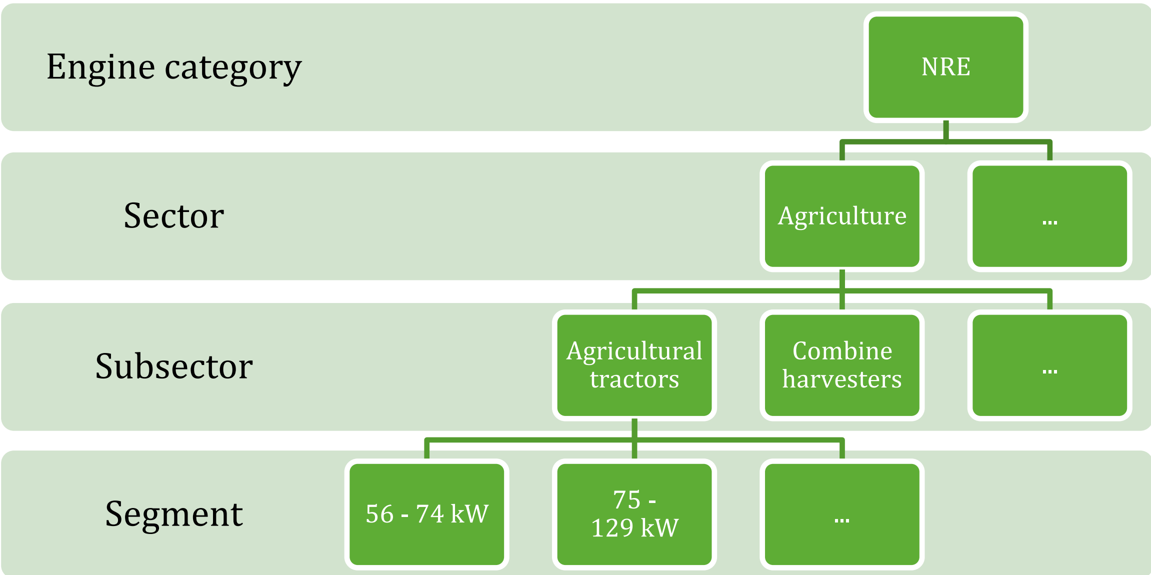
- **NRE:** Engines for non-road mobile machinery intended and suited to move, or to be moved, by road and engines having a reference power of less than 560 kW used instead of Stage V engines of categories IWP, IWA, RLL or RLR.
- **NRG:** Engines with a reference power greater than 560 kW, for use in generating sets.
- **NRSh:** Spark ignition (SI) engines with a reference power less than 19 kW, for use in hand-held machinery.
- **NRS:** SI engines with a reference power less than 56 kW and not included in category NRSh.
- **IWP:** Engines for use in inland waterway vessels, for their direct or indirect propulsion with a reference power greater than or equal to 19 kW.
- **IWA:** Auxiliary engines for use in inland waterway vessels and with a reference power greater than or equal to 19 kW.
- **RLL:** Engines for use in locomotives, for their propulsion or intended for their propulsion.
- **RLR:** Engines for use in railcars, for their propulsion or intended for their propulsion and engines used in place of Stage V engines of category RLL.
- **SMB and ATS**: SMB covers SI engines for use in snowmobiles, ATS covers SI engines for all-terrain vehicles (ATV) and side-by-side vehicles (SbS). The categories SMB and ATS were not considered in the study.

[4] Regulation (EU) 2016/1628: Requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery; Regulation (EU) 168/2013: Establishes uniform standards for the type approval of two- and three-wheel vehicles and quadricycles in Europe; Directive (EU) 2013/53: On recreational craft and personal watercraft

- Additionally, there are motorcycles covered in the study. As they are part of the L-category vehicles according Regulation (EU) No 168/2013, the nomenclature of this document is used. The motorcycles are segmented according to Table 9.
- The group of recreational craft comprises water vessels which are used for recreational purposes, from very small boats with outboard engines and lower power, personal water craft and sailing boats to fishing boats and bigger, high-powered vessels.

Further differentiation is made according to the current version of TREMOD-MM(ifeu 2025). TREMOD-MM is a modelling framework developed by the ifeu to estimate energy consumption and emissions from non-road mobile machinery in Germany. The model is regularly updated and used for national emission reporting, policy analysis and environmental assessments. Since all calculations for the emission inventory and scenarios were done using the TREMOD-MM framework, this practical approach was applied. Therefore, machinery is split into different product categories using sectors, subsectors and segments (Figure 7). These categories were also discussed and, in some cases, adjusted in consultation with industry. For a detailed breakdown of the categories, see the following sections.

Figure 7: Schematic overview of nomenclature



Source: Own illustration by ifeu

2.2 NRE, NRG

The engine categories NRE, NRG of Stage V cover a large share of all land-based NRMM, which currently predominantly use diesel engines and comprise power classes from <18 kW to over 1,000 kW.

Table 2 shows the product categories for the NRE engine classes. It distinguishes between common machine types from the agricultural, forestry, construction, and industrial sectors and shows their typical engine power ranges. The machine types are largely based on the TREMOD-MM model, but have been considered as suitable in consultation with the German Mechanical Engineering Industry Association (VDMA).

Table 2: Product categories for NRE

Sector	Subsector	Power range (kW)
Agriculture	Agricultural tractors	≤ 1,000
Agriculture	Combine harvester	75 ≤ 1,000
Agriculture	Wheel loader	≤ 300
Agriculture	Telehandlers	≤ 300
Construction	Concrete mixers	≤ 18
Construction	Tower cranes	37 ≤ 74
Construction	Mobile and truck-mounted cranes	37 ≤ 1,000
Construction	Construction lifts	≤ 18
Construction	Concrete pumps	18 ≤ 37
Construction	Mortar conveyors and plastering equipment	18 ≤ 37
Construction	Dumpers	≤ 1,000
Construction	Mini excavators	≤ 74
Construction	Crawler excavators	≤ 1,000
Construction	Wheel excavators	≤ 1,000
Construction	Backhoe loaders	≤ 560
Construction	Dozers	37 ≤ 1,000
Construction	Wheel loader	≤ 1,000
Construction	Crawler loader	≤ 1,000
Construction	Compact dumper	≤ 74
Construction	Telehandlers	≤ 1,000
Construction	Motor graders	18 ≤ 1,000
Construction	Ram	75 ≤ 1,000
Construction	Compaction equipment	≤ 19
Construction	Asphalt mixers	≤ 74
Construction	Asphalt boilers	≤ 74
Construction	Road pavers	≤ 1,000
Construction	Construction compressors	≤ 560
Construction	Rollers	18 ≤ 300
Forestry	Forestry tractors	≤ 560
Forestry	Carrier tractors/ forwarders	≤ 560
Forestry	Harvesters	≤ 560

Sector	Subsector	Power range (kW)
Forestry	Debarkers	130 ≤ 300
Other	Forklifts	18 ≤ 130

The category NRG has only one subcategory "Generators". EUROPGEN provided further information and suggested a more detailed categorization of generators. A distinction should be made between:

- Stationary units (designed to stay at one location)
- Mobile units (transportable by truck, forklift)
- Portable units (smaller units which can be moved without forklifts and typically with lower power output)

Stationary generators can also be divided into units with high usage (power plants) and low<=usage (emergency power supply), but the eNRMM study only considered mobile and portable units. Due to time and resource constraints, these categories were aggregated, but the distinction between power classes was made.

Contrary to Stage V, where NRG include only engines >560 kW and smaller generator sets are part of NRE, we analyzed mobile generators in with a power range from <19 kW to 560 kW for the eNRMM study (Table 3).

Table 3: Product categories for NRG

Sector	Subsector	Power range (kW)
Other	Generators	≤ 560

Note: Mobile Generators with an engine power >560 kW have not been identified (see chapter 3.2.1.3)

2.3 RLL, RLR

Table 4 lists the subcategories for RLL and RLR, which are part of the sector "Other". The categories have been selected in accordance with the registration data by EUROSTAT.

Table 4: Product categories for RLL/RLR

Sector	Subsector	Power range (kW)
Other	Locomotives	130 ≤ 10,000
Other	Railcars	300 ≤ 560

2.4 NRS, NRSh

The subcategories for NRS are based on the Model TREMOD-MM and are used in the sectors construction, households and gardening (Table 5).

Table 5: Product categories for NRS

Sector	Subsector	Power range (kW)
Construction	Compaction equipment	≤ 19
Households and Gardening	Lawn Mower private	2 ≤ 5
Households and Gardening	Lawn Mower professional	2 ≤ 5
Households and Gardening	Ride-on Mower / Lawn Tractor private	5 ≤ 19
Households and Gardening	Ride-on Mower / Lawn Tractor (Sport and Hobby)	5 ≤ 19
Households and Gardening	Ride-on Mower / Lawn Tractor (public lawns)	5 ≤ 19
Households and Gardening	Ride-on Mower / Lawn Tractor (company)	5 ≤ 19

Differentiation of handheld equipment (NRSh) is also based on the Model TREMOD-MM. This engine category is used in the sectors forestry, households and gardening (Table 6).

Table 6: Product categories for NRSh

Sector	Subsector	Power range (kW)
Forestry	Chainsaws professional	2 ≤ 5
Households and Gardening	Chainsaws private	1 ≤ 2
Households and Gardening	Chainsaws professional	2 ≤ 5
Households and Gardening	Trimmer private	1 ≤ 2
Households and Gardening	Trimmer professional	1 ≤ 2
Households and Gardening	Other equipment private	1 ≤ 2
Households and Gardening	Other equipment professional	1 ≤ 2

2.5 IWP, IWA

For inland waterway vessels, the subcategories for IWP and IWA cover mostly diesel engines, such as used for freight ships and river passenger ships (Table 7). These can be equipped with small and medium-sized engines, e.g., as auxiliary drives, on-board power generators or multi-engine systems, up to large main propulsion engines with 1,000 kW or more. The categories have been selected in accordance with the registration data by EUROSTAT and data by the Central Commission for the navigation on the Rhine (CCNR).

Table 7: Product categories for IWP/IWA

Sector	Subsector	Power range (kW)
Ships and Motor boats	Day trip ships	18 ≤ 1,000
Ships and Motor boats	River cruise ship	75 ≤ 1,000
Ships and Motor boats	Cargo vessel	75 ≤ 10,000
Ships and Motor boats	Push boat	300 ≤ 10,000

2.6 Recreational craft

Recreational craft are not covered by Stage V but addressed by a separate regulation (see introduction). Research and discussions with the associations ICOMIA, Euromot and EBI revealed that there are no uniform categories commonly used for recreational craft. For this study, we primarily rely on the categories of ICOMIA's boat statistics with regard to the subsectors and summarize them into four categories as shown in the following table. This is a simplification due to the limited availability of data for the emissions inventory. Other studies, e.g. (emisia et al. 2021; Zenié et al. 2023) use different or additional categories in some cases. In addition, however, the categories here are further divided into different power classes.

Table 8: Product categories for recreational craft

Sector	Subsector	Power range (kW)
Ships and Motor boats	Motor boat outboard engine	≤ 100
Ships and Motor boats	Motor boat inboard engine	50 ≤ 200
Ships and Motor boats	PWCs (Personal Watercraft)	12 ≤ 100
Ships and Motor boats	Other boats (incl. sailers)	≤ 50

2.7 Two-wheelers

The categories of powered two-wheelers were differentiated based on the registration data available at EUROSTAT and the categories of EU type approval.

Table 9: Product categories for mopeds and motorcycles

Sector	Subsector	EU category	Power range (kW)
Two-wheelers	Mopeds	L1e-B	≤ 4
Two-wheelers	Motorcycles	L3e-A1	4 ≤ 11
Two-wheelers	Motorcycles	L3e-A2	11 ≤ 35
Two-wheelers	Motorcycles	L3e-A3	> 35

3 Emission inventory EU27, 2025

In this chapter, an inventory for the European (EU27) energy consumption and associated GHG and air pollutant emissions for each engine/product category is developed using the TREMOD-MM model. The results provide an overview of the environmental relevance of the respective categories and form the basis for the impact assessment of possible regulatory options in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**. This chapter describes the bottom-up emission inventory methodology as well as input data and results for all relevant product categories in the EU27 in the year 2025.

3.1 Methodology

The methodology is based on the TREMOD-MM model, which has been used for over 20 years to calculate emissions from mobile machinery in Germany. The approach is comparable to similar models, e.g., the FOEN's nonroad database or the US EPA's NONROAD model. For the eNRMM project, TREMOD-MM was extended to the EU27, and the new drive types electric and H_2 were added for all machine categories.

Energy consumption and emissions for all categories of NRMM and recreational craft are calculated using a bottom-up approach, applying the so-called population approach (Equation 2).

Equation 2: Emission calculation using the population approach

$$emissions \left[\frac{g, MJ}{a}\right] = stock\ [\#] \times use \left[\frac{h}{a}\right] \times power\ [kW] \times load\ [-] \times EF\ [\frac{g, MJ}{kWh}]$$

Stock: total number of machinery/equipment in use, Use: average annual operating hours per machinery/equipment, Power: average rated engine power, Load: average load factor (percentage of rated engine power in use), EF: emission factor

An important factor here is the stock, i.e. the number of all machines or vehicles used in the EU in a specific year. For most categories, unlike for road vehicles, the stock is not directly available from statistics since registration is mostly not mandatory (e.g. for handheld equipment). In these cases, the population is derived from the average annual sales figures and the average lifetime (Equation 3).

Equation 3: Calculation of stock

$$stock\ [\#] = annual\ sales \left[\frac{\#}{a}\right] \times median\ lifetime\ [a]$$

Use of the PRODCOM Database by EUROSTAT

There are currently no official statistics on NRMM sales figures in the EU. These are partly collected and published by associations of machine manufacturers. Additionally, the PRODCOM database was also used as a primary source in the study. Based on Commission Regulation (EC) No 912/2004 of 29 April 2004, member states have to report quantities of produced goods by companies with min. 20 employees accounting to 90 % of the inland production. PRODCOM uses codes and labels to distinguish between a wide range of goods, including machine types. In addition to production volumes, data is also available for foreign trade, i.e., imports and exports. Some key advantages from the authors' perspective are:

- Public accessibility
- Regular updates

- Wide range of categories (some based on performance and drive)
- Consideration of trade with and from third countries

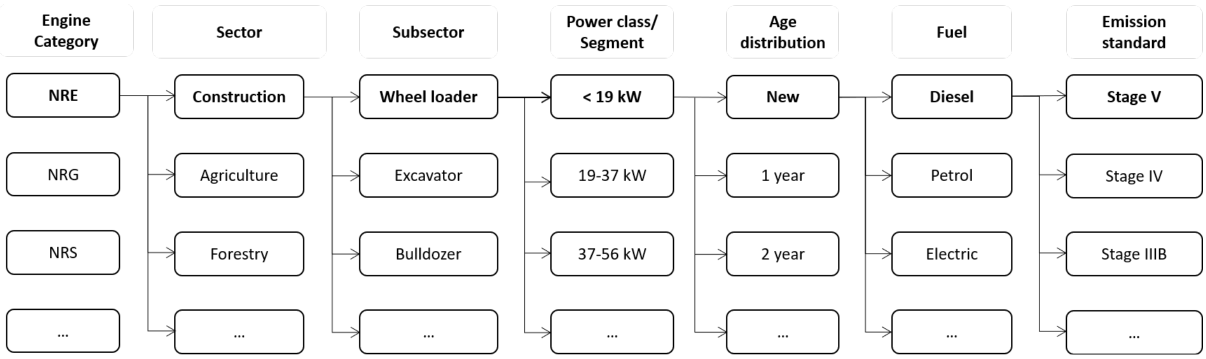
The study therefore used the following approach:

- Annual sales within the EU = Production + Import – Export

However, since calculating annual figures using this formula can lead to very large fluctuations and, in some cases, negative values, the median of the last 20 years was used. In discussions with the VDMA, this approach was deemed fundamentally plausible. However, it was pointed out that the accuracy of the data and the correct allocation of categories by the reporting companies cannot be verified. For this reason, the PRODCOM evaluations were also compared with other sources where possible.

The stock, operating hours, power and energy consumption/emissions are calculated in high differentiation, not only by type of machinery but also by power class, by fuel type and by age. For the total emissions on a higher level, i.e. per power class, per machine type or per sector, the differentiated results can be aggregated in a final step.

Figure 8: Example of the differentiation in the emission inventory TREMOD-MM



Source: Own illustration by ifeu

The population and sales data used for the emission inventory are described in the following subchapters for each category. The values for average annual operating hours, engine power, load factors, emission factors and median lifetime were taken from the TREMOD-MM model and are listed in the annex.

For powered two-wheelers, energy consumption and emissions are determined based on average mileage and average emission factors (Equation 4). Differentiation is made according to the product categories for powered two-wheelers described above.

Equation 4: Emission calculation for powered two-wheelers

$$emissions\left[\frac{g, MJ}{a}\right] = stock\ [\#] \times av.mileage\left[\frac{km}{a}\right] \times av.emission\ factor\ [\frac{g, MJ}{km}]$$

3.2 Input data

3.2.1 Non-Road Mobile Machinery (NRE) and Generators (NRG)

3.2.1.1 Construction

For the construction sector EU-wide population data (stock) was not directly available. The annual sales data from PRODCOM were instead used for this study. Additionally, internal data from the German Mechanical Engineering Industry Association (VDMA) and KGP Auto Intelligence served for validation and filling gaps. The order of magnitude between the different sources is similar. However, more detailed comparisons are not always possible due to different definitions and methods, or can lead to greater deviations (see text box).

Comparison of average annual sales of construction equipment in the EU by different sources

The following four sources were analysed in the study. Due to confidential reason for some sources, only aggregated numbers are given:

- VDMA: ~260,000 sales per year differentiated by subsectors and power class. About 63 % earth moving equipment (e.g. excavators, wheel loaders) and 33 % road/compaction equipment. 42 % of the equipment with >19 kW. Can also include smaller engines (NRS/NRSh)
- Emisia (Mellios et al. 2019): ~290,000 sales per year differentiated by small, light, heavy equipment and power class. 70 % of the equipment >19 kW
- PRODCOM, 2023: ~250,000 sales per year differentiated by subsectors for earthmoving and road/compaction equipment, plus ~480,000 concrete mixers
- KGP, 2023: ~190,000 sales per year differentiated by subsectors

The estimated sales and stock data for each subsector are shown in the following table.

Table 10: Estimated sales, median life and stock for construction equipment, EU27, 2025

Subsector	Sales	Median life	Stock
Mobile and truck-mounted cranes	24,000	12	288,000
Concrete pumps	200	10	2,000
Dumpers	10,500	10	105,000
Mini excavators	47,800	10	478,000
Crawler excavators	24,600	9	222,000
Wheel excavators	8,000	11	89,000
Backhoe loaders	40,200	12	470,000
Dozers	4,700	12	56,000
Wheel loader	24,900	10	239,000
Compact dumper	5,500	9	48,000

Subsector	Sales	Median life	Stock
Telehandlers	22,000	10	209,000
Motor graders	500	12	6,000
Rollers	4,900	10	51,000
Road pavers	1,100	11	12,000
Construction compressors	34,300	11	528,000
Total	**253,200**		**2,803,000**
Total (including concrete mixers)	**739,900**		**7,670,000**

Source: Compiled by ifeu from various sources. Sales figures and inventories rounded to the nearest 100/1,000.

Information on the engine power per category was only available in data provided by the VDMA. However, this information was very aggregated containing the power classes < 19 kW, 19 <= 100 kW, > 100 kW. For this study, the classification by VDMA for the EU is used to adjust the previous shares in TREMOD-MM which have been estimated for the German context (Helms, Heidt 2014). The exact procedure to align the TREMOD-MM and VDMA data is described below and shown in Table 11 using the example of mobile excavators.

The data for the <19 kW class is not adjusted and can be taken directly from the VDMA figures. For the 19-100 kW and >100 kW classes, however, the VDMA data is used to weight the TREMOD-MM data. The TREMOD-MM power classes in these ranges are adjusted for calculation so that their combined shares correspond to the total share of the larger VDMA power class. However, the VDMA share was also adjusted to the 19 <= 129 kW and > 129 kW power class by assigning 25 % of the > 100 kW values to the 18 <= 100 kW power class. This assumes that the number of machines within a power class is evenly distributed across all power classes, which is of course only a rough approximation.

Table 11: Mobile excavators – Sample calculation for adjusting VDMA power classes in TREMOD-MM subdivision

TREMOD-MM Power class	VDMA Share_EU27	VDMA Share_EU27_ad	TREMOD-MM Share_DE	TREMOD-MM Share_EU27
<18 kW	0 %	62.5 %	0	0
18 <= 36kW	50 %		0	0
37 <= 55kW			4.3 %	2.9 %
56 <= 75kW			4.3 %	2.9 %
75 <= 100 kW			85.5 %	56.8 %
100 <= 130kW	50 %			
130 <= 300kW		37.5 %	5.9 %	37.5 %

The share of power classes for construction equipment per machinery type is given in Table 12. The power classes range from <19 kW up to 560 kW.

Table 12: Share of power classes (rated power in kW) for construction equipment

Subsector	<19	<37	<56	<75	<130	<300	<560
Asphalt boilers			50 %	50 %			
Asphalt mixers			50 %	50 %			
Backhoe loaders			50 %	50 %			
Compact dumper	9 %	35 %	28 %	28 %			
Concrete mixers	100 %						
Concrete pumps		50 %				50 %	
Construction compressors	8 %	74 %	8 %	8 %	3 %	0 %	
Construction lifts	100 %						
Crawler excavators			10 %	10 %	52 %	26 %	2 %
Crawler loader		30 %	18 %	18 %	20 %	15 %	
Dozers			2 %	2 %	41 %	56 %	
Dumpers	39 %	5 %	35 %	5 %	7 %	7 %	2 %
Mini excavators	89 %	11 %					
Mobile and truck-mounted cranes					70 %	25 %	5 %
Mortar conveyors and plastering equipment		100 %					
Motor graders				5 %	5 %	84 %	6 %
Ram					100 %		
Road pavers	9 %	7 %	6 %	6 %	39 %	34 %	
Rollers		30 %	22 %	22 %	27 %		
Telehandlers			47 %	47 %	7 %		
Tower cranes			50 %	50 %			
Wheel excavators			3 %	3 %	57 %	38 %	
Wheel loader	37 %	1 %	23 %	23 %	2 %	15 %	

It is assumed that most construction machinery in the NRE category is powered by diesel. In the case of certain construction machinery, e.g. concrete mixers, construction lifts and tower cranes, the TREMOD-MM model has assumed a high proportion of electric motors (usually powered by cable) for many years. For other equipment, there is also a trend toward an increase in electric devices, but the proportions are still very low. According to the VDMA, analyses for Germany indicate that the share of electric machines in sales of compact machines such as crawler excavators, wheel loaders, mobile excavators, compact loaders, backhoe loaders up to 100 kW in 2023 was ~0.8 %.

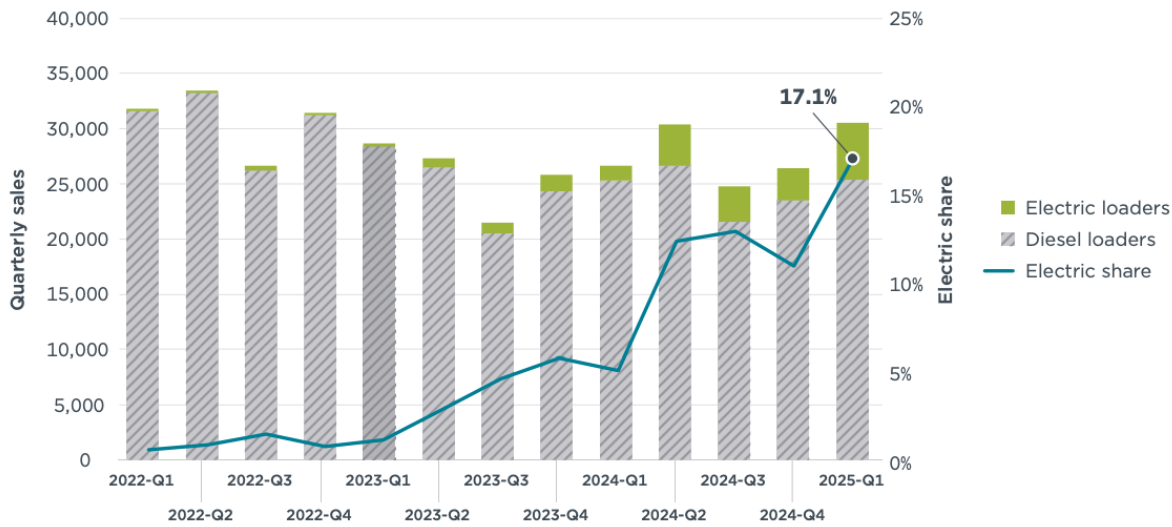
For the inventory 2025, the following shares of electric machines are assumed:

- 1 % for all sorts of excavators, loaders, dumpers and rollers with a rated power of up to 75 kW respectively
- 90 % for concrete mixers
- 100 % for construction lifts and tower cranes

Side note: Electric equipment in China

Similar to the situation with road vehicles, China is currently seeing a faster market uptake of zero-emission construction machinery than in the EU. As Figure 9 shows, the share of electric wheel loaders stood at approximately 17 % in the first quarter of 2025, indicating a steep upward trend. These are not just light-duty machines, as well over half of them had a power output of 130 kW or more.

Figure 9: Development of electric loaders in China



Source: Own illustration by (Li et al. 2025)

3.2.1.2 Agriculture

For the agriculture sector EU-wide population data (stock) was not directly available. The annual sales were estimated from data on production, imports and exports in the EU in the PRODCOM database. In addition, the data from the European Agricultural Machinery Industry Association (CEMA) for agricultural tractors was used for comparison and for a more granular differentiation of tractors with a rated power >90 kW. The estimated stock data for each subsector are shown in the following table.

Table 13: Estimated sales, median life and stock for agriculture equipment, EU27, 2025

Subsector	Sales	Median life	Stock
Agricultural tractors	229,658	36 (15 – 50*)	8,303,640
Combine harvester	21,274	15	319,103
Wheel loader	13,128	14	183,799

Note: * Based on data in the German register, the median life time is lower for bigger tractors and higher for smaller ones.

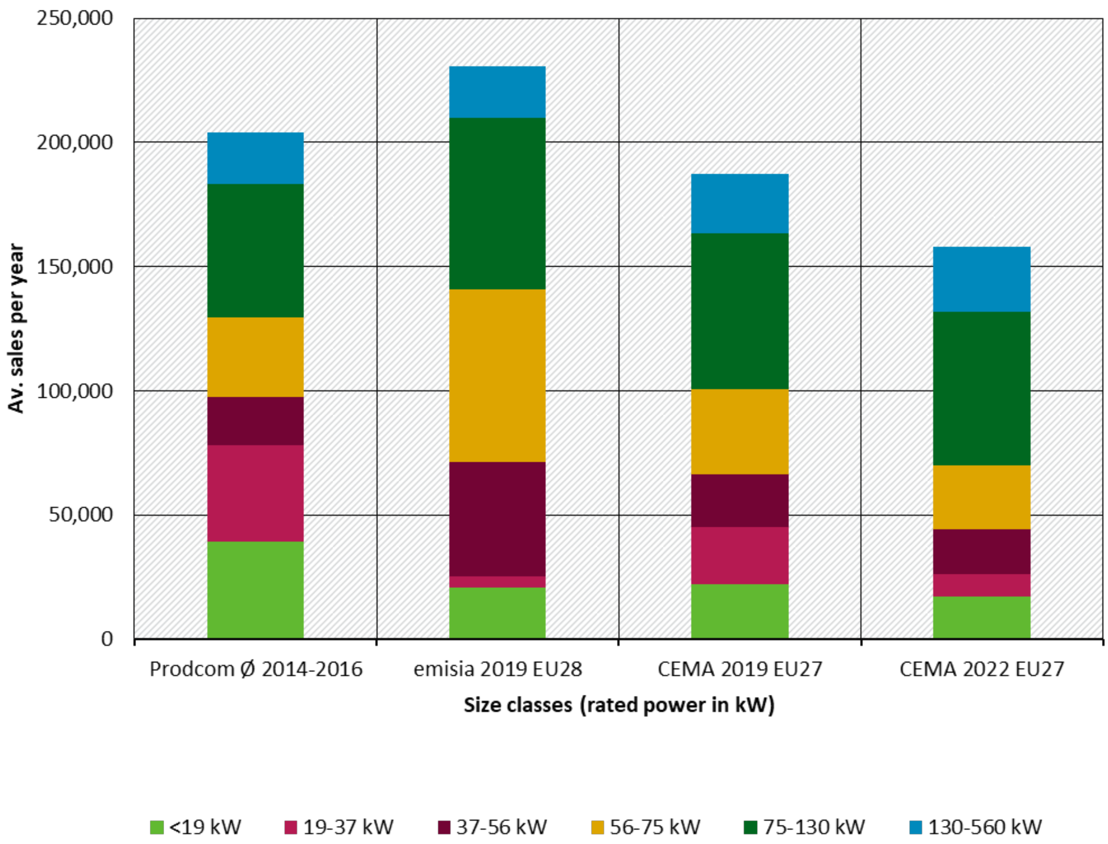
The share of different power classes for tractors results from the annual sales and the average median lifetime for each power class in the PRODCOM database. The average median life is mostly much higher than in the construction sector, especially in the lower power classes (50 years for tractors ≤37 kW and 40 years for 37 <= 74 kW). Therefore, the share of tractors <37 kW in the stock is higher than in the annual sales. The split between the power classes <37 kW and ≥75 kW was estimated based on the data published by CEMA for the year 2022. The share of power classes for combine harvesters was taken from emisia (Mellios et al. 2019), as this was the most recent available source for the EU.

Table 14: Share of power classes (rated power in kW) for agricultural equipment

Subsector	<19	<37	<56	<75	<130	<300	<560
Agricultural tractors	33 %	21 %	12 %	20 %	9 %	4 %	1 %
Combine harvester					8 %	90 %	2 %
Wheel loader		2 %	42 %	42 %	4 %	9 %	

The absolute number of tractors sold annually according to the PRODCOM evaluation roughly corresponds to the figures provided by CEMA. However, the proportion of tractors up to 37 kW is significantly higher in PRODCOM. An evaluation of German statistics from the KBA shows that agricultural tractors often also include smaller off-road vehicles such as mowing tractors and quads. It can be assumed that these also appear in the PRODCOM statistics, even if they are not agricultural tractors. Due to their low power, they are not significantly relevant to overall energy consumption. Nevertheless, further research is needed in this area. The annual sales of combine harvesters from PRODCOM correspond very well with the assumptions of the emisia study (Mellios et al. 2019).

Figure 10: Comparison of agricultural tractor sales in the EU by different sources



Source: Own illustration by ifeu. Notes: Prodcom 2014–2016 refers to the median number in this period

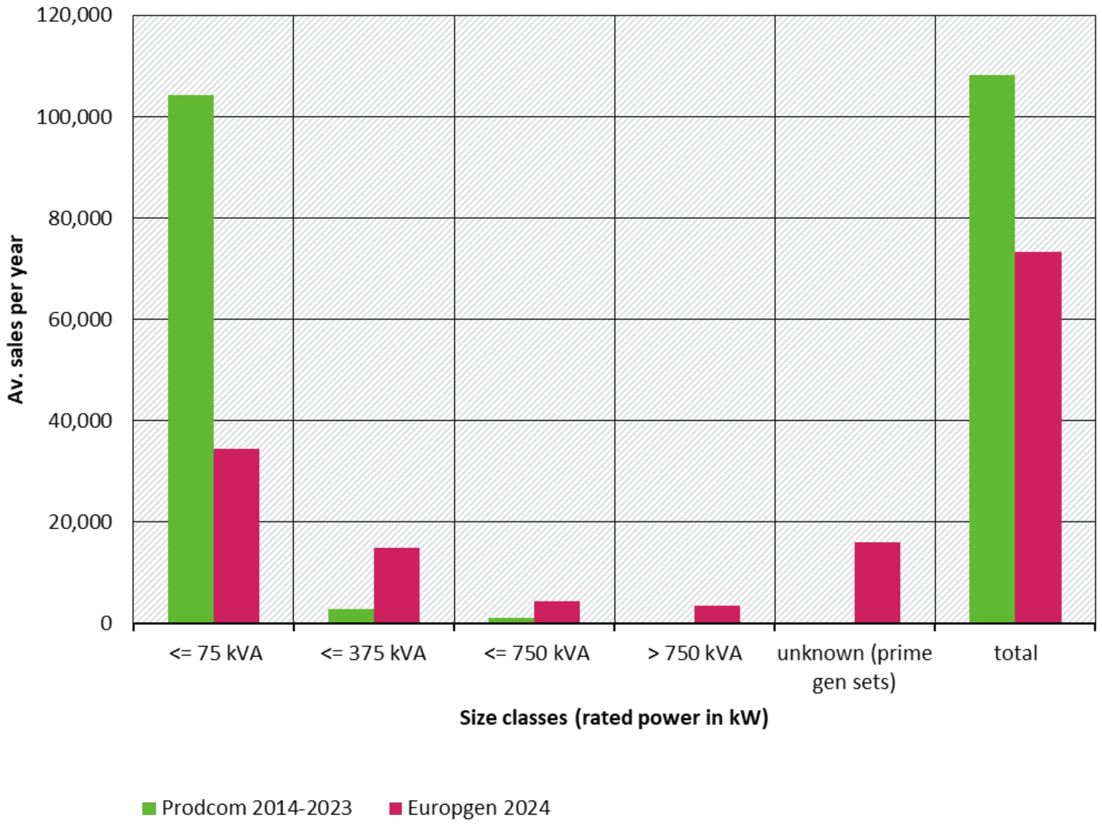
The number of combine harvesters, on the other hand, is less certain. The emisia study (Mellios et al. 2019) puts the figure at around 50,000 units per year, while our calculations based on PRODCOM statistics arrive at just over 20,000, which includes potato harvesters, grape harvesters and forage harvesters in addition to combine harvesters.

We had no information on the proportion of electric machines. Although some manufacturers already offer electric tractors, we were told in personal conversations that demand in the agricultural sector has been very low to date and that electric tractors are more in demand in the municipal sector. Therefore, all agricultural machinery in 2025 is assumed to have Diesel engines.

3.2.1.3 Other (Generators and forklifts)

The average annual sales for generator sets (NRG) and forklifts was estimated from data on production, imports and exports in the EU in the PRODCOM database. The European Association of the Generating Set Industry (Europgen) also provides sales data for generators. These figures are compared with each other in Figure 11.

Figure 11: Comparison of generator sales in the EU by different sources



Source: Own illustration by ifeu. Notes: Prodcom 2014–2023 refers to the median number in this period

However, the data by EUROPGEN for the EU27 (plus the UK) does not include portable (typically smaller) generators and is therefore not directly comparable with our analyses. Furthermore, there is no explanation for the facts that the share of generators > 375 kVA is significantly higher compared to the PRODCOM data.

In order to exclude stationary generators from our study, their share was estimated and calculated using assumptions from TREMOD-MM (based on studies by the US EPA) for each power class. This reduces the number of generators, especially among the more powerful generators, meaning that generators with more than 375 kVA are not used in mobile applications at all. The assumed sales figures and inventories for generators and forklifts are listed in Table 15.

Table 15: Estimated sales, median life and stock for generators, EU27, 2025

Subsector	Sales	Median life	Stock
Generators	85,360	16	1,365,765
Forklifts	221,907	16	3,550,512

The distribution to power classes for forklifts was taken from TREMOD-MM, as the PRODCOM database does not provide any information on this. The differentiation by power class for generators was partly possible with the PRODCOM data. Therefore, engine power output in kVA was converted to kW by multiplication with the factor 0.8. The translation to the power classes in the eNRMM study was estimated based on data for generators in TREMOD-MM. It is assumed, that most generators within the class <60 kW are below 19 kW.

Table 16: Share of power classes (rated power in kW) for generators and forklifts

Subsector	<19	<37	<56	<75	<130	<300	<560
Forklifts		82 %	3 %	3 %	12 %		
Generators	71 %	9 %	5 %	5 %	5 %	6 %	0.03 %

The share of fuel types for forklifts was estimated based on the PRODCOM data and TREMOD-MM. It is assumed that 90 % of new forklifts < 37 kW and 70 % of forklifts > 37 kW are already electric, whereas the remaining forklifts < 37 kW also use LPG and forklifts > 37 kW use diesel. Generator sets in NRMM applications are supposed to run entirely on diesel.

Table 17: Estimated share of fuel types in 2025 for new construction equipment

Subsector	Diesel	Electric	LPG
Forklifts 19-36 kW	0 %	90 %	10 %
Forklifts 37 -129 kW	30 %	70 %	
Generators	100 %		

3.2.2 Locomotives and Railcars (RLL, RLR)

The stock of locomotives and railcars in the EU 27member states is recorded by Eurostat. Eurostat also records the drive system and total engine power. In some cases, data for individual member states are only available for certain years. The year 2020 was used for the inventory. For member states for which no data was available for that year, data from the closest available year was used. This is to ensure that the inventory is as complete as possible.

Table 18: Estimated stock of locomotives and railcars in the EU27

Eurostat/eNRMM subsector	Stock
Locomotives	26,820
Railcars	32,441

The average engine size was estimated based on data on total engine power by (eurostat 2026). The average rated power of locomotives is ~1,500 kW, for railcars ~500 kW. The distribution by power classes is based on own estimations. Data by Eurostat suggested that the average power of electric locomotives is ~2,400 kW, of diesel locomotives ~860 kW. Therefore, for smaller locomotives a higher share of diesel is assumed (Table 20).

Table 19: Share of power classes (rated power in kW) for locomotives and railcars

Subsector	<300	<560	<1,000	≥1,000
Locomotives	20 %	20 %	40 %	20 %
Railcars		100 %		

Table 20: Estimated share of fuel types in 2025 for new rail equipment

Subsector	Diesel	Electric
Locomotives < 560 kW	80 %	20 %
Locomotives > 560 - 1,000 kW	50 %	50 %
Locomotives ≥ 1,000 kW	20 %	80 %
Railcars	26 %	74 %

3.2.3 Spark ignition engines (NRS, NRSh)

The average annual sales for NRS, NRSh were estimated from data on production, imports and exports in the EU in the PRODCOM database. Contrary to the term "spark ignition", electrical appliances in the respective subsectors were also taken into account, and the inventories were divided according to drive types (see the following sections). It is assumed that this equipment is used in the sectors forestry, households and gardening, and construction. When compared with other sources, the number could not be confirmed exactly, but at least the order of magnitude could be verified.

Comparison of sales sumbers of handheld/gardening equipment with other sources

For comparison purposes, data from an earlier EU study conducted by the JRC and the European Garden Machinery Industry Federation (EGMF) was available. The data is not directly comparable due to geographical differences and the inclusion of imports and exports. Nevertheless, the order of magnitude is roughly comparable.

- JRC study ((Krasenbrinck, Dobranskyte-Niskota 2008), approx. 5 million petrol-powered devices in the EU15
- EGMF: approx. 7 million petrol-powered devices produced in the EU (excluding imports)
- PRODCOM: approx. 7 million petrol-powered devices sold in the EU27 + approx. 11 million additional devices with electric motor (in total 18.5 million)

For lawn mowers and chainsaws, the PRODCOM categories do not correspond exactly to the categories in TREMOD-MM. For example, TREMOD-MM distinguishes between lawn mowers and ride-on mowers and between private and professional use. The shares of these categories, e.g., private/professional lawn mowers for the eNRMM study, were taken from TREMOD-MM. It must be emphasised that these assumptions may not be transferable to the EU and are only a rough approximation. However, since this distinction is highly relevant due to large differences in performance, annual operating hours and lifetime, the available assumptions have been used despite the uncertainties.

Table 21: Estimated sales, median life and stock for NRS, NRSh equipment, EU27, 2025

Subsector	Sales	Median life	Stock
Compaction equipment	118,400	10	1,184,000
Chainsaws professional	88,900	12	178,000

Subsector	Sales	Median life	Stock
Lawn Mower private	6,449,700	10	64,497,000
Lawn Mower professional	14,100	10	113,000
Ride-on Mower / Lawn Tractor private	398,900	10	3,989,000
Ride-on Mower / Lawn Tractor (Sport and Hobby)	92,600	9	741,000
Ride-on Mower / Lawn Tractor (public lawns)	3,000	11	24,000
Ride-on Mower / Lawn Tractor (company)	4,200	12	33,000
Chainsaws private	5,119,300	12	40,954,000
Chainsaws professional	206,200	10	412,000
Trimmer private	5,783,900	9	46,271,000
Trimmer professional	275,400	10	551,000
Total	**18,554,600**		**158,947,000**

All devices have generally lower power outputs than 19 kW. They are classified according to Stage V engine classes. The following table assigns the machines to the assumed size classes/segments of the NRS and NRSh according to TREMOD-MM.

Table 22: Share of segments for equipment in NRS, NRSh

Subsector	Stage V subcategory
Compaction equipment	NRS-vr/vi-1b
Chainsaws	NRSh-v-1a
Trimmer	NRSh-v-1b
Lawn Mower	NRS-vr/vi-1a
Ride-on Mower	NRS-vr/vi-1b

The share of fuel types was taken from the current information in the PRODCOM database as far as possible and, if not available, supplemented using assumptions from TREMOD-MM.

Table 23: Estimated share of fuel types in 2025 for new NRS, NRSh

Subsector	Petrol 2-Stroke	Petrol 4-Stroke	Electric
Compaction equipment		99 %	1 %
Chainsaws	85 %		15 %
Trimmers	5 %	11 %	85 %
Lawn Mower private		40 %	60 %
Lawn Mower professional		71 %	29 %

Subsector	Petrol 2-Stroke	Petrol 4-Stroke	Electric
Ride-on Mower		100 %	0 %

3.2.4 IWP, IWA

The stock of inland waterway vessels ("self-propelled barges" and "tug and pushers") in the EU 27 member states is recorded by Eurostat. The data for the year 2021 was used. The number of day trip and river cruise vessels is reported by the CCNR.

Table 24: Estimated stock of motorized inland waterway vessels in the EU27

Eurostat/eNRMM subsector	Stock
Freight ship	8,055
Push boat	2,653
Day trip ship	2,395
River cruise ship*	410

Note: Based on data for river cruise ships in Germany, it is assumed that one vessel has on average 6 engines. Hence, the total power of a vessel can be much higher than the power of one engine.

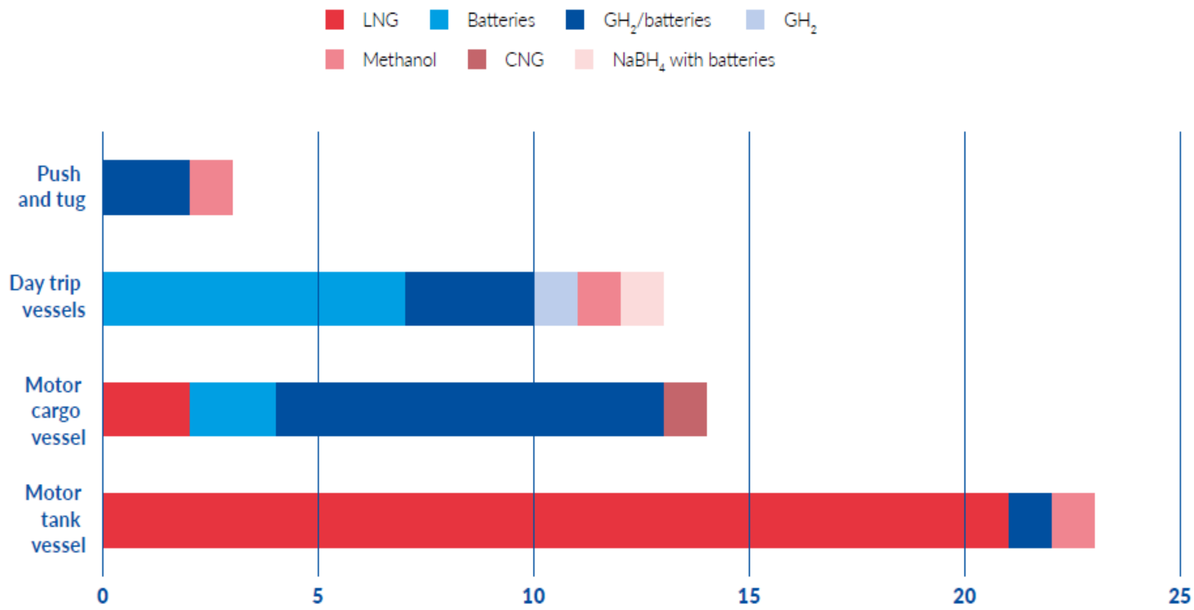
The distribution of power classes for freight ships was estimated based on the tonnage of the fleet given in the market observation report by the CCNR. The average tonnage in the year 2022 is ~1,400 tonnes. Based on data of the TREMOD model, an average engine power of 0.35 kW/ton results in an average engine power of ~500 kW. The distribution across power classes was estimated using data from the German fleet (TREMOD-MM) and weighted to match the average engine power across the entire fleet. For push boats, it is assumed that the power is always above 1,000 kW (averaging 5000 kW). The size distribution for day trip and river cruise ships is also taken from TREMOD-MM, based on data from the German Ship Register by the WSV (Wasser- und Schifffahrtsverwaltung).

Table 25: Share of power classes (rated power in kW) for inland waterway vessels

Subsector	<37	<56	<75	<130	<300	<560	<1,000	≥1,000
Freight ship				10 %	30 %	40 %	18 %	2 %
Push boat								100 %
Day trip ship	10 %	5 %	5 %	15 %	50 %			
River cruise ship				20 %	26 %	35 %	19 %	0 %

Most inland waterway vessels in Europa still have diesel engines. According to the CCNR, inland waterway vessels with alternative propulsion systems already exist, particularly LNG but also battery-electric vessels (Figure 12).

Figure 12: Number of inland waterway vessels in the EU by primary energy carrier



Source: Illustration by (CCNR 2023)

Overall, the number is very small. It was assumed that these ships had come onto the market in the last five years and, based on the newbuilding rates, the following proportions of electric ships in new builds were estimated:

- Freight ship: 2.5 %
- Push boat: 1.25 %
- Day trip ship: 7 %
- River cruise ships: 0 %

For the rest of the fleet, it is assumed for simplicity's sake that these are diesel ships, as gas or methanol propulsion systems were not a focus of the project and cannot yet be represented in the model.

3.2.5 Recreational craft

The number of recreational craft was derived from the International Council of Marine Industry Associations (ICOMIA) Recreational Boating Industry Statistics, which includes reports from various countries, including the EU. Data for 2020–2023 was provided. The total number of recreational craft in Europe (EU27 plus UK and Norway) is estimated at more than 6 million, with approximately 80 % of the boats in EU27 member states registered in France, Finland, Sweden, Italy and Germany. Outboard motorboats account for more than 40 % of the boat fleet and are the largest category in terms of numbers, followed by “others” where the boat type is not known. Some countries also report only the total number of boats without any categorisation. Table 26 gives an overview of the boat fleet in the year 2023 as estimated by ICOMIA.

Table 26: Estimated stock of recreational craft in the Europe (EU27+ UK, NOR) 2023, ICOMIA

Category	Stock
Sailboats / Yachts	803,046
Inboard / Sterndrive Motorboats	799,296
Outboard motor boats	2,300,161
Inflatable boats 2.5kg+ and 20kg+	522,430
PWCs	173,116
Others	1,424,736
Total (categories)	**6,022,785**
Total (including countries without boat categories)	**6,703,414**

For the emission inventory, the categories and numbers have been summarised in four categories in order to simplify the calculation (see Table 27). According to ICOMIA, the Sailboats/Yachts category primarily includes boats in which the engine is only a secondary means of propulsion, i.e., not motor yachts or similar vessels. However, since not all boats have to be registered, some of these figures are estimates, e.g., based on insurance data. According to internal information provided by the European Boating Industry (EBI), it can be assumed that a significant share of these unregistered boats has no propulsion. We assume that 50 % of the "Other" category is operated without a motor, as it may also include canoes, kayaks, etc. Inflatable boats approved for less than 100 kg also do not usually have a motor. For this reason, these categories or shares are not included in the inventory.

Table 27: Stock of motorized recreational craft in the EU27, own estimation

Category eNRMM	Category ICOMIA	Stock
Motorboat outboard engine	Outboard motor boats, Inflatable boats >100kg	2,857,406
Motorboat inboard engine	Inboard / Sterndrive Motorboats	889,624
PWCs	PWCs	192,680
Other boats (incl. sailers)	Sailboats / Yachts, Others*	1,686,669
Total		**5,626,379**

Note: * Only 50 % of other boats are assumed to have engines and are included in the data.

The performance of outboard boats was estimated based on ICOMIA data. Sales figures for outboard motors in the EU by power class were available for this purpose. It is assumed that several motors could be installed per boat. Therefore, the share of larger power classes is higher for boats than for motors. However, these are own assumptions, as no data was available.

The power class shares of inboard boats were taken from TREMOD-MM. During consultation with ICOMIA and other experts, it was noted that recreational boats or motor yachts, for example, which can be either outboard or inboard, can have a very high power demand. This may not be reflected in the 130 kW limit. However, no data was available to derive a reliable breakdown for the total boat fleet.

The power of PWCs and other boats was estimated based on the study by (emisia et al. 2021). The power class shares of the inboard boats were taken from TREMOD-MM.

Table 28: Share of power classes (rated power in kW) for recreational craft

Subsector	OB <3	OB 3-13	OB 12-50	OB >50	IB <15	IB 15-50	IB >50
Motorboat outboard engine	10 %	20 %	30 %	40 %			
Motorboat inboard engine					21 %	58 %	22 %
PWCs				100 %			
Other boats (incl. sailers)		60 %	20 %				

Note: OB: outboard, IB: inboard

According to the Allgemeiner Deutscher Automobil-Club (ADAC), which keeps a register of over 100,000 active boats in Germany, approximately 4 % of boats in the fleet and 6 % of newly registered boats had an electric motor in 2025. Even though this is only a sample of the estimated boat population in the EU27, it can be assumed that similarly small numbers of electric drives are already in use in other EU countries as well. Due to a lack of data and probably only small shares of electrified boats it is nevertheless assumed for the inventory that all boats are powered solely by combustion engines, mainly petrol and some diesel engines. However, this is likely to be a rather conservative assumption.

3.2.6 Powered two-wheelers

The number of powered two-wheelers in the EU27 is recorded by Eurostat. These data were also used as a basis for the emissions inventory. In total, there are almost 40 million motorised two-wheelers in the EU27.

Table 29: Stock of powered two-wheelers in the EU27 according to Eurostat, 2023 (1,000 vehicles)

Category	EU-Class	New registrations	Total stock
Mopeds	L1e B	326	12,544
Motorcycles	L3eA1-3	1,115	26,887
Total		1,440	39,431

Sources: New registrations: (eurostat 2022), Stock: (eurostat 2023)

However, Eurostat does not distinguish between A2 and A3 motorcycles and does not specify the number of electric vehicles. Therefore, the breakdown into categories A2 and A3, as well as gasoline and electric, was carried out using registration data from ACEM. While ACEM statistics do not cover all EU member states, they do cover the most important markets in the EU27.

The inventory data for 2025 and subsequent years were projected using a fleet model based on new registrations and survival curves from the TREMOD model. The following table shows the resulting number of motorised two-wheelers in 2025 by category and drive type. The share of electric vehicles was approximately 3 % on average, but higher among mopeds at almost 7 % and lower among motorcycles.

Table 30: Estimated stock of powered two-wheelers by EU-category and fuel type in the EU27, 2025 (1,000 vehicles)

Category	EU-cat.	Engine capacity	Petrol (1,000 veh.)	BEV (1,000 veh.)	Total (1,000 veh.)	Share EU-category
Moped	L1e B	≤ 50 cm^3	11,473	834	12,308	32 %
Motorcycle	L3e A1	≤ 125 cm^3 ≤ 11 kW	8,903	166	9,068	23 %
Motorcycle	L3e A2	> 125 cm^3 ≤ 35 kW	8,011	14	8,025	21 %
Motorcycle	L3e A3	> 125 cm^3 > 35 kW	9,191	4	9,195	24 %
Total			37,579	1,017	38,596	100 %
Share Fuel			97 %	3 %	100 %	

Table 31 shows the assumptions used to calculate the mileage and energy consumption of powered two-wheelers. These factors were derived using the TREMOD model. For the sake of simplicity, no distinction was made between different power classes of motorcycles.

Table 31: Assumed average mileage and energy consumption of powered two-wheelers, 2025

Parameter	Category	Petrol	BEV
Av. mileage (km/a)	Moped	3,125	3,125
	Motorcycle	2,605	1,520
Av. energy consumption (MJ/km)	Moped	0.80	0.09
	Motorcycle	1.74	0.30

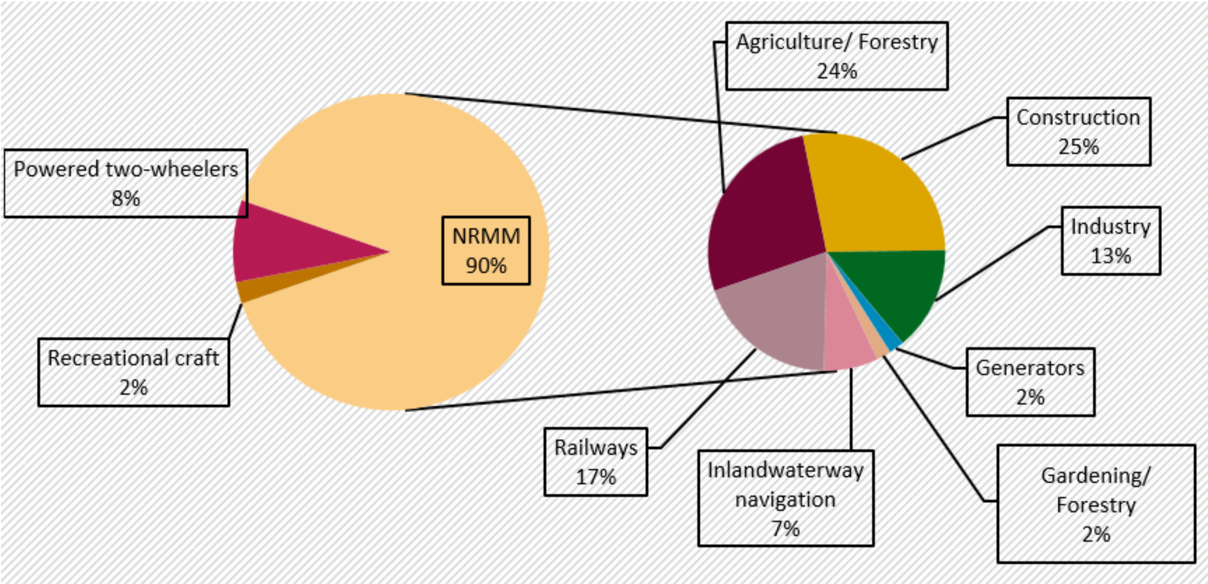
3.3 Results for all categories and sectors, EU27, 2025

The energy requirements and GHG emissions calculated bottom-up using inventory and usage data are described in the following chapters.

3.3.1 Final energy consumption

NRMM account for 90 % in final energy consumption of the three sectors analysed in this study, while powered two-wheelers account for 8 % and recreational craft for 2 %. Within NRMM, machines used in agriculture and construction have the largest share in energy consumption, representing approximately 50 % of the sources examined here. Rail, inland waterway transport, and industrial equipment (forklift trucks) also account for a high proportion of energy consumption (Figure 13).

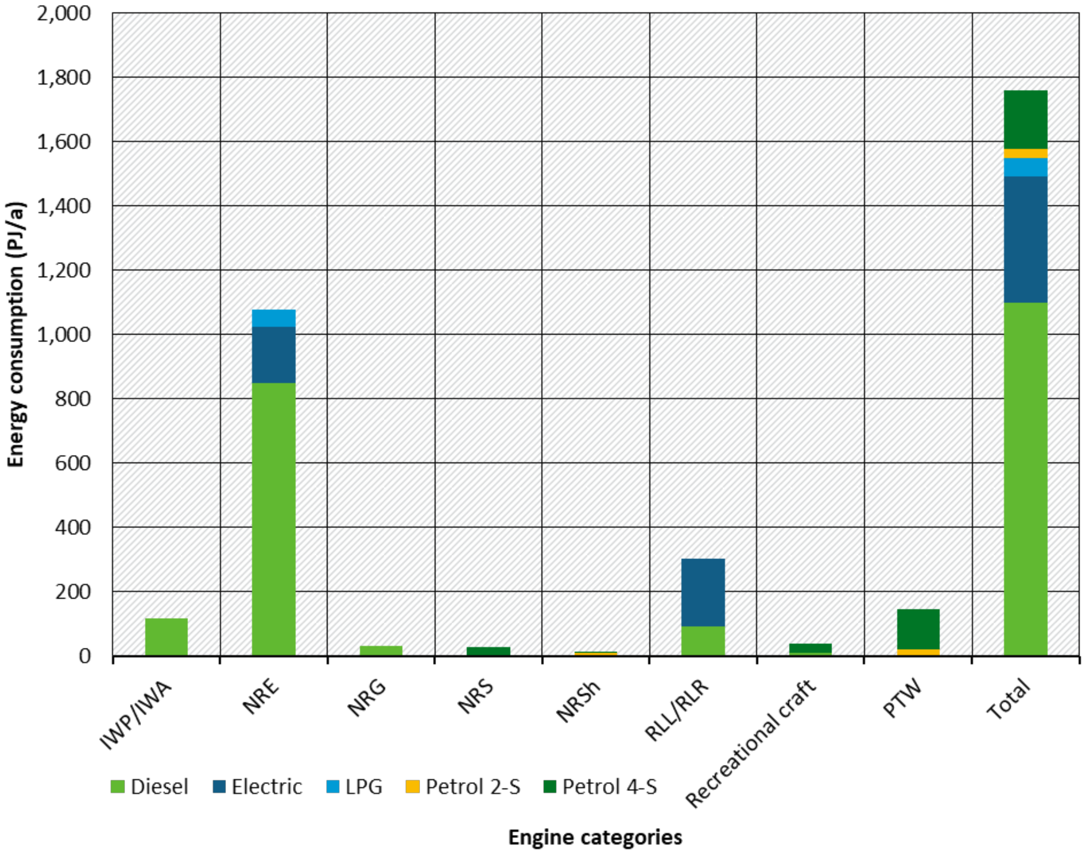
Figure 13: Share in final energy consumption per sector/category, EU27, 2025



Source: Own illustration by ifeu. Note: Energy consumption of fuels, e.g. diesel, petrol can include biofuel shares.

The final energy consumption of all the sectors in the year 2025 in the EU 27 is in total approximately 1,800 PJ (Figure 14). From the engine categories classified under Stage V, NRE account for the largest share. Among the fuel types, diesel causes the highest final energy consumption with approximately 1,100 PJ, followed by gasoline and LPG. It should be noted that the fuel demand can also contain biofuels (pure or as blends), which were not reported due to a lack of available data. A relevant consumption of electricity results primarily from rail transport, but also from some NRE applications like forklifts and certain construction machinery such as cranes.

Figure 14: Final energy consumption per engine category by fuel type, EU27, 2025



Source: Own illustration by ifeu. Note: Energy consumption of fuels, e.g. diesel, petrol can include biofuel shares.

3.3.2 CO_2 emissions

Direct CO_2 emissions (tank-to-wheel) across all examined sectors are estimated at approximately 100 Mt CO_2 in 2025, based on calculated energy consumption, whereat NRMM and recreational craft account for ~ 90 Mt CO_2/a and powered two-wheelers for 11 Mt CO_2/a. There is relatively good agreement with the data reported by the UNFCCC. According to this, NRMM account for approximately 3 % of total emissions from all sectors in the EU27, which is about half of heavy-duty vehicles and a quarter of passenger cars. Powered two-wheelers account for less than 1 % of total emissions (Table 32). Since biofuels were not taken into account in this study, direct emissions are likely to be slightly lower according to the UNFCCC reporting guidelines, considering that in 2023, approximately 6–7 % biodiesel was used in diesel vehicles in the EU transport sector. This share is also likely to be realistic for NRMM as a first approximation. This means that the results of the bottom-up emission inventory are very close to the emission quantities reported by EU member states in the context of UNFCCC reporting (see introduction).

Table 32: Total GHG emissions for NRMM, recreational craft and powered two-wheelers in the EU27 compared to road vehicles and total emissions

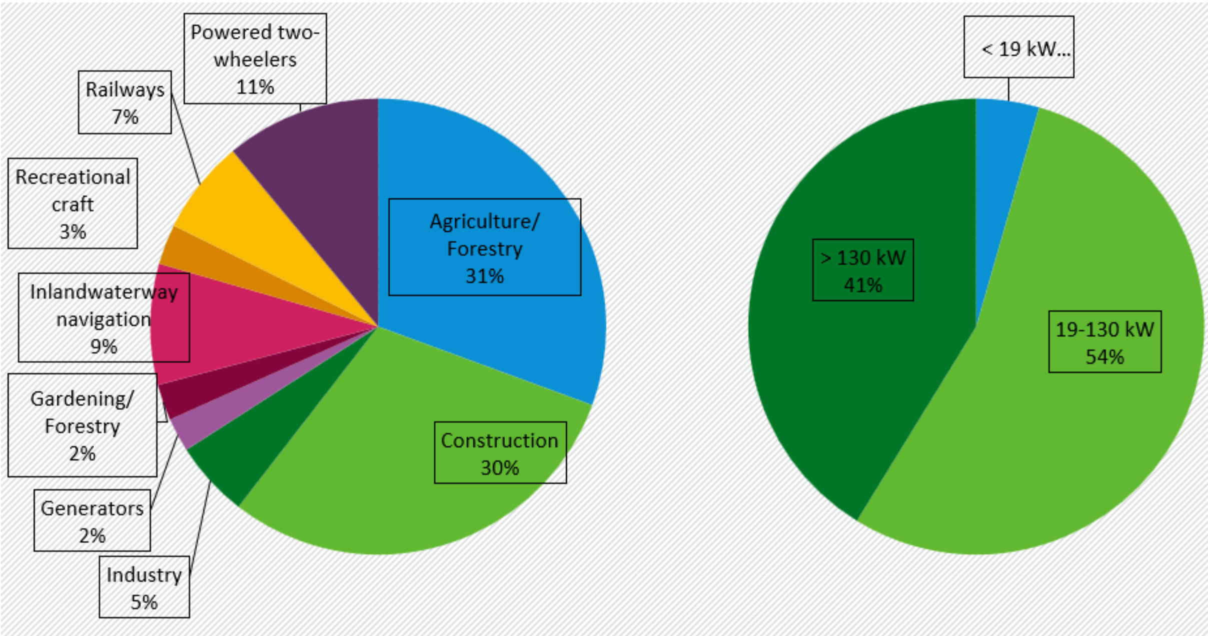
Category	eNRMM, 2025*	UNFCCC, 2023**
Cars		454 (16 %)
Heavy duty trucks and busses		203 (7 %)

Category	eNRMM, 2025*	UNFCCC, 2023**
Powered two-wheelers	11.1	9.3 (0.3 %)
NRMM and recreational craft	89	90 (3 %)
Total net emissions (UNFCCC)		2,907 (100 %)

Note: *eNRMM data based on own calculations, only CO_2, biofuels having similar emissions as fossil fuels. **UNFCCC data: Based on reported data of all member states. CO_2-equivalents. Emissions of biofuels are not fully included.

Within the sectors examined in the eNRMM study, agriculture and construction account for the highest share of CO_2 emissions, representing almost two-thirds of the total (left part of Figure 15). Although their share is significantly lower than that of cars and trucks, it is considerably higher than that of powered two-wheelers, inland waterway transport, and rail transport. The power classes in the graph on the right part of Figure 15 show that small appliances (<19 kW) account for only 5 % of emissions and that it is mainly medium-sized and large appliances that contribute to total emissions.

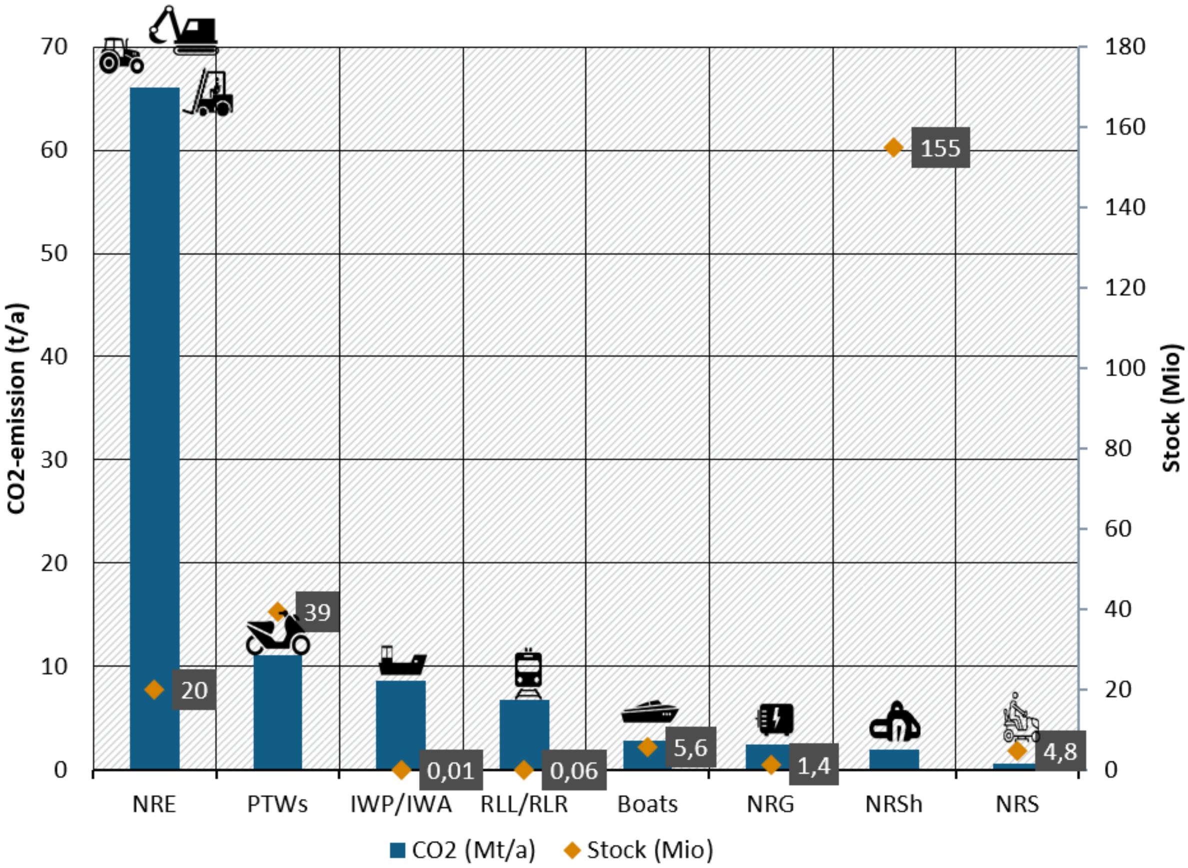
Figure 15: Share in CO_2 emissions per sector (left) and power class (right), EU27, 2025



Source: Own illustration by ifeu

Figure 10 summarises the inventory data and emissions according to the categories of emissions legislation in 2025. Equipment of the NRE category e.g. agricultural machinery such as tractors and combine harvesters, but also larger construction machinery has the highest total CO_2 emissions. Inland ships vessels (IWP/IWA) and trains (RLL/RLR) have very high emissions despite relatively low population due to their high power and/or annual operating hours. Less powerful and intensively used equipment, such as lawn mowers or other garden tools (NRE and NRSh), has correspondingly low overall emissions despite high numbers.

Figure 16: Estimated population and CO_2 emissions per engine/vehicle category in the emission inventory, EU27, 2025



Source: Own illustration by ifeu. Note: The pictograms shown represent examples of applications in the various categories, but do not claim to be exhaustive.

4 Technical potential for electrification

4.1 Methodology

4.1.1 Electrification potential

The Electrification potential (EP) describes the possibility to electrify a machine considering the usage in its standard operating conditions. In this study, the Electrification potential is only based on the technical feasibility. Other factors like production capacity, switch of product portfolio or economic reasons are not considered. Thus, these numbers do not reflect sales numbers.

Battery electric machinery and battery electric vehicles (BEM & BEV) are the focus of this study for general applications, but other options such as cable operation, swappable battery systems, catenary operation etc. are considered.

Looking at technical limitations when it comes to the electrification of non-road mobile machinery and the operation of such, three guiding questions summarize the main challenges of electrification:

- Can a suitable battery be installed in BEM & BEV?
- Can the battery be recharged in the non-working periods?
- Is infrastructure available at the standard operating spot of a machine to build up systems for recharging and operation of BEM & BEV?

To quantify these questions and obstacles individual and independent factors have been created:

- Factor Battery
- Factor Charging
- Factor Infrastructure

Beyond these three main guiding factors, additional aspects may influence the electrification potential. To list a few examples these aspects are temperature influences, requirements for power density, catenary operation etc.

This leads to the demand for two additional factors, that can be used optionally. The factors are:

- Factor Specific
- Factor Special solution

The general approach focuses on the operation of BEM & BEV for one "typical" workday with working conditions reaching from standard to high volume working hours and medium to high power demand during operation. The methodology can be seen in Equation 5.

Equation 5: Electrification potential (EP)

$$EP = fBattery * fCharging * fInfrastructure\ (\ * fSpecific\ ) + fSpecial\ solution$$

EP ... Electrification potential [-]

$f_{Battery}$ ... Factor Battery [-]

$f_{Charging}$ ... Factor Charging [-]

$f_{Infrastructure}$ ... Factor Infrastructure [-]

$f_{Specific}$ ... Factors Specific [-]

$f_{Special\ solution}$ ... Factor Special solution [-]

The values for the individual factors all range from zero to one. However, the overall electrification potential is limited to a maximum of one including the Factor Special Solution. They are described in detail in Chapters 4.1.1.4 to 4.1.1.8. The values used to determine the respective factors can be found in the chapter 4.1.1.10 and 4.2.

4.1.1.1 Boundary conditions

When determining the EP, it is necessary to set clear boundary conditions to contextualize all results produced by the methodology. Following considerations are to be taken in for interpretation of the results in the correct way:

- The EP is only a technical potential, not sales numbers, market shares or any parameter of this kind. It reflects only what is technically achievable.
- The use cases are assumed to stay the same. This means there is no change in behaviour of the user when utilizing electric machinery to fulfil a task, instead of conventional machinery. In other words, operating hours, load factors etc. stay unchanged.
- There are no considerations for price or any other economic aspects when determining the EP or H_2 potential.

4.1.1.2 Considerations for variability in operation

To ensure unhindered operation of BEM & BEV for a wide variety of use cases, it is necessary to consider a standard working day and factor in edge cases with working days that show a very high utilization of the machinery. This ensures coverage of the variability found in the operation of NRMM.

The model proposed tackles this issue by calculating the daily energy demand based on data for standard working hours per day (50^{th} percentile) and working hours for high-volume working days (90^{th} percentile). The calculation can be seen in detail in Chapter 4.1.1.3.

For small powered equipment NRS and NRSh the single factors are calculated for maximum and minimum power and consequently mass and other key figures; the electrification potential is then calculated as average of minimum and maximum.

Powered two-wheelers are segmented in interrupted and continuous operation additionally, defined by the maximum trip distance and the average trip distance. In interrupted operation like daily travel with short distances the maximum trip distance is typically lower and the average trip distance is a small share of the maximum trip distance. In continuous operation like delivery service or recreational long trip operation the maximum trip distance is large and the average trip distance is a high share in the maximum trip distance.

4.1.1.3 Work demand

The daily work demand for the operation of the machinery, tool, vehicle or craft is decisive for the calculation of the electrification potential. In the following, the calculation of this work is described for the different types of machinery.

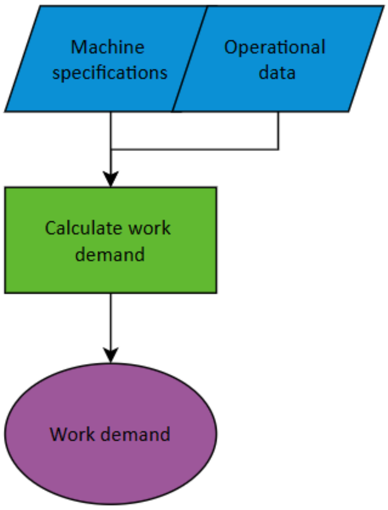
Daily work demand for BEM & BEV in Engine categories NRE, NRG, IWA and IWP

As a basis for further considerations in this Chapter, the daily work demand is calculated. It is calculated by taking the product of rated engine power, the load factor and the daily operating hours.

The work demand for a high-volume working day is calculated with the same approach used for a standard working day but using different daily operating hours. This can be seen in Equation 6 and Equation7.

In principle the work demand is calculated as seen in Figure 17 by taking machine specifications and operational data.

Figure 17: Schematic calculation of energy demand



Source: Own illustration by TU Graz

Equation 6: Daily work demand for a standard working day

Equation7: Daily work demand for high-volume working day

$$W_{D\ hv} = Pe_{rated} * Load * t_{Hv}$$

$W_{D\ avg}$ ... Energy demand for standard working day [kWh]

$W_{D\ hv}$ ... Energy demand for high-volume working day [kWh]

Pe_{rated} ... Rated engine Power [kW]

Load ... Average engine load relative to engine rated power [Pe/Pe_{rated}]

t_{Avg} ... Working hours for standard working day [h]

t_{Hv} ... Working hours for high-volume working day [h]

Work demand for NRS and Recreational Craft

The decisive work demand for small equipment and Recreational Craft is derived from the fuel tank energy content of typical applications. Considering an average fuel tank volume, the specific energy content of the fuel and the average efficiency of the ICE an application based average work demand can be calculated.

Equation 8: Work demand NRS and Recreational Craft

$$W_{D\ avg} = V_{fueltank} * E_{fuel} * \eta_{ICE}$$

$W_{D\ avg}$ ... Average work demand [kWh]

$V_{fueltank}$ ... Volume of the fuel tank [l]

E_{fuel} ... Volumetric energy content of the fuel [kWh/l]

η_{ICE} ...Efficiency ICE [%]

Equation 9: Work demand for duty cycle operation

$$W_{D\ DC} = \frac{P_{rated}}{\eta_{ICE}} * DC * t_{dc}$$

$W_{D\ DC}$ ... Work demand for duty cycle time [kWh]

P_{rated} ... Rated engine power [kW]

DC ... Duty cycle ratio [-]

η_{ICE} .... Efficiency ICE Powertrain [%]

t_{DC} ... Duty cycle time in average operation [h]

Work demand for powered two-wheeler

For powered two-wheelers the maximum trip distances for each vehicle sub-category are assessed and based on these and with fuel consumption data of the sub-categories a trip-based work demand is calculated.

Equation 10: Trip based work demand for powered two-wheeler

$$W_{D\ 100km} = FC * E_{fuel} * \eta_{ICE}$$

$W_{D\ 100km}$ ... Average work demand per 100 km trip [kWh]

FC ... Fuel consumption for 100km [l/100km]

E_{fuel} ... Volumetric energy content of the fuel [kWh/l]

η_{ICE} ...Efficiency ICE [%]

Equation 11: Work demand for maximum trip distance powered two-wheelers

$$W_{D\ trip\ max} = \frac{W_{D\ 100km}}{100} * d_{trip\ max}$$

$W_{D\ trip\ max}$ = WD 100km /100 * trip distance max

$W_{trip\ max}$ ... Work demand for maximum trip distance [kWh]

$d_{trip\ max}$ ... distance of maximum trip [km]

4.1.1.4 Factor Battery

Using the daily work demand as defined in 4.1.1.3, battery mass and volume are calculated using the specifications found in chapter 4.1.1.10.

By analysing the machinery mass, battery mass and volume and the amount of additional battery packs (for swappable battery systems), the factor battery is determined. The Factor Battery hereby represents a composition of restraints and considerations taking in mass and volume of the battery. There are further details and slight adaptions depending on which type of machinery is being analysed.

Determining Factor Battery for BEM & BEV in Engine categories NRE, NRG, IWA and IWP

As outlined in the Chapter 4.1.1.3 the work demand for operation units is calculated by multiplying the installed engine power with the load and the daily operating hours, resulting in a total work demand for one day of operation. Going from there, the necessary battery size is calculated by dividing the work demand by the product of motor efficiency (see Chapter 4.1.1.4) and the net to gross energy content ratio of the battery (Equation 12)

The battery mass and volume are calculated as defined in Equation 13 and Equation 14, technical specifications for the battery are defined in Chapter 4.1.1.10.

The assessment of mass and volume constraints regarding the possible installation of a battery in an existing machine is executed through a qualitative analysis based on battery mass, volume and vehicle/machine mass.

In the model used, there were six options to specify the suitability of battery installation, as seen in Table 33.

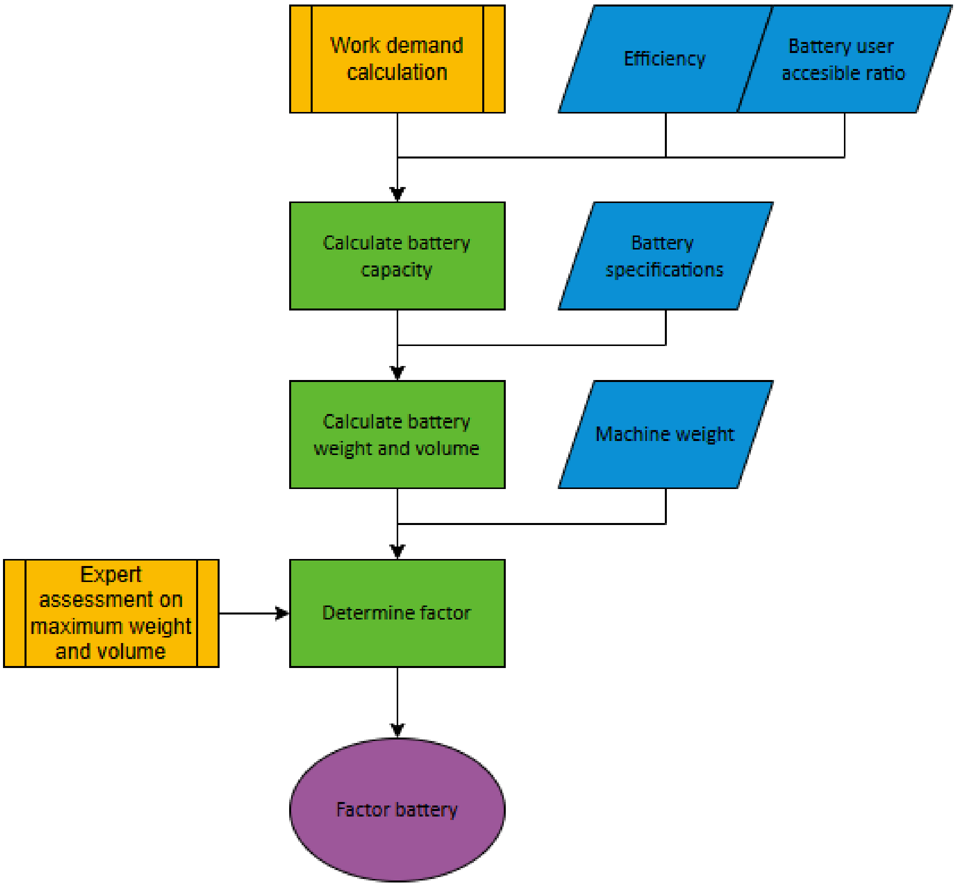
Table 33: Factor Battery for BEM & BEV in Engine categories NRE, NRG, IWA and IWP

Classification of suitability for battery instalment	Factor battery [-]
Yes	1.00
Suitable	0.75
Possible	0.50
Low	0.25
No	0.00

*Used for machinery where no battery is installed, e.g. fully cable operated.

The methodology for determining the Factor Battery can be seen in principle Figure 18.

Figure 18: Schematic calculation of Factor Battery



Source: Own illustration by TU Graz

Equation 12: Battery capacity for standard working day

$$C_{\text{Bat avg}} = \frac{W_{D\,avg}}{\eta M * AR_{User}}$$

Equation 13: Battery mass for standard working day

$$m_{\text{Bat avg}} = C_{\text{Bat avg}} * \frac{specific\ energy}{1{,}000}$$

Equation 14: Battery volume for standard working day

$$V_{\text{Bat avg}} = C_{\text{Bat avg}} * \frac{energy\ densitiy}{1{,}000}$$

Equation 15: Mass of the BEM & BEV

$$m_{\text{BEM \& BEV}} = m_{\text{Machinery}} + m_{\text{Diff}} + m_{\text{Bat hv}}$$

$C_{\text{Bat avg}}$ ... Battery capacity for standard working day [kWh]

$W_{\text{D avg}}$ ... Energy demand for standard working day [kW]

η_M ... Efficiency of the electric motor [-]

AR_{User} … Battery accessible ratio of the battery by the user (net to gross energy content) [-]

$m_{Bat\ avg}$ … Battery mass for standard working day [kW]

$m_{Bat\ hv}$ … Battery mass for high-volume working day [kg]

$m_{BEM\ \&\ BEV}$ … Mass of the BEM & BEV [kg]

m_{Diff} … Mass difference between fuel tank and ICE compared to electric motor [kg]

$m_{Machinery}$ … Mass of the machinery including fuel tank and ICE [kg]

specific energy … energy stored in the battery per unit of mass [Wh/kg]

$V_{Bat\ avg}$ … Battery volume for standard working day [L]

energy density … energy stored in the battery per unit of volume [Wh/L]

Determining factor battery for BEM Engine categories NRS

Based on the work demand for a duty cycle and considering the battery packs gravimetric energy density, the mass of a battery pack necessary to run the duty cycle is calculated. As it turned out that the battery pack mass for the full duty cycle duration is far away from any feasibility, The following approach was taken: Based on a 2025 available battery mass, which is assumed to be feasible, an acceptable percentage of mass increase is defined. And, a feasible reduction of duty cycle duration was introduced taking more frequently battery changes into consideration. These factors were assessed from stakeholder discussions; as they are market and consumer / operator driven, the used values are careful assumptions.

The battery factor then is the relation between the calculated battery pack mass and the typical available battery pack mass derived from market studies of electric power equipment. The battery factor is top limited with 1.

Equation 16: Battery capacity for duty cycle operation

$$\mathrm{C_{Bat\ DC}} = \frac{W_{D\ DC}}{\eta_e}$$

$C_{BAT\ DC}$ … Energy capacity of battery for duty cycle [kWh]

η_e … Efficiency electric powertrain [%]

Equation 17: Battery mass for duty cycle operation NRS

$$\mathrm{m_{bat\ DC}} = \mathrm{C_{Bat\ DC}} * \text{ specifiy energy}$$

Specific energy mass ... energy stored in battery per unit mass [kWh/kg]

$m_{bat\ DC}$ ... Battery mass for duty cycle operation [kg]

Equation 18: Maximum feasible battery mass NRS

$$\mathrm{m_{bat\ max}} = \mathrm{m_{bat\ 2025}} * \mathrm{f_{m\ add}}$$

$m_{bat\ 2025}$ ... Mass of 2025 available battery [kg]

$f_{m\ add}$ .... Acceptable mass increase battery [%]

$m_{bat\ max}$ ... Maximum battery mass which is feasible to be installed [kg]

Equation 19: Battery factor NRS

$$\frac{m_{bat\ max}}{m_{bat\ DC}} \geq 100\% \rightarrow f_{battery} = 1$$

$$\frac{m_{bat\ max}}{m_{bat\ DC}} < 100\% \rightarrow f_{battery} = \frac{m_{bat\ max}}{m_{bat\ DC}}$$

$f_{battery}$ ... Factor battery [-]

Determining factor battery for powered two-wheelers

Based on the work demand for a maximum trip distance and considering the battery volumetric and gravimetric energy densities the mass and volume of an equivalent battery for same trip distance can be calculated. Similar to the mass assessment of the NRS additional factors for feasible increased mass and volume are introduced. These additional multiplicative factors were assessed from stakeholder discussions; as they are market and consumer / operator driven the used values are careful assumptions.

The battery factor is the inverse of the higher value of battery mass and battery volume factor, limited to 1 if higher as 1 and 0.05 as lowest value.

Equation 20: Energy demand for maximum trip distance powered two-wheelers

$$W_{D\ trip\ max} = \frac{W_{D\ 100km}}{100} * d_{trip\ max}$$

$W_{D\ trip\ max}$ = WD 100km /100 * trip distance max

$W_{trip\ max}$ ... Work demand for maximum trip distance [kWh]

$d_{trip\ max}$ ... distance of maximum trip [km]

Equation 21: Battery capacity for maximum trip distance powered two-wheelers

$$C_{Batt\ trip\ max} = \frac{W_{D\ trip\ max}}{\eta_e}$$

$C_{Batt\ trip\ max}$ ... Battery capacity for maximum trip distance [kWh]

η_e ... Efficiency electric powertrain [%]

Equation 22: Battery mass for maximum trip distance powered two-wheelers

$$m_{batt\ max\ trip} = \frac{C_{Batt\ trip\ max}}{e_{mass}}$$

e_{mass} ... energy stored in battery per unit of mass [kWh/kg]

$m_{batt\ max\ trip}$ .... Mass of battery for maximum trip length [kg]

Equation 23: Battery mass factor for maximum trip distance powered two-wheelers

$$f_{\text{batt mass 2W}} = \frac{m_{\text{batt}}}{(m_{\text{tank}} + f_{\text{m add veh}} * m_{\text{veh}})}$$

$f_{\text{m add veh}}$ ... Acceptable mass increase of battery as percentage of vehicle gross mass [%]

m_{veh} ... Vehicle gross mass [kg]

$f_{\text{batt mass 2W}}$ ... Battery mass factor [%]

Equation 24: Battery volume for maximum trip distance powered two-wheelers

$$V_{\text{batt}} = \frac{C_{\text{batt trip max}}}{e_{\text{vol}}}$$

V_{batt} ... Battery volume [l]

e_{vol} ... Energy stored in the battery per unit volume [kWh/l]

Equation 25: Battery volume factor for maximum trip distance powered two-wheelers

$$f_{\text{batt vol 2W}} = \frac{V_{\text{batt}}}{V_{\text{tank}} * (1 + f_{\text{V add tank}})}$$

V_{tank} ... Tank volume [l]

$F_{\text{V add tank}}$ ... Additional volume factor [%]

$F_{\text{batt vol 2W}}$ ... Battery volume factor [%]

Equation 26: Battery factor powered two-wheelers

$$\left[\frac{1}{\text{MAX}\ (f_{\text{batt mass 2W}}\ \text{or}\ f_{\text{batt vol 2W}})}\right] > 1\ \rightarrow f_{\text{battery}} = 1$$

$$\left[\frac{1}{\text{MAX}\ (f_{\text{batt mass 2W}}\ \text{or}\ f_{\text{batt vol 2W}})}\right] < 1 > 0.05\ \rightarrow f_{\text{battery}} = \left[\frac{1}{\text{MAX}\ (f_{\text{batt mass 2W}}\ \text{or}\ f_{\text{batt vol 2W}})}\right]$$

$$\left[\frac{1}{\text{MAX}\ (f_{\text{batt mass 2W}}\ \text{or}\ f_{\text{batt vol 2W}})}\right] \leq \text{limit}\ \rightarrow f_{\text{battery}} = 0.05$$

F_{battery} ... Battery factor [-]

Determining factor battery for Recreational Craft

The battery factors for Recreational Craft are based on battery capacities derived from exemplarily layout for different craft categories in (Zenié et al. 2023). With these battery capacities a battery mass is calculated and finally a ratio between the calculated battery mass and the actual mass of ICE fuel tank mass and fuel mass.

The battery factor is then the inverse of the higher value of battery mass and battery volume factor, limited to 1 if higher as 1 and 0.05 as lowest value.

Equation 27: Battery mass Recreational Craft

$$m_{\text{batt RC}} = \frac{C_{\text{batt}}}{e_{\text{mass}}}$$

C_{batt} ... Battery capacity for same trip distance as ICE powered craft [kWh]

$m_{\text{batt RC}}$ ... Mass of battery Recreational Craft [kg]
e_{mass} ... Energy stored in the battery per unit mass [kWh/kg]

Equation 28: Battery mass factor Recreational Craft

$$f_{\text{batt mass RC}} = \frac{m_{\text{batt RC}}}{(m_{\text{tank}} + m_{\text{tank}} * f_{\text{m add}})}$$

$f_{\text{batt mass RC}}$ ... Battery mass factor Recreational Craft [%]

$f_{\text{m add}}$ ... Acceptable mass increase factor Recreational Craft [%]

Equation 29: Battery volume Recreational Craft

$$V_{\text{batt RC}} = \frac{C_{\text{batt}}}{e_{\text{vol}}}$$

e_{vol} ... Energy stored in the battery per unit volume [kWh/l]

$V_{\text{batt RC}}$ ... Battery volume Recreational Craft [l]

C_{batt} ... Battery capacity for same trip distance as ICE powered craft [kWh] (Zenié et al. 2023)

Equation 30: Battery volume factor Recreational Craft

$$f_{\text{batt vol RC}} = \frac{V_{\text{batt RC}}}{(V_{\text{tank}} + V_{\text{tank}} * f_{\text{v add}})}$$

$f_{\text{batt vol RC}}$ ... Battery volume factor Recreational Craft [%]

$f_{\text{v add}}$ ... Acceptable volume increase of battery [%]

Equation 31: Battery factor Recreational Craft

$$\left[\frac{1}{\text{MAX}\ (f_{\text{batt mass RC}}\ \text{or}\ f_{\text{batt vol RC}})}\right] > 1\ \rightarrow f_{\text{battery}} = 1$$

$$\left[\frac{1}{\text{MAX}\ (f_{\text{batt mass RC}}\ \text{or}\ f_{\text{batt vol RC}})}\right] < 1 > 0.05\ \rightarrow f_{\text{battery}} = \left[\frac{1}{\text{MAX}\ (f_{\text{batt mass RC}}\ \text{or}\ f_{\text{batt vol RC}})}\right]$$

$$\left[\frac{1}{\text{MAX}\ (f_{\text{batt mass RC}}\ \text{or}\ f_{\text{batt vol RC}})}\right] \leq \text{limit}\ \rightarrow f_{\text{battery}} = 0.05$$

f_{battery} ... Battery factor

4.1.1.5 Factor Charging

As mentioned in Chapter 4.1.1, one of the main criteria for Electrification is the requirement to supply electric machinery with sufficient energy during non-working hours to recharge the battery for operating one workday.

Depending on machinery and battery size, a permanent or a swappable battery pack is installed. Permanently installed batteries have to be charged on-site, whereas swappable battery packs can be charged off-site (e.g., charging depot).

Distinguishing between regular (overnight) charging and opportunity charging, overnight charging utilizes the down time after working periods to recharge the battery and opportunity charging uses smaller windows of down time during working periods to recharge part of the battery, typically using a higher charging power than the overnight charger.

Summarizing the above, key points for charging are:

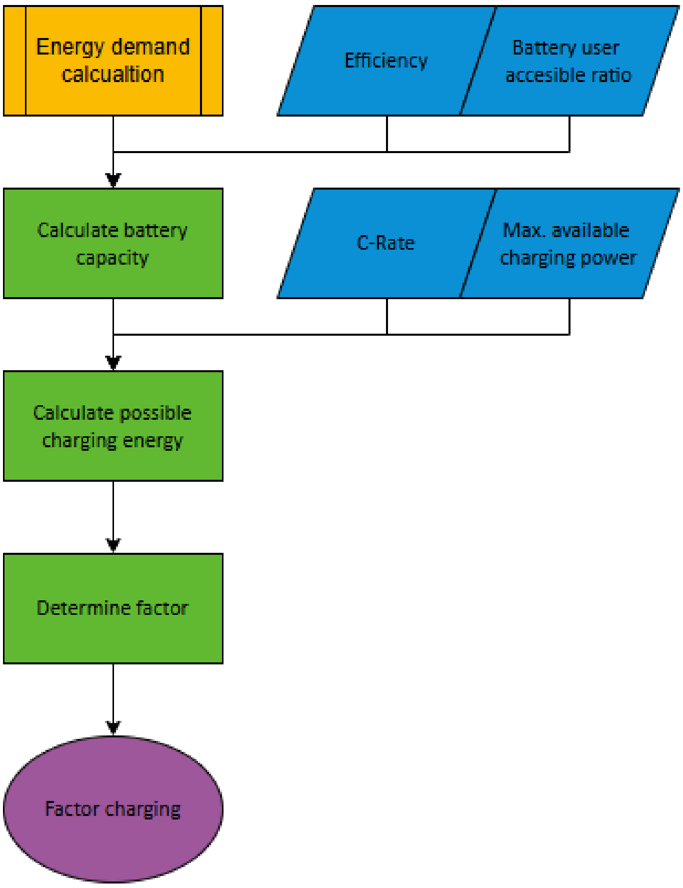
- The size respectively the energy capacity of the battery
- The C-rate of the battery, differentiated between charging and discharging
- The maximum available charging power
- The available time for charging the battery during one working day separated in overnight and opportunity charging.

Determining the Factor Charging in principle is done after the following methodology:

- Determine the necessary energy demand for operation using machine specifications and operational data as explained above
- Calculate the required battery capacity in kWh from the energy demand s explained above
- Calculate the possible charging energy using maximum available charging power from the grid and C-rate in combination with the battery capacity and the available time for charging
- Compare the energy demand and the amount of energy that can possibly be charged to determine the Factor Charging.

The methodology for calculating the Factor Charging is shown in Figure 19.

Figure 19: Schematic calculation of Factor Charging



Source: Own illustration by TU Graz

Determining Factor Charging for BEM & BEV in Engine categories NRE, NRG, IWA and IWP

Table 34 shows the logic used for determining the Factor Charging.

Table 34: Logic for determining Factor Charging

Factor Charging [-]	Possible energy charged ≥ battery capacity standard working day	Possible energy charged ≥ battery capacity high-volume working day
1.0	Yes	Yes
0.5	Yes	No
0.0	No	No

Calculating the energy demand is done by using the formula described in Equation 6. The amount of energy, which can possibly be charged, is calculated by using the formula in Equation 32. Again, the approach for high-volume working days only differs by using different operating hours.

Opportunity charging reduces the amount of energy, that has to be recharged in the overnight non-working periods. The amount of energy of opportunity charging is calculated based on the time available during a working day and the opportunity charging power (see Chapter 4.2.1.1).

To ensure sufficient operational capacity a maximum reduction of the battery size has been set.

- Reduction limit for Opportunity charging:

  To maintain reliable operation under uncertain opportunity-charging intervals, the installed battery capacity can be reduced to a minimum of 75 % of the originally required size.

- Reduction limit for cable operation:

  For machinery utilizing cable operation, the installed battery capacity can be reduced to 20 % of the original battery size. This ensures the machinery is still able to move without a cable connection.

The C-rate of the battery limits charging power. E.g., a battery sized at 50 kWh with a C-rate of 2 h^{-1} can only be charged at up to 100 kW, even if the charging station would be capable of supplying a higher power output.

Equation 32: Energy charged between working periods for standard working day

$$\mathrm{E_{C\ Avg}} = \mathrm{P_{Charger}} * (24\,h - t_{Avg} - t_{Opp}) + \mathrm{E_{Opp}}$$

Equation 33: Energy retrieved from opportunity charging

$$\mathrm{E_{Opp}} = \mathrm{P_{Opp}} * t_{\mathrm{Opp}}$$

$E_{C\ avg}$ ... Energy charged between working periods for standard working day [kW]

$P_{Charger}$ ... Charging power [kW]

t_{Avg} ... Operating hours for standard working day [h]

t_{Opp} ... Hours for opportunity charging [h]

E_{Opp} ... Energy retrieved from opportunity charging [kWh]

P_{Opp} ... Charging power opportunity charger [kW]

Determining factor charging for Engine categories NRS

As NRS are equipped with swappable battery packs, the factor charging is derived based on the number of battery packs needed for continuous operation. This number of necessary battery packs is calculated using charging and operation duration for one battery pack assuming a multi-charger with battery pack rotation and a battery change duration of 2min. The needed total number of battery packs is derived as the ratio between the calculated number of needed battery packs and the number of battery packs which are feasible to carry with the operator. This number was defined in discussions with OEM and operators to a value of 5 battery packs to carry with.

Equation 34: Electric power at battery NRS

$$\mathrm{P_{batt\ avg}} = \frac{\mathrm{P_{avg}}}{\eta_e}$$

P_{avg} ... Average Power [kW]

η_e ... Efficiency electric powertrain [%]

$P_{batt\ avg}$ ... Average electric power at battery [kW]

Equation 35: Operation time of battery pack NRS

$$t_{\text{op batt pack}} = \frac{C_{\text{Batt}}}{P_{\text{Batt avg}}} * 60$$

$t_{\text{op batt pack}}$ ... Operation time of battery pack [min]

$C_{\text{batt DC}}$ ... Battery capacity for duty cycle operation time [kWh]

Equation 36: Charging time of battery pack NRS

$$t_{\text{char batt pack}} = \frac{60}{C_{\text{charge}}}$$

$t_{\text{char batt pack}}$ ... Charging time for battery pack [min]

C_{charge} ... C-rate charging [h^-1]

Equation 37: Number of battery packs for continuous operation

$$\#_{\text{battpack}} = \frac{(t_{\text{char batt pack}} + t_{\text{batt change}})}{(t_{\text{operation batt pack}} + 1)}$$

$\#_{\text{batt pack}}$ ... Number of battery packs necessary for continuous operation [-]

$t_{\text{batt change}}$ ... Time for battery change [min]

Equation 38: Charging factor NRS

$$\left[\frac{\#_{\text{batt pack}}}{\#_{\text{feasible}}} > 1\right] f_{\text{charging}} = 1$$

$$\left[\frac{\#_{\text{batt pack}}}{\#_{\text{feasible}}} \leq 1\right] f_{\text{charging}} = \frac{\#_{\text{batt pack}}}{\#_{\text{feasible}}}$$

$\#_{\text{batt pack feasible}}$ ... Number of battery packs feasible to carry with [-]

f_{charging} ... Factor charging [-]

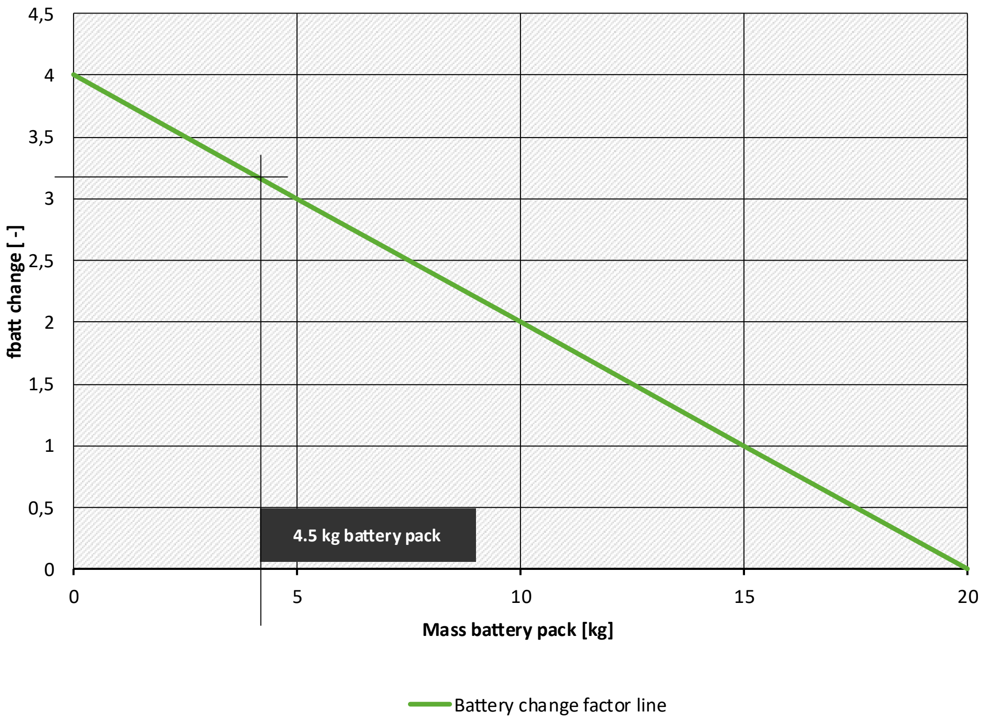
Determining factor charging for powered two-wheelers

The charging factor for powered two-wheelers is calculated for two different options: the feasibility of swappable batteries and the use of installed battery packs.

Battery change factor

For option 1, the use of swappable batteries, the battery change factor is determined which gives the feasibility of swappable battery use. This factor is calculated based on the calculated mass of the battery pack (Equation 22), which is designed for maximum trip distance, and the ideal and maximum mass which is assumed to be feasible for battery pack change by the vehicle operator. Both values are derived from existing electrified two-wheelers with swappable battery packs; different Two-Wheeler categories have different ideal and maximum battery pack masses. A linear interpolation between the ideal (battery mass battery change factor of 2) and the maximum feasible battery mass (battery mass battery change factor of 1) is done giving a percentage of battery pack change feasibility between 0.05 and 1. The battery change factor is top limited with 1. In Figure 20 the battery change factor is illustrated for small mopeds L1e-b with ideal battery pack mass of 10kg and maximum battery pack mass of 15kg. The battery pack mass is 4.5kg which gives a battery change factor of 3.1.

Figure 20: Example factor battery change for small L1e-b Mopeds



Source: Own illustration by TU Graz

For non-swappable battery pack systems, the available and needed times for charging are calculated. A distinction is made between interrupted and continuous operation where for interrupted operation a longer available charging time is assumed. Needed charging times are derived from energy content of the battery and the C-rate, assuming an 80 % SOC target.

The charging factor is then the maximum value of battery change factor and the ratio of available charging time and actual charging time. The charging factor is limited to 1.

Equation 39: Energy demand for average trip distance Two-Wheeler

$$E_{\text{trip avg}} = \frac{E_{100\text{km}}}{100} * d_{\text{trip avg}}$$

E_{100km} ... Energy demand for 100km trip [kWh]

$E_{\text{trip avg}}$ ... Energy demand for average trip [kWh]

$d_{\text{trip avg}}$ ... Distance of average trip [km]

Equation 40: Battery capacity for average trip two-wheeler

$$C_{\text{batt trip avg}} = \frac{E_{\text{trip avg}}}{\eta_e}$$

$C_{\text{batt trip avg}}$ ... Battery capacity for average trip distance [kWh]

η_e ... Efficiency electric powertrain [%]

Equation 41: Charging time two-wheeler

The charging time depends on the battery capacity, the c-rate and the available power connection, which restricts the charging power to an upper limit.

$$[\mathrm{C_{batt\ trip}} * \mathrm{C_{charge}} \leq \mathrm{P_{charger}}] \rightarrow \mathrm{t_{charging}} = \frac{\mathrm{C_{batt\ trip\ avg}}}{\mathrm{C_{batt\ trip\ max}} * \mathrm{C_{charge}}} * 60$$

$$[\mathrm{C_{batt\ trip}} * \mathrm{C_{charge}} > \mathrm{P_{charger}}] \rightarrow \mathrm{t_{charging}} = \frac{\mathrm{C_{batt\ trip\ avg}}}{\mathrm{P_{charger}}} * 60$$

$\mathrm{C_{charge}}$ ... C-rate forC_{charge} ... $C - rate\ for\ charging\ [h^{-1}]$

$\mathrm{t_{charging}}$ ... Time for charging the battery with average trip energy [min]

$\mathrm{P_{charger}}$ ... Maximum available charging power [kW]

Equation 42: Factor charging two-wheeler

$$Max\left[f_{batt\ change}\ or\ \frac{t_{charging\ available}}{t_{charging}}\right] > 100\% \rightarrow f_{charging} = 1$$

$$Max\left[f_{batt\ change}\ or\ \frac{t_{charging\ available}}{t_{charging}}\right] \leq 100\% \rightarrow f_{charging} = Max\left[f_{batt\ change}\ or\ \frac{t_{charging\ available}}{t_{charging}}\right]$$

$\mathrm{t_{charging\ available}}$ ... available charging time, dependend on vehicle class and operation type [min]

Determining factor charging for Recreational Craft

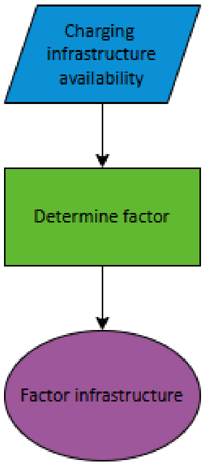
The calculation of the charging factor for recreational craft follows the same procedure as for powered two-wheelers, as for recreation craft the option for swappable batteries exists. Dependent on the feasibility for swappable battery use, the factor charging is calculated according Equation 42.The

4.1.1.6 Factor Infrastructure

Continuing from the previous Chapters 4.1.1.4 and 4.1.1.5, the next criterion in determining the electrification potential is tackled by the infrastructure factor found in Equation 5. This factor is again independent of all other factors and quantifies the availability of charging infrastructure – so whether a connection to the power grid or a generating set/battery pack and an appropriate charging solution can be set up on site or at the charging depot.

The methodology for determining the Factor Infrastructure in principle can be seen in Figure 21. The standard site of operation for each segment has been considered when determining the Factor infrastructure. An urban or industrial site leads to a high factor, whereas rural and remote sites lead to low Factors.

Figure 21: Schematic determination of Factor Infrastructure



Source: Own illustration by ifeu

Determining Factor Infrastructure for BEM & BEV in Engine categories NRE, NRG, IWA and IWP

An approach was developed to factor in this limitation using three different tiers for classification: “Yes”, “Partial” and “No”.

- “Yes”: Charging infrastructure is easily accessible
- “No”: There is no charging infrastructure reasonably accessible
- “Partial”: Approximately 50 % of the use cases have easy access to charging infrastructure

Evaluating the availability proved difficult due to limited data availability. Further research could improve the accuracy for this topic.

Table 35: Factor Infrastructure for BEM & BEV in Engine categories NRE, NRG, IWA and IWP

Classification for accessibility of infrastructure	Factor Infrastructure [-]	Description
Yes	1.0	Charging infrastructure is easily accessible
Partial	0.5	Charging infrastructure is reasonably accessible
No	0.0	Charging infrastructure is not accessible

Determining Factor Infrastructure for BEM & BEV in categories NRS, NRSh, Two-wheeler and Recreational Craft

For these classes a more granular classification was used due to the different operation environment. The approach uses seven different tiers for classification from “charging possible in all cases” to “not possible”

Evaluating the availability proved difficult due to limited data availability. Further research could improve the accuracy for this topic.

Table 36: Factor Infrastructure for BEM & BEV in categories NRS, NRSh, Two-wheeler and Recreational Craft

Classification	Factor Infrastructure [-]	Description
All cases	1.0	Charging infrastructure is available
Almost all cases	0.9	Charging infrastructure is available in almost all cases
Most cases	0.7	Charging infrastructure is available in most cases
50 %	0.5	Charging infrastructure is available in 50 % of the cases
Several cases	0.2	Charging infrastructure is available in several cases
Seldom cases	0.05	Charging infrastructure is available in seldom cases
Not available	0	Charging infrastructure is not available

4.1.1.7 Factor Specific: f_{Power} for NRS, NRSh, Two-Wheeler and Recreational Craft

For several applications the above-described factors battery, charging and infrastructure are not solely decisive for an assessment of the electrification potential. With the factor power a specific factor for the ability of the electric powertrain to reach the power demand is introduced. This factor describes the maximum power delivery of the battery and is dependent on the battery size and the discharge rate and is 1 if the power demand can be fulfilled and lower if not. As the energy demand and the power demand are not coupled, the two factors battery and power are calculated and assessed separately.

Table 37: Factor power for BEM & BEV in categories NRS, NRSh, Two-wheeler and Recreational Craft

Factor Power [-]	Description
1.0	Maximum power demand can be fulfilled
$0 < f_{power} > 1$	Maximum power demand can be fulfilled partly
0.0	Maximum power demand cannot be fulfilled

Equation 43: Maximum electric power at battery NRS

$$P_{batt\ max} = \frac{P_{max}}{\eta_e}$$

P_{max} ... Rated power [kW]

η_e ... Efficiency electric powertrain [%]

$P_{batt\ max}$ ... Maximum electric power at battery [kW]

Equation 44: Minimum battery energy content for power delivery

$$C_{batt\ discharge\ min} = \frac{P_{batt\ max}}{C_{discharge}}$$

$C_{discharge}$ ... C-rate for $_{discharge}$ ... $C - \text{rate for discharge } [h^{-1}]$

$C_{batt\ discharge\ min}$ ... Minimum battery energy capacity for maximum power delivery [kWh]

Equation 45: Factor power for NRS, NRSh, Two-Wheeler and Recreational Craft

$$f_{power} = \frac{C_{batt\ max}}{C_{batt\ discharge\ min}} \perp \text{Maximum } f_{power} = 1$$

$C_{batt\ max}$ ... Energy content of the battery [kWh]

f_{power} ... Factor power [-]

4.1.1.8 Factor Special solution

The EP illustrates the technical feasibility of electrification based on the different, already introduced factors, which represent a fleet average working day by the 50th percentile and high-volume by the 90th percentile for each segment. However, construction sites, mining applications, ferries and other applications offer use of electrification, even in some cases where electrification is deemed not possible according to the fleet average method introduced in this study (Hooli, Halim 2025; Kanchiralla et al. 2025; Pate et al. 2025). Such use cases are mainly dependent on specific options regarding for example the infrastructure (e.g. next to a power station or self-energy production) or the possibilities of direct energy supply to the machine (e.g. catenary use due to fixed routes or cable operation due to fixed working spots). If such special solutions are available for a segment, the electrification potential based on technological feasibility shall not be zero. Thus, another factor is introduced, the "Factor Special" solution. This factor takes such special use cases into account. Adding the Factor Special solution to the product of the remaining factors ensures that EP does not result in zero for such cases (see Equation 5).

Before applying this factor, each segment is analysed regarding the existence of any special solutions. If yes, the factor is set active and increases the EP to a specific value if the EP calculated by the calculation method is below that specific value for this segment. This value for the Factor Special solution is set to 0.1 for all applicable segments for 2030 and 2050. There is no differentiation between different special solution technologies, all result in the same factor. Essentially meaning it can only ever be 0 or 0.1, as seen in Equation 46.

Equation 46: Value for Factor Special solution

$$f_{Special\ Solution} = \begin{cases} 0 \text{ when no Special solution exists} \\ 0.1 \text{ when Special solution exists and EP without special solution} < 0.1 \end{cases}$$

4.1.1.9 Rationale for multiplicative approach

An analysis was done to evaluate two different methods to determine the EP. These two methods, a multiplicative and an additive approach, are described in Equation 47 and Equation 48.

Comparing the results when using the different formulas for the same set of factors shows, that the results produced by an additive approach are in all cases higher than the ones calculated by the multiplicative approach. However, a deciding point is the handling of the case where one or more factors equals zero". If any machinery has zero for one of the factors, the multiplicative approach leads to zero for the Electrification potential. Meaning if one criterion is not fulfilled, electrification is not possible. An example is a machine in which the battery can be installed and recharged based on the energy demand, but the machine works usually at spot where not grid connection is given. Such a machine cannot be electrified. Using the additive approach does not lead to an Electrification potential of zero. This can be seen in Table 38. Thus, the additive approach would need additional functions for considering these cases. Following the target of creating a simple approach leaded to the discontinuation of the additive calculation.

However, looking at the entire approach for calculating the Electrification potential described in chapter 4.1.1 shows that the additive method is also used to fine tune the model for representing special use cases, as discussed in chapter 4.1.1.8.

Equation 47: Additive Electrification potential

$$\mathrm{EP}_{\mathrm{Add}} = \frac{f_{Battery} + f_{Charging} + f_{Infrastructure}}{3}$$

Equation 48: Multiplicative Electrification potential

$$\mathrm{EP}_{\mathrm{Mult}} = \mathrm{f}_{\mathrm{Battery}} * f_{\mathrm{Charging}} * f_{\mathrm{Infrastructure}}$$

Table 38: Example calculations for comparison of additive and multiplicative approach

Segment	F_Battery [-]	F_Charging [-]	F_Infra-Structure [-]	EP_mult [-]	EP_add [-]
Mini excavators < 18 kW	1.00	1.00	1.00	1.00	1.00
Telescopic loaders 75–130 kW	0.75	0.50	1.00	0.38	0.75
Harvesters 75–130 kW	1.00	0.00	1.00	0.00	0.67
Crawler excavators 560–1,000 kW	0.00	0.00	0.50	0.00	0.17

$\mathrm{EP}_{\mathrm{Add}}$ ... EP Calculated with additive approach [-]

$\mathrm{EP}_{\mathrm{Mult}}$ ... EP calculated with multiplicative approach [-]

f_{Battery} ... Factor Battery [-]

f_{Charging} ... Factor Charging [-]

$f_{\mathrm{Infrastructure}}$ ... Factor Infrastructure [-]

4.1.1.10 Technical specifications

This chapter provides insight into the technical specifications and considerations for calculation of the EP. Key points covered are battery specifications, available charging power and drivetrain efficiency.

The chapter is split into the respective classes covered in Chapter 2.1, as each class has unique requirements and use cases.

Batteries for Engine categories NRE, NRG, IWA and IWP

Key points of the methodology found in Chapter 4.1.1.4 factor in the technical specifications of the energy storage system used in BEM & BEV. Thus, it is necessary to define parameters to represent the physical capabilities of the energy storage system. The main points considered to build a representative model are:

- The specific energy of the battery in Wh/kg
- The energy density of the battery in Wh/L
- The charge rate (C-rate) of the battery in h^{-1}
- The user accessible ratio of the battery
- The efficiency of the propulsion technology

The predominant technologies used in batteries in the next years will be Lithium-ion (Li-ion) batteries using nickel manganese cobalt (NMC) or lithium iron phosphate (LFP) as cathode materials (Hettesheimer et al. 2023). To accurately represent a fleet average battery, values for both technologies were gathered and combined to build the fleet representative model.

Literature shows values for specific energy reaching from 320 to 360 Wh/kg and values for energy density from 800 to 960 Wh/L as a range of possible performance characteristics for Li-ion batteries on the cell level as an outlook for 2035 and onward (Stephan et al. 2023).

(Hettesheimer et al. 2023) gathered Li-ion battery characteristics for 2030 and shows a range of 200 to 250 Wh/kg for specific energy in Li-ion battery cells using LFP as cathode material and a range of 500 to 550 Wh/L for energy density. The characteristics of Li-ion battery cells using NMC as a cathode material range from 300 to 400 Wh/kg for the specific energy and from 700 to 1,000 Wh/L depending on the cell type. For charging capabilities, a possible range of the C-rate from 2 to 4 h^{-1} is listed.

Targets for 2030 reach from 240 to 290 Wh/kg for Li-ion batteries using NMC cathodes on the system level (Islam et al. 2023).

For converting data representing cell level values into system level values, the data can is multiplied with a cell/system mass ratio or cell/system volume ratio (Biemann et al. 2023).

The battery user accessible ratio (ratio of net to gross battery capacity) was set at 85 %, as found in (Wang et al. 2020), The user accessible ratio was used in a similar approach in (Biemann et al. 2023).

Table 39 shows a summary of the listed literature data.

Table 39: Data for specific energy and energy density from different literature sources

Parameter	Range	Year	Level	Technology
Specific energy [Wh/kg]	300–400	2030	Cell	Li-ion (NMC)
Specific energy [Wh/kg]	200–250	2030	Cell	Li-ion (LFP)
Energy density [Wh/L]	700–1,000	2030	Cell	Li-ion (NMC)
Energy density [Wh/L]	500–550	2030	Cell	Li-ion (LFP)
Specific energy [Wh/kg]	240–290	2030	System	Li-ion (NMC)
Specific energy [Wh/kg]	320–360	2035	Cell	Li-ion
Energy density [Wh/L]	800–960	2035	Cell	Li-ion

A market survey on existing products, either traction batteries for electric cars or battery packs used by OEMs of BEM & BEVs used in construction has been conducted. Values have been found reaching from 118 to 170 Wh/kg for specific energy of Li-ion batteries using NMC cathodes on the system level and a range of 203 to 266 Wh/L for the energy density on the system level.

Li-ion batteries using LFP as a cathode material showed values from 129 to 139 Wh/kg for the specific energy on the system level.

Table 40 summarizes the findings from the market survey. Additional data can be found in Chapter A.2.

Table 40: Data for specific energy and energy density from market survey

Parameter	Range	Year	Level	Technology
Specific energy [Wh/kg]	118–170	2025	System	Li-ion (NMC)
Energy density [Wh/L]	203–266	2025	System	Li-ion (NMC)
Specific energy [Wh/kg]	129–138	2025	System	Li-ion (LFP)

Consolidating findings regarding battery technology used by BEM & BEVs in the Engine categories NRE, NRG, IWA and IWP led to the following results found in Table 41. The data in columns "Value 2030" and "Value 2050", represent the battery technology used for calculating the results for 2030 and 2050.

As discussed above, Li-ion batteries utilizing LFP and NMC cathodes will be the predominant technologies in the NRMM sector. After a round of expert discussions, it was decided, that Li-ion batteries will be the basis for calculation. For this reason, data is consolidated by grouping all found data into Li-ion batteries utilizing either NMC or LFP cathodes. With the expected production capacities (Hettesheimer et al. 2023) these average values are weighted 50/50 to build one battery model.

Table 41: Specific energy, energy density and c-rate used here for BEM & BEVs in the engine categories NRE, NRG, IWA and IWP

Parameter	Value 2030	Value 2050	Level	Technology
Specific energy [Wh/kg]	180	220	System	Generic Li-ion
Energy density [Wh/L]	300	400	System	Generic Li-ion
C-rate [h^-1]	2.0	3.5	System	Generic Li-ion

Charging power for Engine categories NRE, NRG, IWA and IWP

Looking at the methodology proposed in Chapter 4.1.1.5 for determining the possibility of recharging a battery during non-working periods shows, that a definition of available charging power is necessary. Expert discussions at Graz University of Technology with the Institute of Electrical Power Systems and with experts from the inland waterway navigation sector at CCNR led to the results in Table 42. It shows the available charging power for BEM & BEV in different Engine categories.

Engine categories NRE and NRG utilize a Low-Voltage (LV) mobile solution for charging. For opportunity charging the Medium-Voltage (MV) grid is utilized. BEM & BEV falling under the Engine categories of IWA or IWP utilize the LV grid using a mobile or stationary solution depending on the Segment. For opportunity charging again the MV grid is utilized.

Table 42: Maximum available charging power for BEM & BEV in Engine categories NRE and NRG

Parameter	Value 2030	Value 2050	Engine Categories	Technology
Max. available charging power [kW]	43	80	NRE / NRG	LV mobile
Max. available charging power [kW]	50	80	IWA / IWP	LV mobile
Max. available charging power [kW]	100	300	IWA / IWP	LV stationary
Max. available charging power [kW]	500	5000	NRE / NRG / IWA / IWP	Medium Voltage*

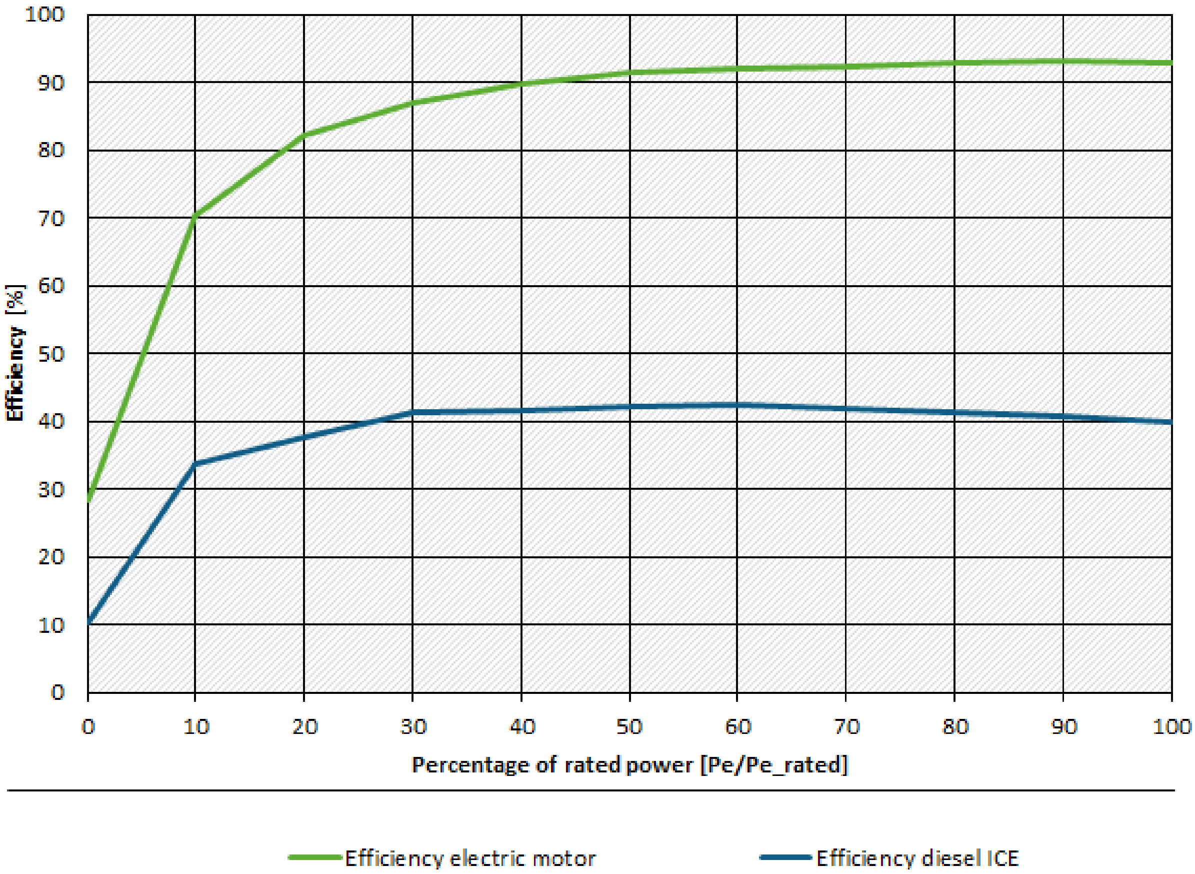
*For opportunity charging

Motor efficiencies for Engine categories NRE, NRG, IWA and IWP

Motor efficiencies are needed for the calculation of energy demands in some cases. If usage is data is based on diesel fuel consumption, the efficiencies are used for transferring the fuel energy in a demanded electric energy.

For modelling the propulsion system motor efficiencies are factored in to calculate the daily energy demand. The difference for the electric motor and one for the conventional diesel internal combustion engine can be found in Figure 22. The efficiency curves are based on TUG expert data from the work on HDV CO_2 standards.

Figure 22: Motor efficiencies for electric motor and diesel ICE



Source: Own illustration by TU Graz

Batteries for Engine categories NRS and NRSh

For small equipment in the class NRS and NRSh market surveys showed typical specific energies as well as C-rates for charging and discharging according Table 43.

Table 43: Data for specific energy and C-rates from market survey

Parameter	Range	Year	Level	Technology
Specific energy [Wh/kg]	127–178	2025	System	Li-ion (NMC)
C-rate charge [h^-1]	1.4–2.5	2025	System	Li-ion (NMC)
C-rate discarge [h^-1]	6.13–13.24	2025	System	Li-ion (NMC)

With these data a battery model for 2030 and 2050 was developed (Table 44).

Table 44: Specific energy and C-rates of NRS and NRSh for 2030 and 2050

Parameter	Value 2030	Value 2050	Engine Categories	Technology
Specific energy [Wh/kg]	230	280	NRS / NRSh	LV mobile
C-rate charge [h^-1]	2.3	4	NRS / NRSh	LV mobile
C-rate discarge [h^-1]	13.3	23.3	NRS / NRSh	LV mobile

Motor efficiencies for Engine categories NRS and NRSh

Efficiencies of ICE and electric motor are based on TUG expert data.

Table 45: Motor efficiencies for electric motor and gasoline ice NRS and NRSh

Parameter	Efficiency [%]
Efficiency ICE gasoline	20
Efficiency electric motor	85

Charging power for Engine categories NRS and NRSh

As the charging power demand of the NRS and NRSh category is rather low, standard 220V 10A power supply fulfills these demands and no further assessment is made.

Batteries for powered two-wheelers

For the batteries of two-wheelers, the specific energy, energy density and the c-rates are the same as for engine categories NRE, NRG, IWA and IWP. Additionally, a c-rate for discharging was defined based on market survey.

Table 46: Specific energy, energy density and c-rates for powered two-wheelers

Parameter	Value 2030	Value 2050	Level	Technology
Specific energy [Wh/kg]	180	220	System	Generic Li-ion
Energy density [Wh/L]	300	400	System	Generic Li-ion
C-rate charge [h^-1]	2.0	3.5	System	Generic Li-ion
C-rate discharge [h^-1]	12.9	15.7	System	Generic Li-ion

As the maximum charging power defines the charging duration, these values were defined in expert discussions at Graz University of Technology with the Institute of Electrical Power Systems (Table 47) and based on market surveys of 2025 two-wheelers charging technology.

Table 47: Maximum available charging power for powered two-wheelers

Parameter	Value 2030	Value 2050	Engine Categories	Technology
Max. available charging power [kW]	3.2	6.4	Two-wheeler	LV mobile

Motor efficiencies for powered two-wheelers

Efficiencies of ICE and electric motor are based on TUG expert data from research projects and defined for the different vehicle categories (Table 48).

Table 48: Motor efficiencies for electric motor and gasoline ice in powered two-wheeler applications

Parameter	Efficiency L1e-b	Efficiency L3e-A1	Efficiency L3e-A2	Efficiency L3e-A3
Efficiency ICE gasoline [%]	6	15	17	13

Parameter	Efficiency L1e-b	Efficiency L3e-A1	Efficiency L3e-A2	Efficiency L3e-A3
Efficiency electric motor [%]	60	60	60	60

Batteries for recreational crafts

For the batteries of recreational crafts, the specific energy, energy density and the c-rates are the same as for engine categories NRE, NRG, IWA and IWP. Additionally, a c-rate for discharging was defined based on market survey.

Table 49: Specific energy, energy density and c-rates for recreational crafts

Parameter	Value 2030	Value 2050	Level	Technology
Specific energy [Wh/kg]	180	220	System	Generic Li-ion
Energy density [Wh/L]	300	400	System	Generic Li-ion
C-rate charge [h^-1]	2.0	3.5	System	Generic Li-ion
C-rate discharge [h^-1]	12.9	15.7	System	Generic Li-ion

As the maximum charging power defines the charging duration, these values were defined in expert discussions at Graz University of Technology with the Institute of Electrical Power Systems and based on market surveys of 2025 powered two-wheelers charging technology (Table 50).

Efficiencies of ICE and electric motor are based on TUG expert data from research projects and defined for the different vehicle categories (Table 50).

Table 50: Efficiencies for electric motor and gasoline ice and charging power for recreational crafts

Craft type	BTE ICE [-]	$Eff_{El\ powertrain}$ [-]	P_{charge} 2030 [kW]	P_{charge} 2050 [kW]
Inflatable Boat 20kW	0.31	0.87	11	22
Runabout / day cruiser 260kW	0.29	0.87	22	50
Fishing Boat 135kW	0.28	0.87	22	50
PWC 44kW	0.31	0.56	6.4	22
PWC 135kW	0.31	0.87	11	22
Sailing Boat 3kW	0.31	0.56	6.4	22
Sailing Boat 12kW	0.31	0.56	6.4	22
Sailing Boat 21kW	0.30	0.87	11	22
Outboard 0–3kW	0.31	0.56	6.4	22
Outboard 3–12kW	0.31	0.56	6.4	22
Fishing Boat 44kW	0.31	0.87	22	50

4.1.2 H_2 potential

As outlined in Chapter 1, this project focuses on the determination of EP. While H_2 potential is elaborated in this chapter, it is done by use of a simplified approach.

For interpreting the results in a correct way, it is important to clarify that the following calculated hydrogen potentials are add-ons on top of the EPs. Add-on potential means that the EP is calculated first as preferable option according to the project boundary conditions and only the remaining gap is analysed for the possibility of the use of hydrogen. This means that the machines, which can be powered by either electricity and hydrogen, will be electrified due to the boundary conditions of the project. Thus, the combined result of the EP plus the add-on hydrogen potential represents the potential of the combination of electrification and hydrogen. The split of electrification and hydrogen could be different by using different boundary conditions than electrification first.

4.1.2.1 Engine categories NRE, NRG, IWA and IWP

Hydrogen propulsion systems are already available for some machine segments, mainly on a prototype level, but in some cases already as series product. This shows the principal feasibility of the use of hydrogen propulsion systems for machine segments of the engine categories NRE, NRG, IWA and IWP. Nevertheless, hydrogen needs to be available at the spot where the machines work for refuelling. Thus, the main factor for the feasibility for the use of hydrogen is the Factor Infrastructure. Taking the high costs for setting up the hydrogen infrastructure into account brings us to the assumption that hydrogen availability will be limited compared to electrification. We assume that hydrogen infrastructure is only available near sites with well-established infrastructure. At these spots infrastructure will also be available for electrification, thus the requirement is set that the Factor Infrastructure needs to be 1.0 for having hydrogen as possible solution. (IEA 2024; Komatsu 2023).

Calculating the H_2 potential for machinery in Engine categories NRE, NRG, IWA and IWP is done using the following approach:

- For 2030:
  - Any machinery segment with a Factor Infrastructure of 1.0 and for which solutions for H_2 operation exists, is assumed to have a H_2 potential of 2.5 %. At this point, most machines are prototypes and thus a market penetration on this level is assumed. Looking at the trends, most machines are designed as H_2 ICEs at this point, thus all machines are assumed to use internal combustion engines in 2030.
  - Exception: Ships and generators, these segments are considered to utilize H_2 fuel cells (FC) according to the development trends discussed with experts.
- For 2050:
  - Any machinery segment with a Factor Infrastructure of 1.0 that can be operated via hydrogen will have a hydrogen potential equal to half of the remaining share (gap, see Chapter 4.3.2.6) subtracting the EP.

    Of this H_2 potential:

  - 75 % is assumed to utilize H_2 ICEs and
  - 25 % is assumed to use H_2 FCs.

  These numbers are based on the trends published by different manufacturers and expert discussions (Liebherr 2022; Ries 2025).

- Example:

  A segment showing an EP of 80 % will have a gap of 20 %. Half of that (10 %) is considered to be H_2, split into 7.5 % H_2 ICEs and 2.5 % H_2 FCs.

- Exception:

  Ships and generators utilize 100 % of the H_2 potential as H_2 FCs proven by expert discussions.

4.1.2.2 Engine categories NRS, NRSh

Hydrogen propulsion systems have been shown in very few research applications, mainly as hydrogen ICE using hydrogen tanks on the machinery. The principal feasibility of the use of hydrogen propulsion systems for machine Segments of the Engine categories is given in some segments whereas the very limited operation time and the hydrogen supply leads to extremely low potential for a mass production.

Calculating the H_2 potential for machinery in Engine categories NRS and NRSh is done using the following approach:

► For 2030:

- Any machinery segment with a factor infrastructure of 1.0 and for which solutions for H_2 operation exists, is assumed to have a H_2 potential of 2.5 %. For applications where the factor Infrastructure is lower than 1.0 and bigger than 0.25, the H_2 potential is 1 %; if the factor infrastructure is lower than 0.25 the H_2 potential is 0.
- At this point, most machines are prototypes and thus a market penetration on this level is assumed. Looking at the trends, most machines are designed as H_2 ICEs at this point, thus all machines are assumed to use internal combustion engines in 2030.

► For 2050:

- Any machinery Segment with a Factor Infrastructure of 1.0 that can be operated via hydrogen will have a hydrogen potential equal to 25 % of the remaining share (gap, see chapter 4.3.3.3 after subtracting the EP).

  Of this H_2 potential:

  - 75 % is assumed to utilize H_2 ICEs and
  - 25 % is assumed to use H_2 FCs.

4.1.2.3 Powered two-wheelers

For very few applications demonstrators using hydrogen propulsion systems have been shown, both as hydrogen ICE as well as fuel cell systems. The principal feasibility of the use of hydrogen propulsion systems for two-wheeler is given in some segments whereas the restricted available storage volume for the hydrogen tank leads to the very limited operation time making a mass production hydrogen propulsion for two-wheeler unlikely.

However, calculating the H_2 potential for powered two-wheelers is done using the following approach:

- For 2030:
  - Any powered two-wheeler category with a factor infrastructure of 1.0 and for which solutions for H_2 operation exists, is assumed to have a H_2 potential of 2.5 %. For applications where the factor Infrastructure is lower than 1.0 and bigger than 0.25, the H_2 potential is 1 %; if the factor infrastructure is lower than 0.25 the H_2 potential is 0.
  - At this point, most applications are prototypes and thus a market penetration on this level is assumed. Looking at the trends, most vehicles are designed as H_2 ICEs at this point, thus all machines are assumed to use internal combustion engines in 2030.
- For 2050:
  - Any two-wheeler category with a factor infrastructure of 1.0 and for which solutions for H_2 operation exists, is assumed to have a H_2 potential of 10 %. For applications where the factor Infrastructure is lower than 1.0, the H_2 potential is 5 %.
  - Any machinery Segment with a Factor Infrastructure of 1.0 that can be operated via hydrogen will have a hydrogen potential equal to 25% of the remaining share (gap, see chapter 4.3.4.3 after subtracting the EP) share.
  - Of this H_2 potential:
    - 75 % is assumed to utilize H_2 ICEs and
    - 25 % is assumed to use H_2 FCs.

4.1.2.4 Recreational Craft

For some applications demonstrators using hydrogen propulsion systems have been shown, mainly as fuel cell systems. The principal feasibility of the use of hydrogen propulsion systems for recreational craft is given in some segments whereas the restricted available storage volume for the hydrogen tank leads to the limited operation time making a broad market introduction of hydrogen propulsion for recreational craft unlikely. Calculating the H_2 potential for recreational craft is done using the following approach:

- For 2030:
  - Any recreational craft category with a factor infrastructure of 1.0 and for which solutions for H_2 operation exists, is assumed to have a H_2 potential of 2.5 %. For applications where the factor Infrastructure is lower than 1.0 and bigger than 0.25, the H_2 potential is 1 %; if the factor infrastructure is lower than 0.25 the H_2 potential is 0.
  - At this point, most recreational crafts are prototypes and thus a market penetration on this level is assumed. Looking at the trends, most machines are designed as H_2 FC at this point, thus all crafts are assumed to use fuel cell propulsion in 2030.
- For 2050:

- Any recreational craft with a factor infrastructure of 1.0 and for which solutions for H_2 operation exists, is assumed to have a H_2 potential of 10 %. For applications where the factor Infrastructure is lower than 1.0, the H_2 potential is 5 %.
- Any machinery Segment with a Factor Infrastructure of 1.0 that can be operated via hydrogen will have a hydrogen potential equal to 25 % of the remaining share (gap, see Chapter 4.3.5.2 after subtracting the EP) share.
- Of this H_2 potential:
  - 25 % is assumed to utilize H_2 ICEs and
  - 75 % is assumed to use H_2 FCs.

4.2 Operational data

Operational data is crucial for determining the energy demand of the machines or vehicles and thus an important factor for the possibility to install a battery and to recharge it in the available downtime. The following part gives an overview on the data for the different Engine categories.

4.2.1 NRE, NRG, IWA and IWP

4.2.1.1 General methodology data acquisition

Operating hours and load factors, being central points for the methodology to calculate the energy demand per working day as proposed in Chapter 4.1, are the focus of the data acquisition. The required data are obtained either by extraction from telemetry data (Chapter 4.2.1.2), by a survey, or a combination of both. Additionally, there are further sources, namely surveys and data provided by manufacturers, being used to expand the dataset (Chapter 4.2.1.4).

For Overnight charging, the standard process, the data are analysed for how long machinery is not in use overnight (between two working days).

For Opportunity charging breaks during the working day are analysed. The minimum duration for breaks feasible for opportunity charging is set at 30 minutes, durations below are considered too short to be feasibly used for opportunity charging. Thus, the data are analysed for periods (≥ 30 minutes) of downtime during the typical shift, which can be utilized for recharging the battery.

4.2.1.2 Telemetric data

Data basis

Telemetric data were provided by an OEM for the following Subsectors:

- Dump trucks: 5 machines with one engine size monitored for a total of 992 working days
- Bulldozers: 14 machines with 5 different engine sizes monitored for a total of 1 409 working days
- Crawler excavators: 43 machines with 15 different engine sizes monitored for a total of 4,280 working days
- Wheel excavators: 36 machines with 12 different engine sizes monitored for a total of 5 717 working days

- Wheel loaders: 116 machines with 4 different engine sizes monitored for a total of 25 647 working days

The data was selected by the manufacturer to represent the fleet average within a segment in terms of area of work and operation profiles.

Each dataset is split in events. A recorded event typically last for several minutes (with exceptions lasting less than a minute or more than one hour). Depending on the dataset events either contain the duration and the operation state (working, driving or idling) or separate entries for time that has been spent working, driving or idling during one event. The datasets include timestamps and energy consumption.

Methodology

Key parameters extracted out of the telemetric data are:

- Operating hours
- Load factor

Operating hours are extracted for all working days. From the distribution of the operating hours of the single working day, representative datapoints for standard (50th percentile) and high-volume working days (90th percentile) are calculated. In principle the data is analysed as follows:

- Gather all data for one unique machine
- Analyse data for each day per machine
- Analyse distribution for working hours per day and determine the values for 50th and 90th percentile for each machine
- Elaborate machine segment representative values by grouping all machines of a segment, weighted according to the number of recorded workdays per machine.

The datasets either contain fuel consumption (which is logged in litres of fuel consumed per event) or the amount of electric energy consumed during a work event (logged in kWh). For datasets containing the electric energy consumption, the load can be calculated directly using the duration and rated power. For datasets with logged fuel consumption, the approach is as follows:

- Take a standard value for modern internal combustion engines as an initial engine efficiency value to calculate the engine work output from the logged fuel consumption per event
- Determine the load per event using the calculated engine work, the recorded duration and the rated engine power of the engine
- Obtain an updated efficiency value from the engine efficiency map[5] based on the calculated load
- Repeat the process using the new efficiency value until the changes in load and efficiency between iterations fall below a defined threshold of 1 %

[5] Generic data on engine efficiency maps are available at TU Graz based on the work for the heavy-duty vehicle CO_2 standards.

In detail the process is executed as follows:

By using a heating value q for diesel, the quantity of fuel L_{Fuel} is converted to energy.

Equation 49: Energy stored in fuel

$$E_{Fuel} = L_{Fuel} \cdot q$$

Average power and load factor are calculated for each iteration k

Equation 50: Average power and load

$$P^{(k)} = \frac{W^{(k)}}{t^{(k)}}, Load^{(k)} = \frac{P^{(k)}}{Pe_{rated}}$$

Where t is the recorded duration in seconds and Pe_{rated} is the rated engine power in kW.

Update the efficiency via the efficiency map.

Equation 51: Motor efficiency

$$\eta^{(k+1)} = \eta_{map}\left(L^{(k)}\right)$$

Until the relative changes are below a defined threshold ε (set at 0.01):

Equation 52: Relative change for efficiency and load

$$\frac{|\eta^{(k+1)} - \eta^{(k)}|}{\eta^{(k)}} < \varepsilon \text{ and } \frac{|Load^{(k+1)} - Load^{(k)}|}{Load^{(k)}} < \varepsilon$$

E_{fuel} ... Energy stored in fuel [kWh]

L_{fuel} ... Amount of fuel consumed in litres [L]

q .... Heating Value [kWh/L]

P ... Average power [kW]

Pe_{rated} ... Rated engine power [kW]

η ... Motor efficiency [-]

k ... Iteration step [-]

4.2.1.3 Aggregated data

Of course, time-resolved data as telemetric data is the preferred option because of the high level of detail, but also aggregated data per working day is very usable. The following sections describe the different sources for such aggregated data.

Survey by TU Graz and FVT

TU Graz and FVT tried to gather aggregated operational data by a survey send out to different associations. For that reason, we created a template, which includes all segments, in total 179. Main requested points of the survey for each Segment are:

- Empty and maximum machinery weight
- Operating hours for standard working day

- Operating hours for high-volume working day
- Load factors
- Downtime or break duration
- Availability of telemetric data

Parallel to sending out the survey, meetings with VDMA and Euromot were arranged, who agreed to fill in the survey, to define clearly what kind of data is expected to be provided.

In a follow-up meeting the results of the survey and the further use of the data combined with first interim results were discussed with the associations. Adaptions to the results of the survey were made in cases of misunderstandings in coordination with the associations. This was mainly in done meetings of small expert groups.

In some cases, the associations suggested to extend the data set by additional categories. These suggestions were discussed in the meetings and after the clarification we took over the proposals.

In total a request for 179 different Segments was made, of which partial or full datasets were provided for 100 Segments.

TREMOD-MM

TREMOD is a transport emission model developed and maintained by ifeu, used to calculate CO_2 and pollutant emissions. Within the TREMOD model family, TREMOD-MM focuses on NRMM applications. (ifeu 2025).

Within TREMOD-MM, data containing annual operating hours can be found. The dataset from TREMOD-MM covers data for 25 Subsectors and a total of 113 Segments, which have been compiled from various sources (operator data, second-hand market, literature). Further details are provided in the appendix. It is used to calculate daily operating hours for different machinery.

Other sources

Data for operation of a tractor (Varlese 2024) and data from an engine manufacturer are used to expand the dataset further.

Stock and rated engine power of inland waterway vessels are logged for Germany, including information about the type of vessel (WSV 2023).

A small survey of an agricultural user provides additional insight into use cases and fuel consumption during various tasks.

Additional data stems from surveys done in Luxembourg and Switzerland in the NRMM sector.

4.2.1.4 Consolidation and prioritization of different data sources

In the analysis of different data sources, some Segments overlap, while others have limited or no data. The model was fed according to the following hierarchy when multiple sources were available:

- Telemetric data:

  Used for calculations, with other sources serving only for validation.

- Aggregated data (no telemetric data):

  Results from multiple sources are averaged. Each source is weighted equally.

- No available data:
  - Data from a neighbouring Segment with similar working profile within the same Subsector is used, if available.
  - Otherwise, data from Segments in a different Subsector with similar use cases is used.

In total there are 164 Segments for the Engine categories NRE and NRG, of which 114 utilize aggregated data and 10 Segments use telemetric data. Of the remaining 40 Segments, 35 Segments use data from neighbouring Segments. The operational data for the five remaining Segments is based on expert judgement considering all available data.

For the Engine categories IWA and IWP, there are a total of 15 Segments, all of which utilize aggregated data.

4.2.2 Operational data NRS and NRSh

Small engine equipment has a big variety of applications and within the applications a big span of rated power. To structure the broad field of applications, three main application types of hand-held equipment and two main application types of ground-guided tools have been identified. To cope with the power variety which is connected to the use type, the sub-classes hobby use and professional use were defined.

The operational data was generated from market studies of available products accompanied by information from OEM.

Table 51: Operational data of NRS and NRSh

Category	Power max [kW]	Efficiency ICE [-]	Duty cycle [-]	Power average [kW]	Operation time / day average [h/day]	Mass fuel in tank [kg]
Chainsaw / Hobby	2.3	20	50	1.2	1	0.5
Chainsaw / Professional	6.4	20	70	4.5	5.5	1
Trimmer / Hobby	2.2	20	50	1.1	1	0.5
Trimmer / Professional	2.8	20	70	2	8	0.8
Other hand-held / Hobby	1.4	20	50	0.7	1	0.5
Other hand-held / Professional	6.2	20	70	4.3	5.5	3.6
Lawn-mower / Hobby	3.2	25	50	1.6	1	1
Lawn-mower / Professional	3.2	25	70	2.2	5.5	2.3

Category	Power max [kW]	Efficiency ICE [-]	Duty cycle [-]	Power average [kW]	Operation time / day average [h/day]	Mass fuel in tank [kg]
Riding mower / Hobby	17.9	25	70	9	1	6
Riding mower / Professional	17.9	25	70	12.5	5.5	34.1

4.2.3 Operational data powered two-wheelers

For the two-wheeler category operational data are defined for the four different vehicle categories moped (L1e-b), small motorcycle (L3e-A1), medium size motorcycle (L3e-A2) and big motorcycle and for two different use cases. The interrupted use case represents an operation where charging is possible between single trips; the continuous operation represents driving in long trips without possibility for re-charging. For each of these categories several operational data were extracted from market analysis and average data defined based on expert knowledge of TU Graz and in discussions with OEM (Table 52).

Table 52: Operational data two-wheeler

Two-wheeler category	Use case	Tank volume [l]	Tank weight [kg]	Max. trip length [km]	Average trip length [km]
L1e-b	Interrupted	5	4.7	30	12.5
L1e-b	Continuous	5	4.7	60	35
L3e-A1	Interrupted	12	10	75	20
L3e-A1	Continuous	12	10	112.5	35
L3e-A2	Interrupted	16	12.8	112.5	60
L3e-A2	Continuous	16	12.8	187.5	75
L3e-A3	Interrupted	18	15.3	150	125
L3e-A3	Continuous	18	15.3	300	200

For the conversion of ICE to electric powertrain two values for the user acceptable additional volume V_{add} and mass M_{add} of the powertrain were extracted from market studies of existing electric power two-wheeler and discussed with OEMs. As for two-wheeler swappable battery packs are possible and the battery pack weight must be handled by the user, the feasibility was checked based on the battery pack mass which is ideal $M_{batt-pack-ideal}$ and maximum for battery change $M_{batt-pack-max}$ (Table 53).

Table 53: Operational data two-wheeler additional volume and weight, swappable battery pack weight

Two-wheeler category	Use case	V_{add} [%]	M_{add}[%]	$M_{bat-pack-ideal}$[kg]	$M_{bat-pack-max}$[kg]
L1e-b	Interrupted	50	10	10	15
L1e-b	Continuous	50	10	10	15
L3e-A1	Interrupted	50	20	10	40

Two-wheeler category	Use case	V_{add} [%]	M_{add}[%]	$M_{bat\text{-}pack\text{-}ideal}$[kg]	$M_{bat\text{-}pack\text{-}max}$[kg]
L3e-A1	Continuous	50	20	10	40
L3e-A2	Interrupted	50	30	10	40
L3e-A2	Continuous	50	30	10	40
L3e-A3	Interrupted	30	30	10	40
L3e-A3	Continuous	30	30	10	40

4.2.4 Operational data Recreational Craft

For recreational craft the data was extracted from a study conducted by Ricardo for ICOMEA with the focus on Decarbonisation for the Recreational Marine Industry (Zenié et al. 2023). The selected craft categories in this study were extended with additional power classes; in total 11 craft categories were used for the EP calculation:

- Inflatable Boat 20kW
- Runabout / day cruiser 260kW
- Fishing Boat 135kW
- PWC 44kW
- PWC 135kW
- Sailing Boat 3kW
- Sailing Boat 12kW
- Sailing Boat 21kW
- Outboard ≤ 3kW
- Outboard 3 ≤ 12kW
- Fishing Boat ≤ 44kW

Table 54: Operational data Recreational Craft – General data

Craft type	Power max [kW]	Fuel	Propulsion	Boat weight [kg]	Fuel tank empty ICE [kg]	Fuel tank [l]	BTE ICE* [-]	Range ICE ** [h]	Running [h/a]
Inflatable Boat 20kW	20	Gasoline	single, outboard	700	8	70	0.3	32.5	35
Runabout / day cruiser 260kW	260	Gasoline	Single, multiple, inboard	3 500	30	270	0.3	13.8	43
Fishing Boat 135kW	110	Gasoline	single, outboard	1 500	19	170	0.3	12.0	35

Craft type	Power max [kW]	Fuel	Propulsion	Boat weight [kg]	Fuel tank empty ICE [kg]	Fuel tank [l]	BTE ICE* [-]	Range ICE ** [h]	Running [h/a]
PWC 44kW	44	Gasoline	Jet Drive	200	8	30	0.3	4.1	156
PWC 135kW	135	Gasoline	Jet Drive	381	8	70	0.3	4.3	156
Sailing Boat 3kW	3	Gasoline	single, outboard	200	1	5	0.3	2.9	24
Sailing Boat 12kW	12	Gasoline	single, outboard	1 300	5	12	0.3	2.3	24
Sailing Boat 21kW	21	Gasoline	single outboard	4 800	8	70	0.3	24.5	24
Outboard 0-3kW	2,7	Gasoline	single outboard	100	1	5	0.3	2.9	35
Outboard 3-12kW	12	Gasoline	single outboard	200	5	12	0.3	2.3	35
Fishing Boat 44kW	44	Gasoline	single, outboard	1 000	12	50	0.3	6.8	35

*Brake thermal efficiency

**h in typical duty cycle

Table 55: Operational data Recreational Craft – Data electric powertrain

Craft type	Efficiency el. powertrain [-]	E-machine power max [kW]	Battery capacity [kWh]	Range el [# typ. trips]	Range el [h in typ. duty cycle]	E-machine power av. [kW]
Inflatable Boat 20kW	0.87	20	25	2	4	4
Runabout / day cruiser 260kW	0.87	195	175	1	3	49
Fishing Boat 135kW	0.87	110	138	1	3	32
PWC 44kW	0.56	44	10	1	1	10
PWC 135kW	0.87	135	41	2	1	36
Sailing Boat 3kW	0.56	1.6	1	1	3	0
Sailing Boat 12kW	0.56	12	10	1	4	3
Sailing Boat 21kW	0.87	21	49	1	4	11
Outboard ≤ 3kW	0.56	1.6	1	1	3	0

Craft type	Efficiency el. powertrain [-]	E-machine power max [kW]	Battery capacity [kWh]	Range el [# typ. trips]	Range el [h in typ. duty cycle]	E-machine power av. [kW]
Outboard 3 ≤ 12kW	0.56	12	10	1	4	3
Fishing Boat < 44kW	0.87	44	44	1	3	13

Table 56: Operational data Recreational Craft – additional volume and weight, swappable battery pack weight

Craft type	Add. weight factor mass battery [-]	Add. volume factor vol battery [-]	Available time for charging 80 % [min]	Ideal battery weight for battery change [kg]	Max battery weight for battery change [kg]
Inflatable Boat 20kW	0.30	0.3	720	10	40
Runabout / day cruiser 260kW	1	1	720	10	40
Fishing Boat 135kW	1	1	720	10	40
PWC 44kW	0.30	0.3	720	10	40
PWC 135kW	0.30	0.3	720	10	40
Sailing Boat 3kW	0.30	0.3	720	10	40
Sailing Boat 12kW	1	1	720	10	40
Sailing Boat 21kW	1	1	720	10	40
Outboard 0-3kW	1	1	720	10	40
Outboard 3-12kW	1	1	720	10	40
Fishing Boat 44kW	1	1	720	10	40

4.3 Results

4.3.1 Categorization of results

The calculation of the Electrification potentials contains uncertainties, which can be mainly related to the database. Taking that into account it is reasonable to transfer the EP results in five classifications instead of the numbers resulting from calculations. The classes for EPs are "very low", "low", "moderate", "high" and "very high" as seen in Table 57.

Table 57: Categorization of EP results

Classification	EP from	to
Very high	80 %	100 %

Classification	EP from	to
High	60 %	80 %
Moderate	40 %	60 %
Low	20 %	40 %
Very low	0 %	20 %

In addition, the results are combined to groups according to the emission regulation Stage V, which are NRE, NRG, IWA, IWP, NRS and NRSh, and in addition powered two-wheelers and recreational craft. In these groups, the results of the different machine or vehicle categories are weighted by their relative CO_2 emissions, which have been calculated with TREMOD-MM, to illustrate fleet representative results.

4.3.2 NRE, NRG, IWA and IWP

This Chapter shows results for the Engine categories NRE, NRG, IWA and IWP. Results presented are the EP and H_2 potentials.

To showcase the methodology presented in the previous Chapters, there are excerpts from the calculations done for the following Segments:

- Mini excavators <18 kW
- Telescopic loaders 75 – 130 kW
- Harvesters 75 – 130 kW
- Crawler excavators 560 – 1,000 kW

For short the Segments will be referred to as *Mini excavator*, *Telescopic loader*, *Harvester* and *Crawler excavator* in the following Chapters. The calculations showcased are done with technical specifications for the year 2030.

4.3.2.1 Example Calculations

We will now take a closer look at four of the Segments to show the application of the methodology presented in Chapter 4.1. In Table 58 operational data (namely, the 50th and 90th percentile daily working hours and the load factor) and the rated engine power can be found.

Table 58: Operational data for example calculations

Segment	Pe_rated [kW]	Load [-]	Work_hours_P50 [h]	Work_hours_P90 [h]
Mini excavator, 15kW	15	0.35	2.0	4.1
Telescopic loader, 104kW	104	0.50	5.0	9.1
Harvester, 104kW	104	0.31	4.6	9.2
Crawler excavator, 809kW	809	0.55	5.6	11.6

Pe_{rated} … Rated engine power [kW], Load … Engine load [-], Work $hours_{P50}$ … Daily working hours 50th percentile [h], Work $hours_{P90}$ … Daily working hours 90th percentile [h]

After gathering operational data and machinery specifications we calculate the daily energy demand (see Chapter 4.1.1.3, Equation 6 and Equation7). The daily energy demand for the example calculations can be found in Table 59.

Table 59: Daily energy demands for example calculations

Segment	Daily energy demand P50 [kWh]	Daily energy demand P90 [kWh]
Mini excavator, 15kW	10	21
Telescopic loader, 104kW	260	477
Harvester, 104kW	150	299
Crawler excavator, 809kW	2,502	5,133

Daily energy demadn$_{P50}$ … Energy demand for standard working day [kWh],
Daily energy demand$_{P90}$ … Energy demand for high-volume working day [kWh]

Going from there, we calculate the necessary battery capacity (kWh) (see Chapter 4.1.1.4, Equation 12). The battery capacities for the example calculations can be found in Table 60.

Table 60: Battery capacities for example calculations

Segment	η_M [-]	AR_User [-]	Battery capacity P50 [kWh]	Battery capacity P90 [kWh]
Mini excavator, 15kW	0.88	0.85	13	28
Telescopic loader, 104kW	0.91	0.85	335	615
Harvester, 104kW	0.87	0.85	202	403
Crawler excavator, 809kW	0.92	0.85	3 204	6 572

ηM … Efficiency of the electric motor [-], ARUser … Battery accessible ratio of the battery by the user [-],
Battery capacityP50 … Battery capacity for average working day [kWh],
Battery capacityP90 … Battery capacity for high-volume working day [kWh]

So far, we have calculated daily energy demand and necessary battery capacities for the four Segments. Using these battery capacities, we calculate battery sizes and weights (See Chapter 4.1.1.4, Equation 13 and Equation 14). As reference year we use the values for 2030 found in Table 41. The battery weights and sizes for the example calculations can be found in Table 61.

Table 61: Battery sizes and volumes for example calculations

Segment	m_Bat P50 [kg]	m_Bat P90 [kg]	V_Bat P50 [m³]	V_Bat P90 [m³]
Mini excavator, 15kW	75	155	0.04	0.09
Telescopic loader, 104kW	1,860	3,416	1.12	2.05
Harvester, 104kW	1,123	2,238	0.67	1.34
Crawler excavator, 809kW	17,799	36,511	10.68	21.91

$m_{Bat\ P50}$ … Mass of the battery for average working day [kg],
$m_{Bat\ P90}$ … Mass of the battery for high-volume working day [kg],
$V_{Bat\ P50}$ … Volume of the battery for average working day [m³],
$V_{Bat\ P90}$ … Volume of the battery for high-volume working day [m³]

Taking the specifications in Table 62 concerning available charging power and the operational data in Table 62, we calculate the available charging energy during non-working hours (see Chapter 4.1.1.5, Equation 32).

Table 62: Available charging energy for example calculations

Segment	Non-working hours P50 [h]	Non-working hours P10 [h]	Available charging energy P50 [kWh]	Available Charging energy P90 [kWh]
Mini excavator, 15kW	22	20	591*	855
Telescopic loader, 104kW	19	15	818	639
Harvester, 104kW	19	15	834	638
Crawler excavator, 809kW	18	12	790	535

*Restricted by C-Rate of the battery

Summarized in Table 63 we can see battery weights, battery volumes and the determined Factor Battery (see Chapter 4.1.1.4) for each Segment. Looking at the calculated values for weight and volume of the batteries, a matching classification (Suitability for battery installation) is chosen by expert assessment. For mini excavators, the required batteries are relatively small and can be easily installed. For telescopic loaders and harvesters, constraints with vehicle mass and possible space for installation lead to a slightly lower classification. For crawler excavators in the segment from 560 to 1,000 kW of rated engine power the batteries turn out to large and heavy to be reasonably installed in the machinery itself.

Table 63: Factor battery for example calculations

Segment	Battery weights [kg]	Battery volumes [m³]	Suitability for battery installation [-]	Factor Battery [-]
Mini excavator, 15kW	75 / 155	0.04 / 0.09	Yes	1.00
Telescopic loader, 104kW	1,860 / 3,416	1.12 / 2.05	Suitable	0.75
Harvester, 104kW	1,123 / 2,238	0.67 / 1.34	Suitable	0.75
Crawler excavator, 809kW	17,799 / 36,511	10.68 / 21.91	No	0.00

"/" is used to separate values for 50^{th} and 90^{th} percentile

We determine the Factor Charging (see chapter 4.1.1.5) by comparing the available charging energy to the battery capacities.

Table 64: Factor charging for example calculations

Segment	Available charging energies [kWh]	Battery capacities [kWh]	Factor Charging [-]
Mini excavator, 15kW	591* / 855	13 / 28	1.00
Telescopic loader, 104kW	818 / 639	335 / 615	1.00
Harvester, 104kW	834 / 638	202 / 403	1.00
Crawler excavator, 809kW	790 / 535	3,204 / 6,572	0.00

*Restricted by C-Rate of the battery

"/" is used to separate values for 50th and 90th percentile

We derive the Factor Infrastructure (see chapter 4.1.1.6).

Table 65: Factor infrastructure for example calculations

Segment	Charging infrastructure availability [-]	Factor Infrastructure [-]
Mini excavator, 15kW	Yes	1.00
Telescopic loader, 104kW	Yes	1.00
Harvester, 104kW	Partial	0.50
Crawler excavator, 809kW	No	0.00

Taking all the individual factors from the previous steps and consolidating them into one table lets us calculate the EP (see Chapter 4.1.1, Equation 5).

Note that the multiplication would result in an EP of 0.00 for the Segment "Crawler excavator". However, application examples show that there are special solutions on the market for crawler excavators using cable operation in the case of high-powered crawler excavators e.g., in mining operations. Thus, the potential cannot be 0.0 if machines are available and in use. To take that into account the Factor Special solution is set active for this Segment and leads to an Electrification potential of 0.10 (see Chapter 4.1.1.8).

Table 66: Electrification potential for example calculations

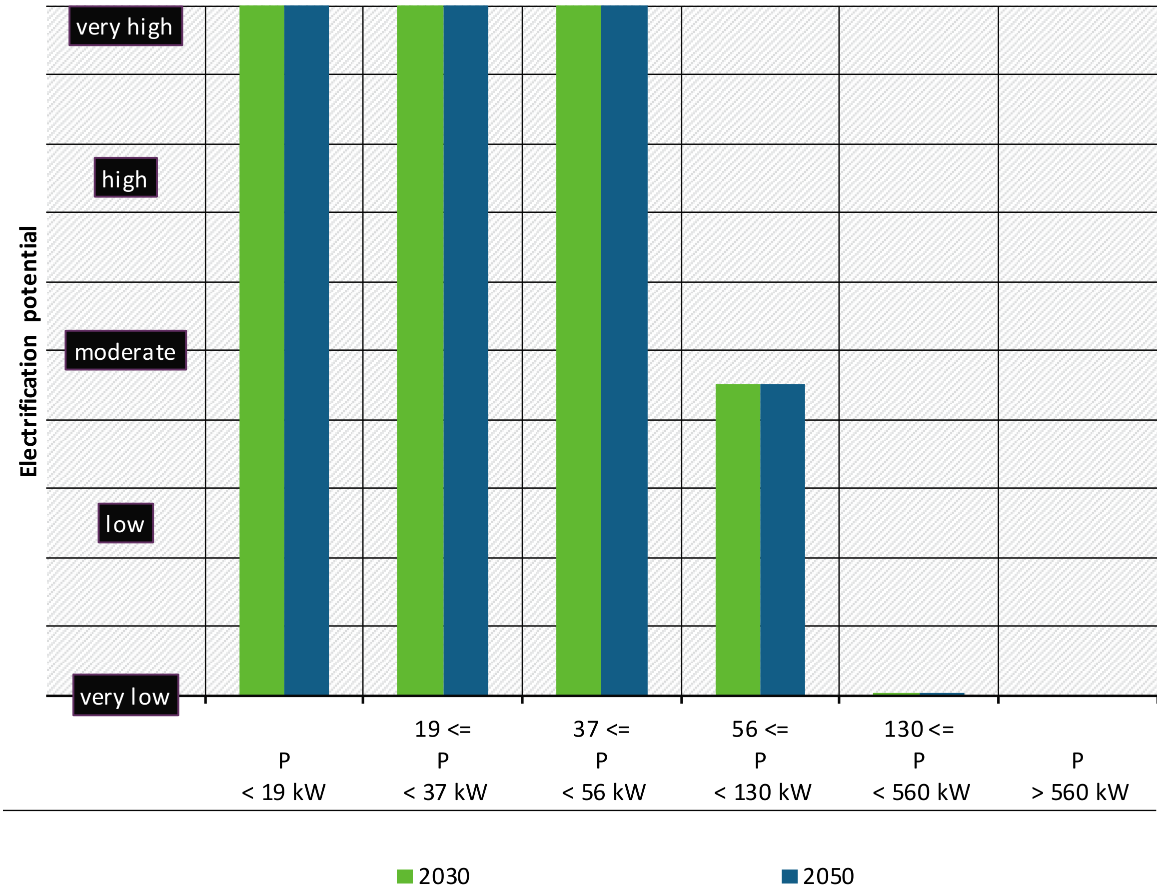
Segment	Factor battery [-]	Factor charging [-]	Factor infrastructure [-]	Electrification potential [-]
Mini excavator, 15kW	1.00	1.00	1.00	1.00
Telescopic loader, 104kW	0.75	1.00	1.00	0.75
Harvester, 104kW	0.75	1.00	0.50	0.38
Crawler excavator, 809kW	0.00	0.00	0.00	0.10*

*Through special solution factor

4.3.2.2 Results Sector Agricultural and forestry machinery

Figure 23 shows the EP results for the agricultural and forestry Sector in 2030 and 2050. A trend can be seen that larger machinery is harder to electrify. This is attributed to higher installed engine Power and higher operating hours. No increase in EP between 2030 and 2050 can be attributed to the tendentially larger machinery used in this sector. An increase in battery technology and higher charging power do not solve restrictions concerning infrastructure availability and the large batteries needed to ensure operation to the same extent.

Figure 23: Electrification potentials for agricultural and forestry machinery

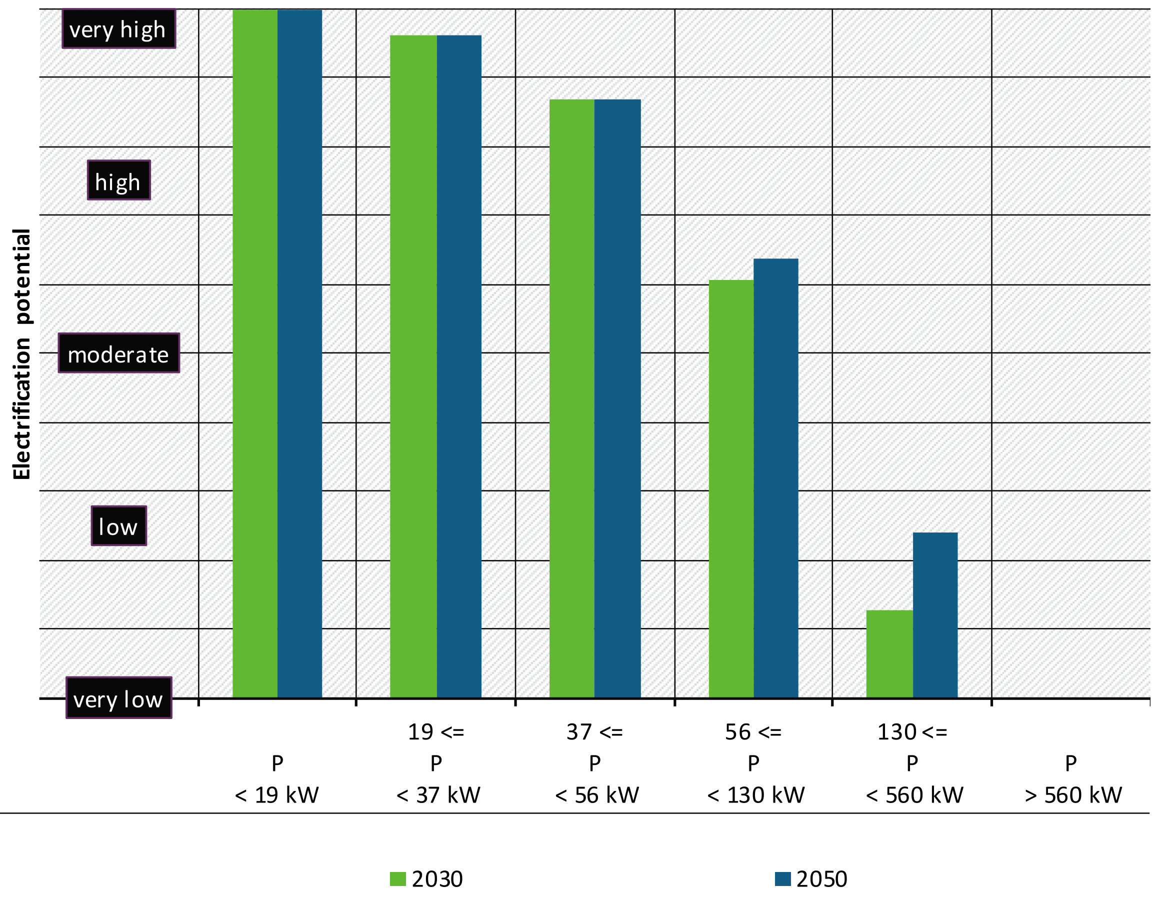


Source: Own illustration by TU Graz

4.3.2.3 Results Sector Construction machinery

Figure 24 shows the EP results for the construction Sector in 2030 and 2050. A slight increase can be seen for the EP in 2050, due to improvements in the battery technology and higher available charging power. The same trend as above remains, where larger machinery (with comparatively higher rated Power and/or operating hours) is harder to electrify.

Figure 24: Electrification potentials for construction machinery

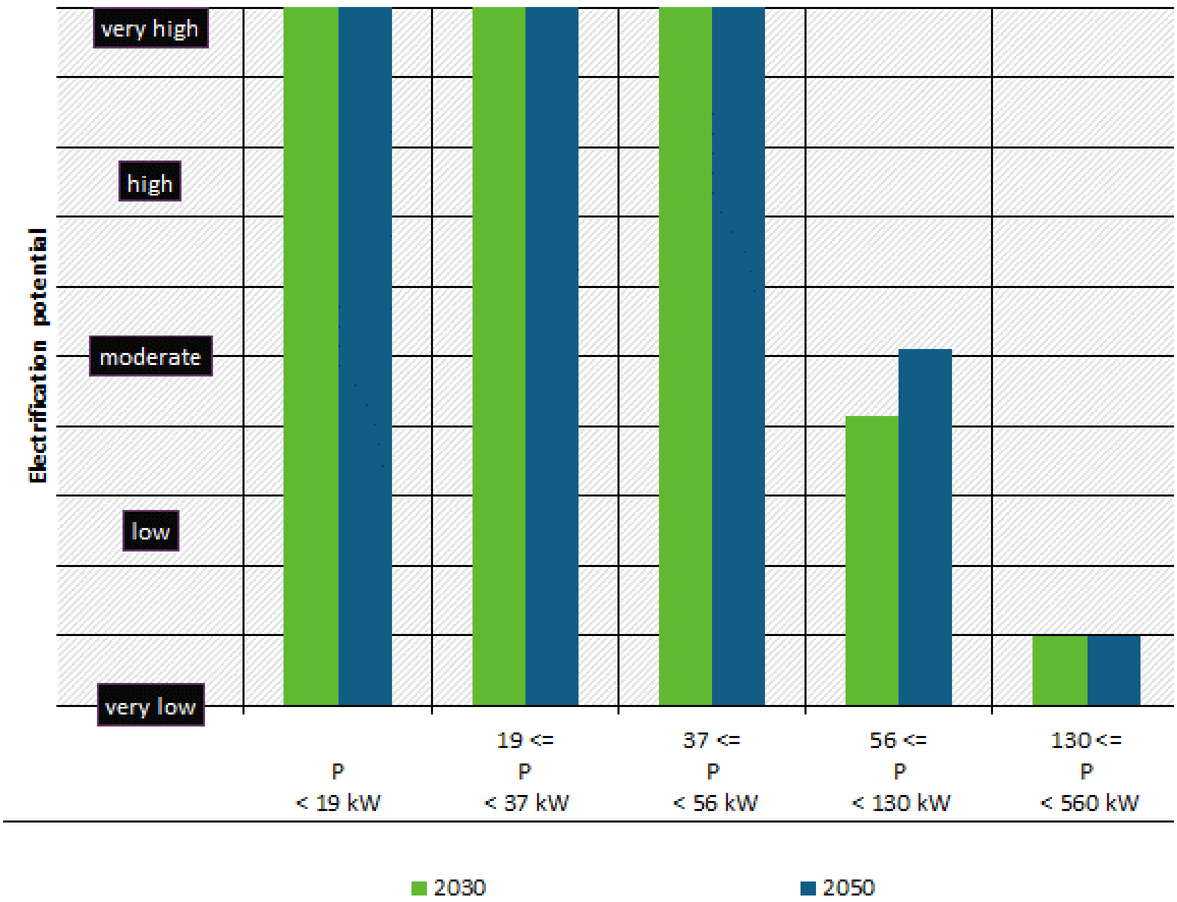


Source: Own illustration by TU Graz

4.3.2.4 Results generators, forklifts and tower cranes

Figure 25 shows the EP results for the generators in 2030 and 2050. Again, a slight increase in EP for 2050 can be seen. The same general trend for larger machinery can be seen as above.

Figure 25: Electrification potentials for mobile generators

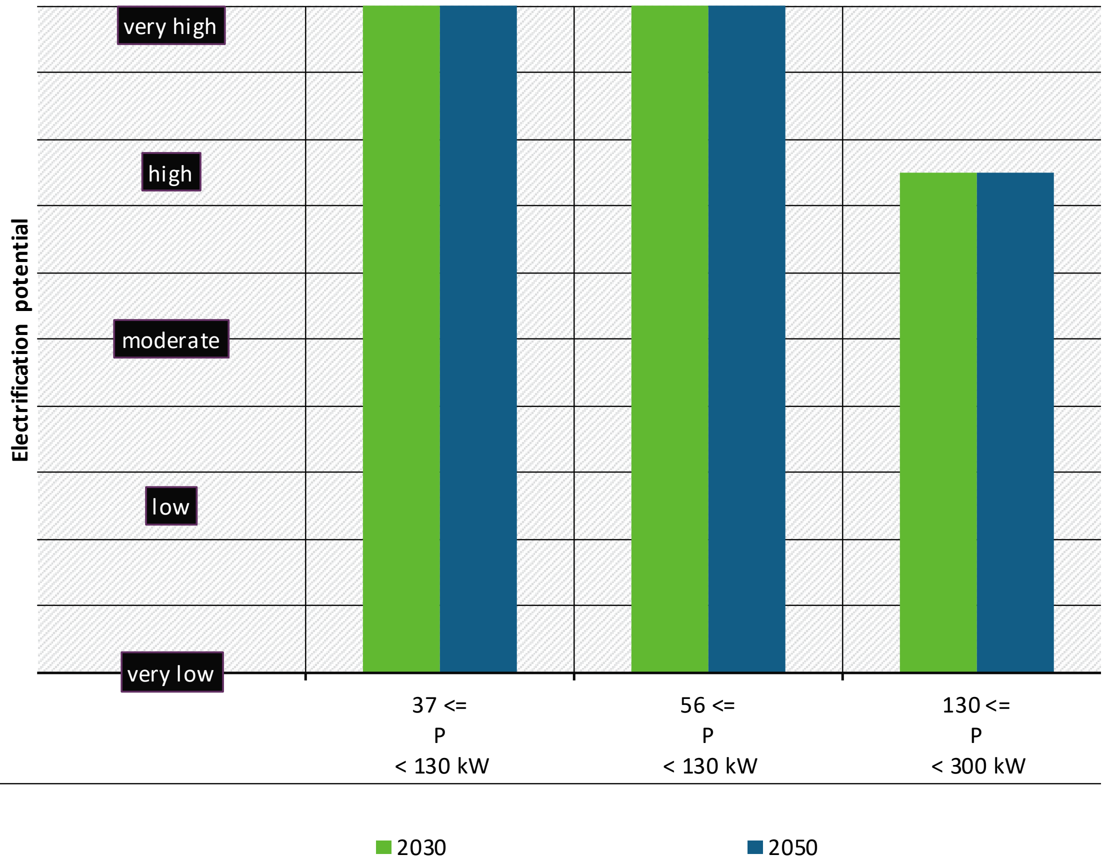


Source: Own illustration by TU Graz

Generators are often relevant for the energy supply of critical infrastructure, even if these are mainly stationary and not mobile applications as regarded in this study. In emergencies critical infrastructure must be kept operational. This must be considered when transferring the results into regulation options.

Figure 26 shows the results for forklifts. While no data for smaller power ranges (37kW and below) could be gathered, the EP for forklifts is very high in these segments, supported by the widespread market adoption of forklifts with battery change systems used today.

Figure 26: Electrification potentials for forklifts



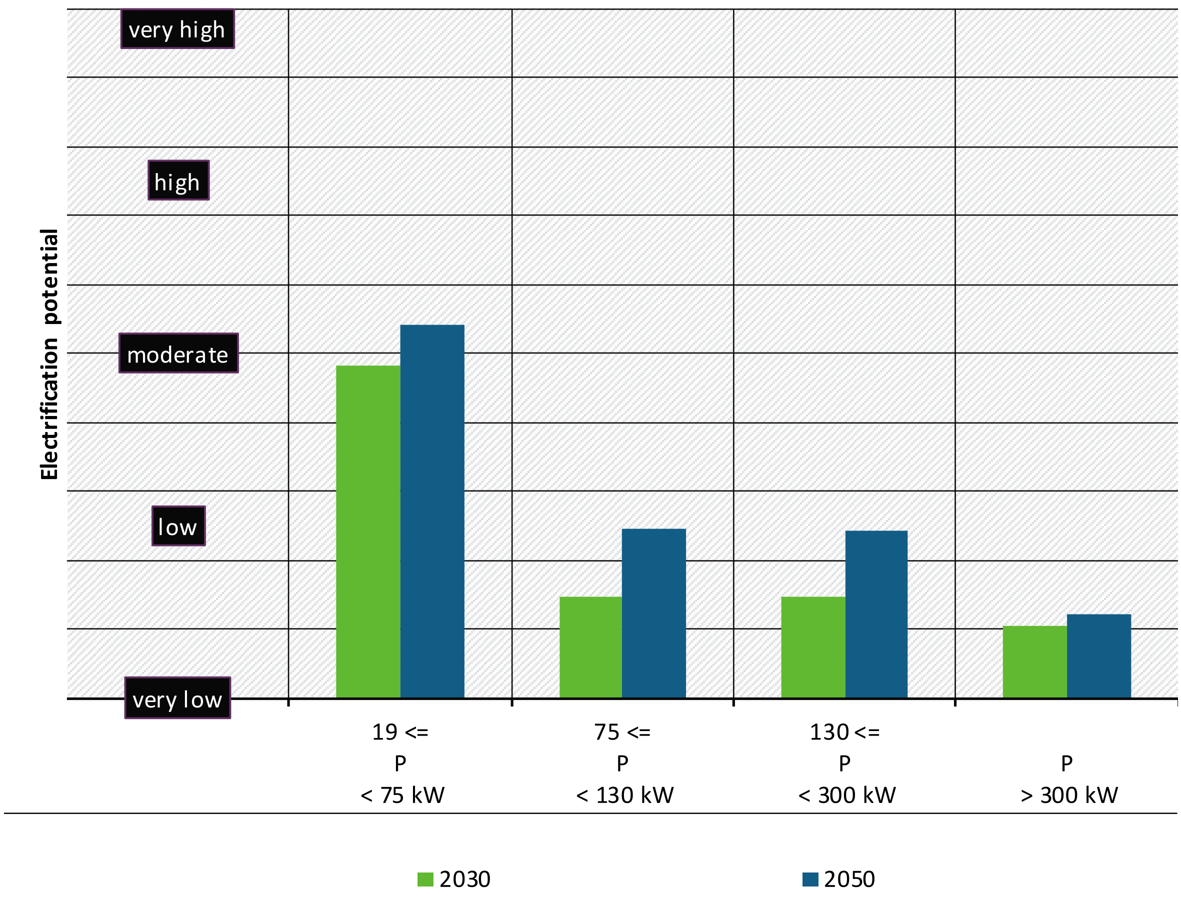
Source: Own illustration by ifeu

Lastly there is one segment for tower cranes (in the range from 37 to 55kW), showing a very high EP. Tower cranes are operated directly via electricity, either from the power grid or from generating sets.

4.3.2.5 Results for Engine categories IWA and IWP

Figure 27 shows the EP results for the Engine categories IWA and IWP for 2030 and 2050. A slight increase in EP can be seen for 2050, attributed to the improvement in battery technology and higher available charging power.

Figure 27: Electrification potentials for machinery in Engine categories IWA and IWP

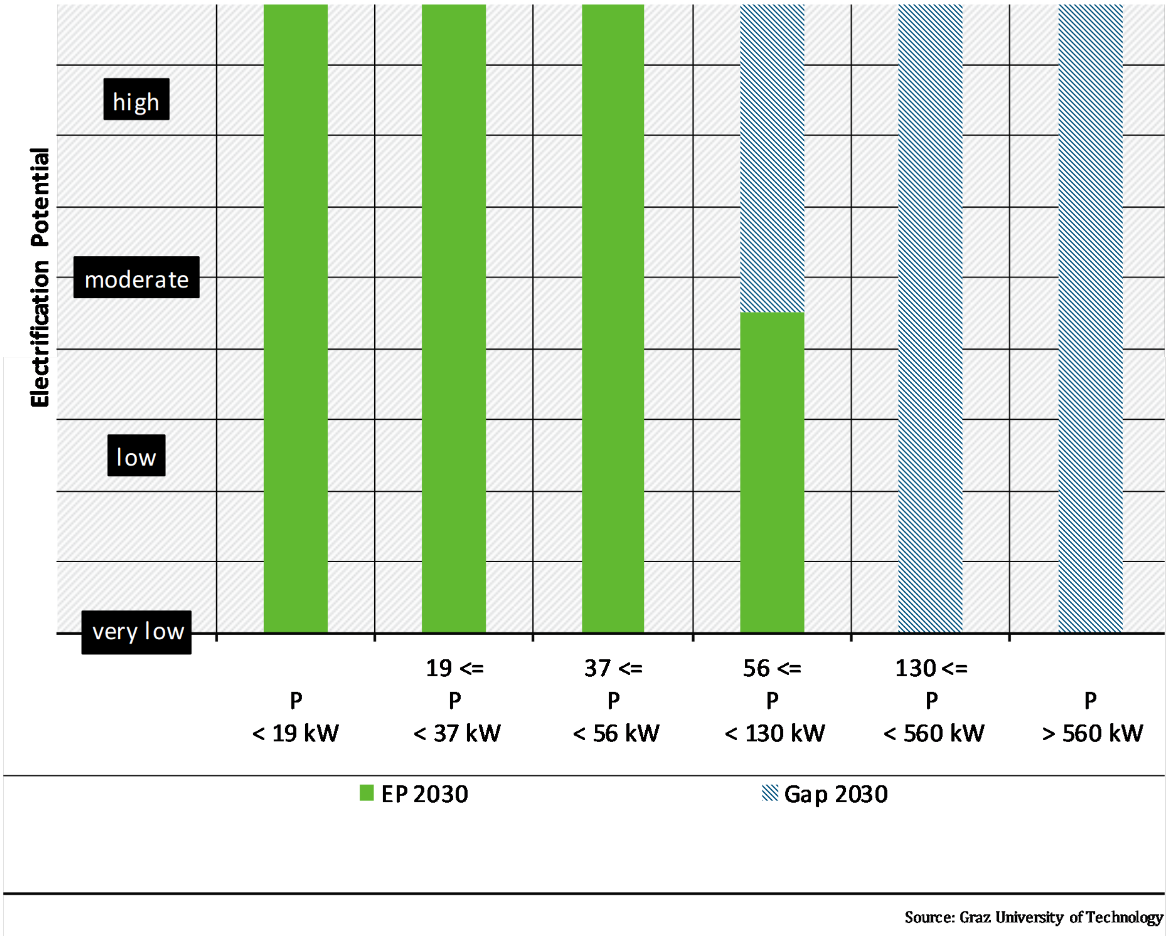


Source: Own illustration by ifeu

4.3.2.6 Gap

Figure 28 shows the EP results for agricultural and forestry machinery in 2030. The blue striped bars illustrate the remaining gap, which cannot be covered by electrification. This gap is especially high in Segments with high engine power. A simplified analysis of the hydrogen potential shows that this technology can cover only a few percent of this gap in 2030. Other CO_2 neutral solutions like biofuels or synthetic fuels can also not replace fossil fuels completely due to limited availability at this time. Thus, fossil fuels will play an important role in the sector agricultural and forestry machinery in 2030.

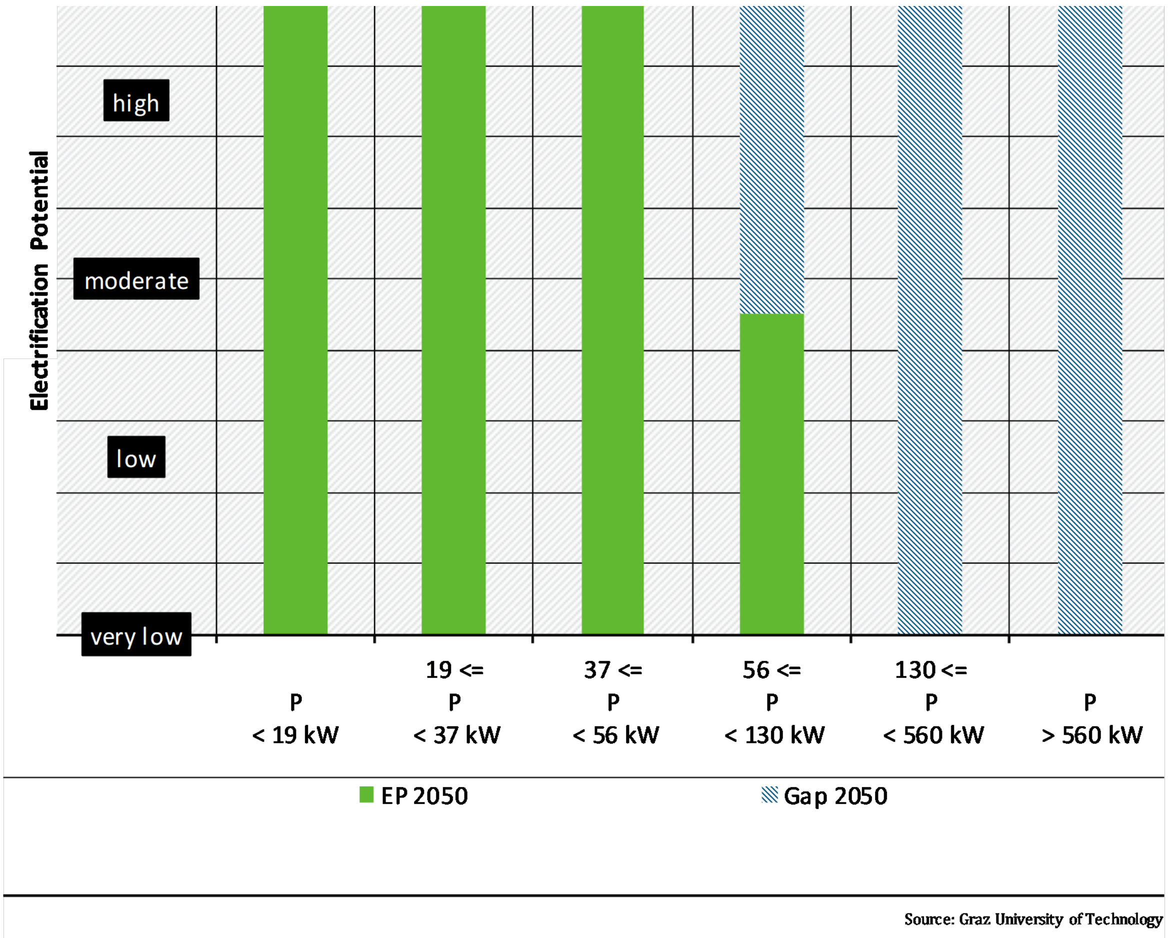
Figure 28: Gap for agricultural and forestry machinery in 2030



Source: Own illustration by TU Graz

Figure 29 shows the EP results for agricultural and forestry machinery in 2050. The EP increases from 2030 to 2050, but still a gap remains that cannot be covered by electrification. Based on the simplified H_2 potential analysis, hydrogen will cover a bigger part than in 2050 than in 2030. However, the combination of hydrogen and electrification, which is higher than solely electrification, will still leave about half (56 to 130 kW) or even more (> 130 kW) of the CO_2 emissions of the machines uncovered. Thus, other CO_2 neutral options like biofuels or synthetic fuels are needed to reach CO_2 neutrality in the sector agricultural and forestry machinery in 2050.

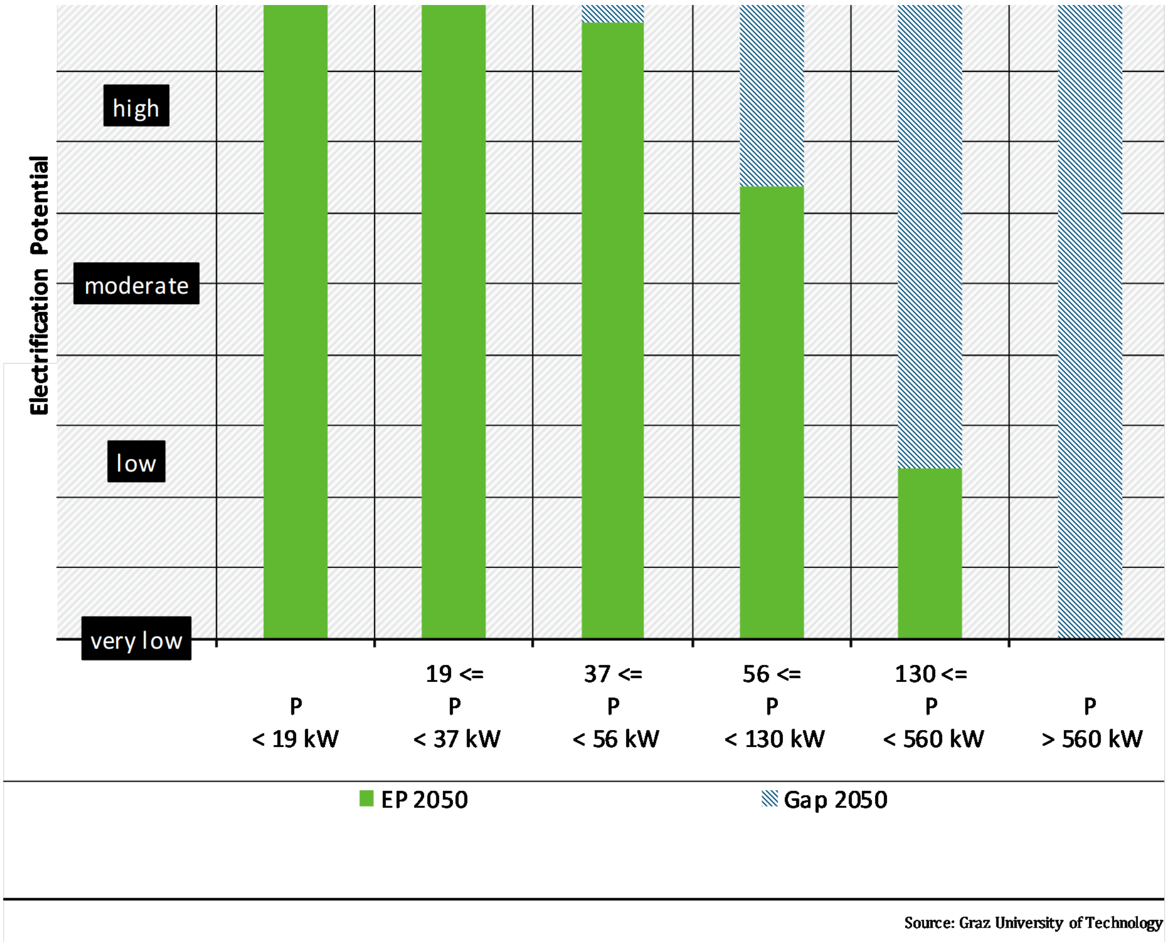
Figure 29: Gap for agricultural and forestry machinery in 2050



Source: Own illustration by TU Graz

Figure 30 shows the EP results for construction machinery in 2050. Also, in this Sector a gap remains, which cannot be solely covered by electrification, again increasing with raising engine power. The combination of electrification and hydrogen, which is calculated by the same simplified approach as for the agricultural and forestry sector, decreases the gap more than solely electrification, but less than halving it. This confirms the demand for other CO_2 neutral options in the NRMM sector still in 2050.

Figure 30: Gap for construction machinery in 2050



Source: Own illustration by TU Graz

4.3.2.7 Interpretation, discussion and limitations

The results show a high diversity of electrification potential (EP) across different Segments, ranging from very low to very high. Therefore, no clear or straightforward grouping of Segments into “high” or “low” EP categories is possible.

Despite this heterogeneity, some general trends can be identified for all Sectors. Machinery and vehicles with higher installed power tend to show lower Electrification potential. Similarly, Segments with high daily operating hours generally show lower EP. Additionally, providing sufficient charging infrastructure (meaning enough power from the grid and appropriate charging solutions on site) is critical for the EP, as Segments with limited or no infrastructure show very few possibilities for electrification.

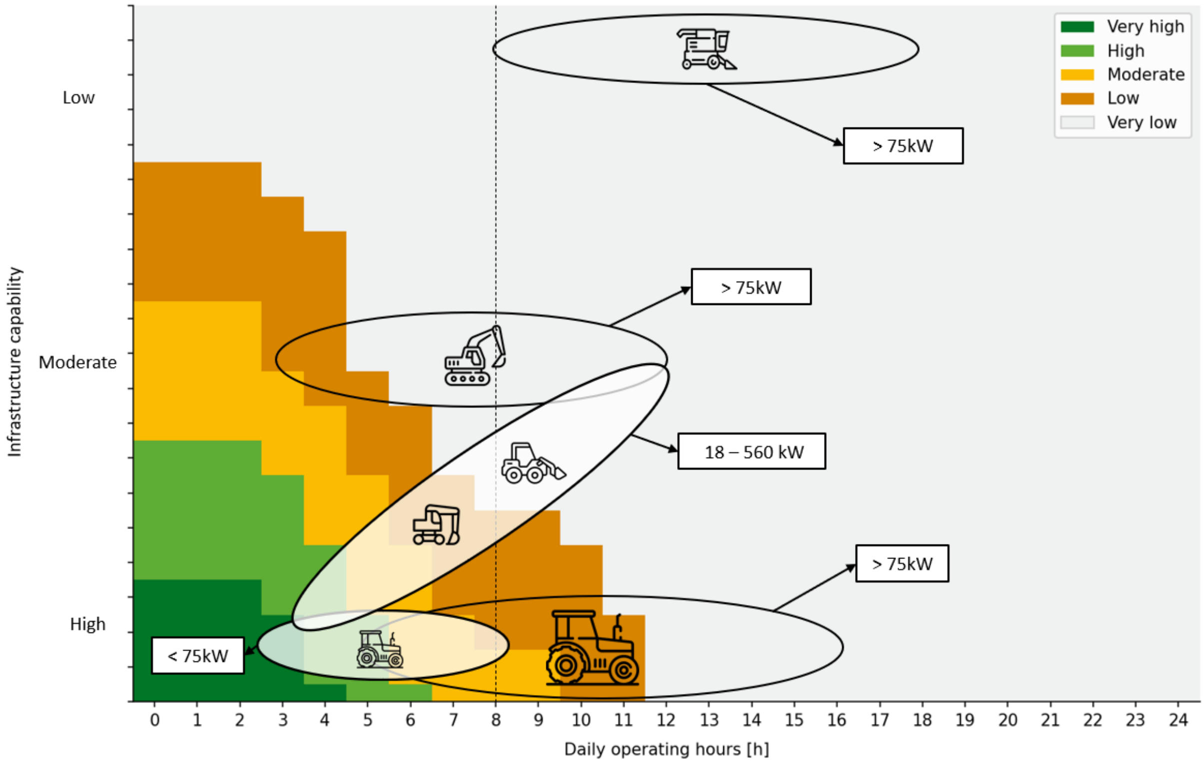
Looking ahead from 2030 to 2050, an increase in electrification potential is observed across all Segments. However, these increases are marginal. Segments that are difficult to electrify in 2030 remain challenging to electrify in 2050.

Figure 31 shows exemplary five different subsectors and their respective EP, as indicated by the colour regions in the background. Because battery size and therefore the factors battery and charging scale with daily operating hours an overview can be generated by plotting EP against the daily operating hours and infrastructure availability covering the three main factors.

The subsectors agricultural tractors, combine harvesters, crawler excavators, wheel loaders and mobile excavators have been chosen to give a representative outlook for the engine category NRE, with these subsectors contributing a large share of CO_2 emissions in this category.

The oval shapes represent the spread of daily operating hours reaching from possible operating hours for different use cases. Again, it can be seen that a combination of low daily operating hours and good infrastructure availability lead to a high or even very high EP, while high daily operating hours or insufficient infrastructure availability, especially the combination of both, leave few opportunities for electrification. The spread of the ovals covering different electrification potentials highlights the importance of specific mission profiles and boundary conditions even for identical subcategories.

Figure 31: Excerpt of NRMM Electrification for the engine category NRE in 2050



Source: Own illustration by ifeu

As can be seen for agricultural tractors, depending on size class, the use cases and thereafter EP do vary with installed engine power.

For certain combinations of Segment, use case, and power class, substantial gaps remain. This highlights the continued need for alternative low-carbon technologies beyond direct electrification.

4.3.3 NRS, NRSh

This chapter shows results for the engine categories NRS and NRSh with the result for EP. To showcase the methodology presented in the previous chapters, there are excerpts from the calculations done for the segment NRSh and within this segment the application class of Chainsaw in professional and hobby use. The NRS and NRSh applications have a wide power variety itself, therefor a calculation for minimum power and consequential mass and maximum power is calculated. The EP is then calculated for the average.

For short the segments will be referred to as *Chainsaw professional and Chainsaw hobby* in the following chapters. The calculations showcased are done with technical specifications for the year 2030.

4.3.3.1 Example Calculations

We will now take a closer look at four of the segments to show the application of the methodology presented in chapter 4.1. In Table 67 the operational data and rated engine power for the maximum variant can be found.

Table 67: Operational data for example calculations NRSh maximum variant

Data	Chainsaw professional	Chainsaw hobby
$P_{tool\ ICE\ max}$ [kW]	6.4	2.3
Efficiency ICE [%]	20	20
Duty Cycle WOT [-]	0.7	0.5
$P_{tool\ ICE\ avg}$ [kW]	4.48	1.15
$DC_{avg\ /\ day}$ [h]	5.5	1
m_{tank} [kg]	0.98	0.5
m_{empty} [kg]	9.9	6.6

$P_{tool\ ICE\ max}$ … Maximum power of the tool [kW]

$P_{tool\ ICE\ avg}$ … Average power of the tool [kW]

Duty cycle WOT … share of full load operation [-]

$DC_{avg/day}$ … Average operation time per day [h]

m_{tank} … Mass of fuel tank [kg]

m_{empty} … Mass of tool without fuel [kg]

After gathering operational data and machinery specifications we calculate the mass of the battery for typical use duration. The maximum acceptable mass is calculated from available battery pack mass and a feasible mass increase. With this we can derive the battery factor by comparing the battery mass for typical use duration in 2030 with the acceptable maximum battery mass (Table 68) (see Chapter 4.1.1.4 and Equation 19).

Table 68: Factor battery example calculation NRSh maximum variant

Data	Chainsaw professional	Chainsaw hobby
$m_{batt\ duty\ cycle}$ [kg]	3.87	0.5

Data	Chainsaw professional	Chainsaw hobby
$F_{mass\ batt\ add}$ [%]	10	10
$m_{batt\ max\ acc}$ [kg]	2.21	2.21
Duty cycle duration [min]	10.00	5.0
$f_{battery}$	0.55	1

$f_{battery}$ ... Factor battery [-]

$m_{batt\ duty\ cycle}$ ... Mass of battery with energy content for whole duty cycle operation [kg]

$f_{mass\ batt\ add}$ ... Maximum acceptable additional battery mass factor [-]

$m_{batt\ max\ ass}$ ... Maximum acceptable battery mass [kg]

With the maximum electric power at the battery and the discharge rate the required battery capacity for this power delivery can be calculated. A comparison between this battery capacity and the actual battery capacity delivers the factor power (Table 69).

Table 69: Factor power example calculation NRSh maximum variant

Data	Chainsaw professional	Chainsaw hobby
$P_{batt\ max}$ [kW]	6.40	2.7
$C_{discharge}$ [h^{-1}]	13.3	13.3
$C_{batt\ discharge\ min}$ [kWh]	0.56	0.2
$C_{batt\ max}$ [kWh]	0.46	0.46
f_{Power}	0.81	1

$P_{batt\ max}$.. Maximum electric power at the battery [kW]

$C_{discharge}$ ... Discharge rate [h^-1]

f_{power} ... Factor power [-]

As NRS and NRSh are typically equipped with swappable battery packs, the required number of battery packs for continuous operation in contrast to the number of battery packs which is feasible to carry with the operator is decisive for the factor battery. The required number of battery packs depends on the operation duration of one battery pack, defined by the battery capacity and the energy demand of the tool, and the charging duration.

Table 70: Factor charging example calculation NRSh maximum variant

Data	Chainsaw professional	Chainsaw hobby
$t_{\_operation\ batt}$ [min]	5.20	20.3
t_{charge} [min]	26	26
# battery packs feasible [-]	5.00	5.0
# battery packs required [-]	7.00	3.00
$f_{charging}$	0.71	1

$t_{operation\ batt}$ ... Operation time using one battery pack [min]

t_{charge} ... Charging duration for 100 % SOC including necessary battery pack cooling time [min]

$\#_{batt\ pack\ feas}$ ... Number of battery packs feasible to carry with [-]

$\#_{batt\ pack\ req}$ ... Number of battery packs required for continuous operation [-]

f_{charge} ... Factor charging [-]

Table 71: Factor infrastructure example calculation NRSh maximum variant

Data	Chainsaw professional	Chainsaw hobby
Acces to grid	50 %	allmost all cases
$f_{infrastructure}$	0.5	0.9

Taking all the individual factors from the previous steps and consolidating them into one table the electrification potential (Table 72) can be calculated (chapter 4.1.1, Equation 5).

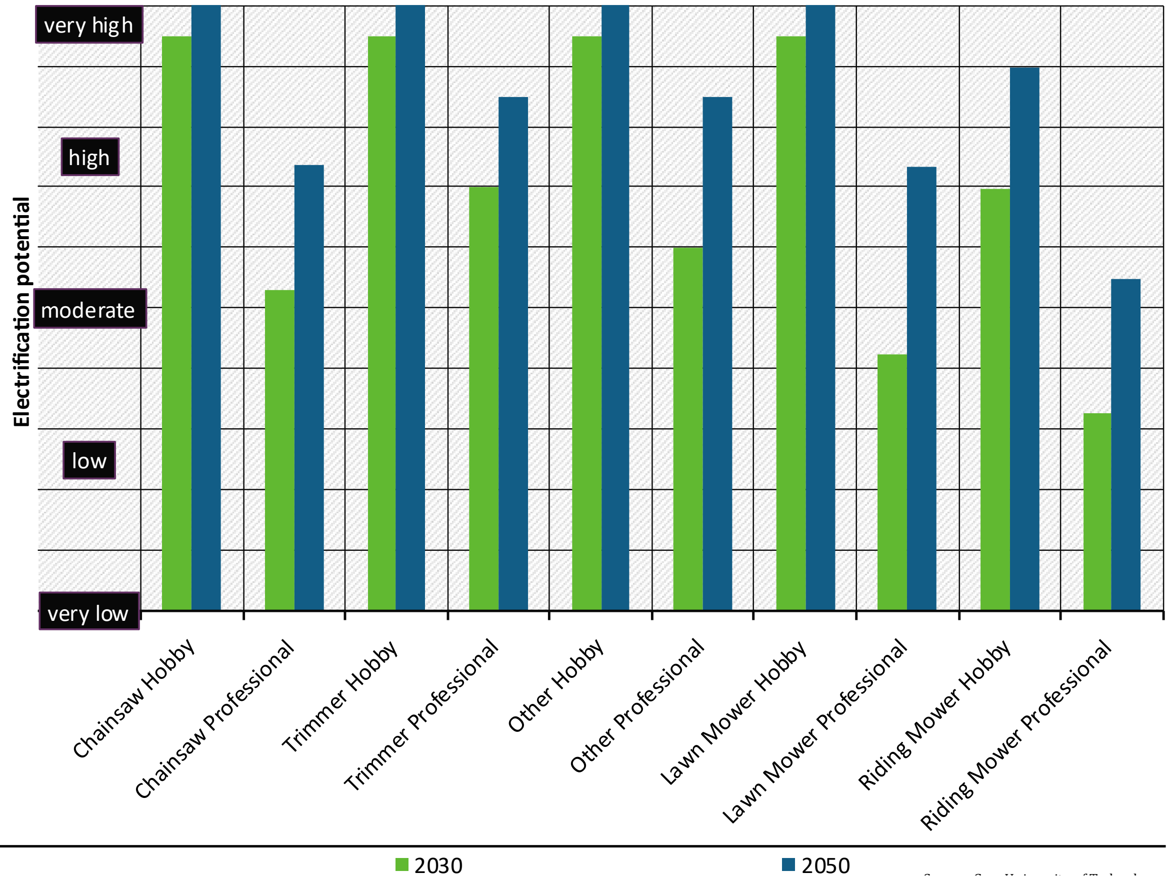
Table 72: Electrification potential example calculation NRSh maximum variant

Data	Chainsaw professional	Chainsaw hobby
$f_{battery}$	0.55	1.00
f_{power}	0.81	1.00
$f_{charging}$	0.71	1.00
$f_{infrastrutur}$	0.50	0.90
Electrification potential	0.16	0.90

4.3.3.2 Results for Engine categories NRS, NRSh

The final EP is calculated for average operation (chapter 4.1.1.2).

Figure 32: Electrification potentials for machinery in Engine categories NRS and NRSh

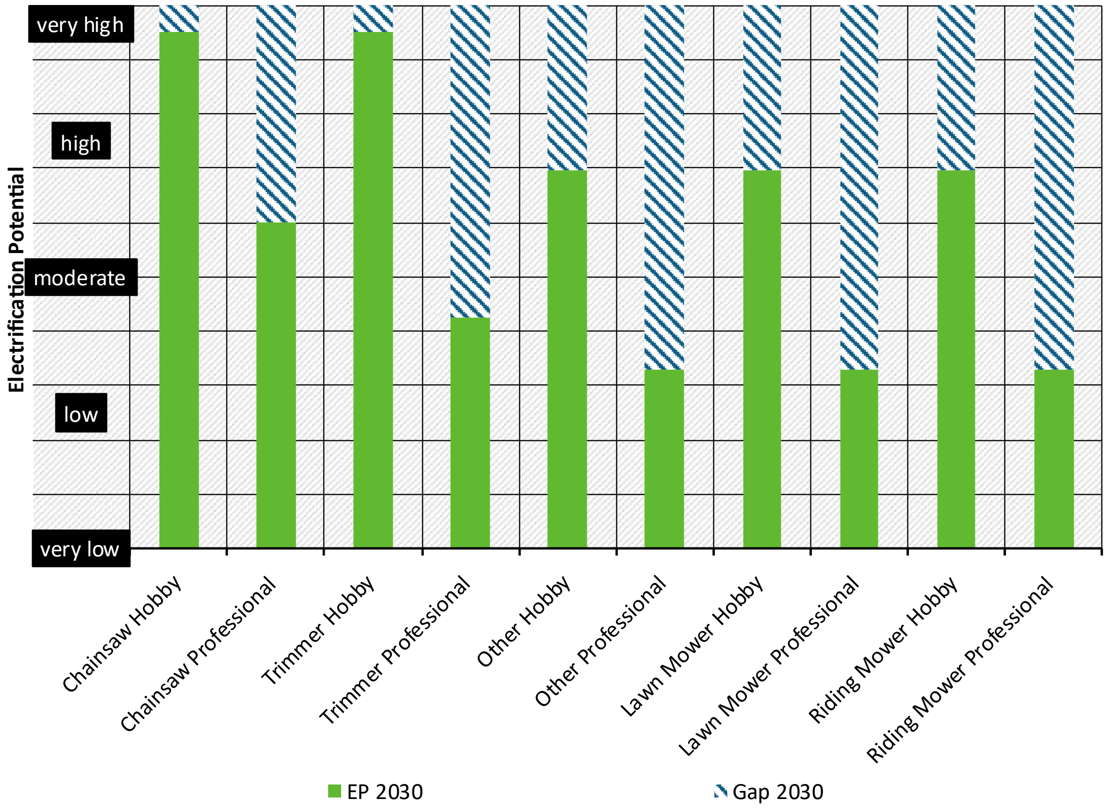


Source: Own illustration by TU Graz

4.3.3.3 Gap

Figure 33 shows the EP results for small machinery NRS and hand-held machinery NRSh in 2030. The blue striped bars illustrate the remaining gap, which cannot be covered by electrification. This gap is especially high in applications with high engine power. A simplified analysis of the hydrogen potential shows that this technology can cover only a few percent of this gap in 2030. Other CO_2 neutral solutions like biofuels or synthetic fuels can also not replace fossil fuels completely due to limited availability at this time. Thus, fossil fuels will play an important role for these machine categories in 2030.

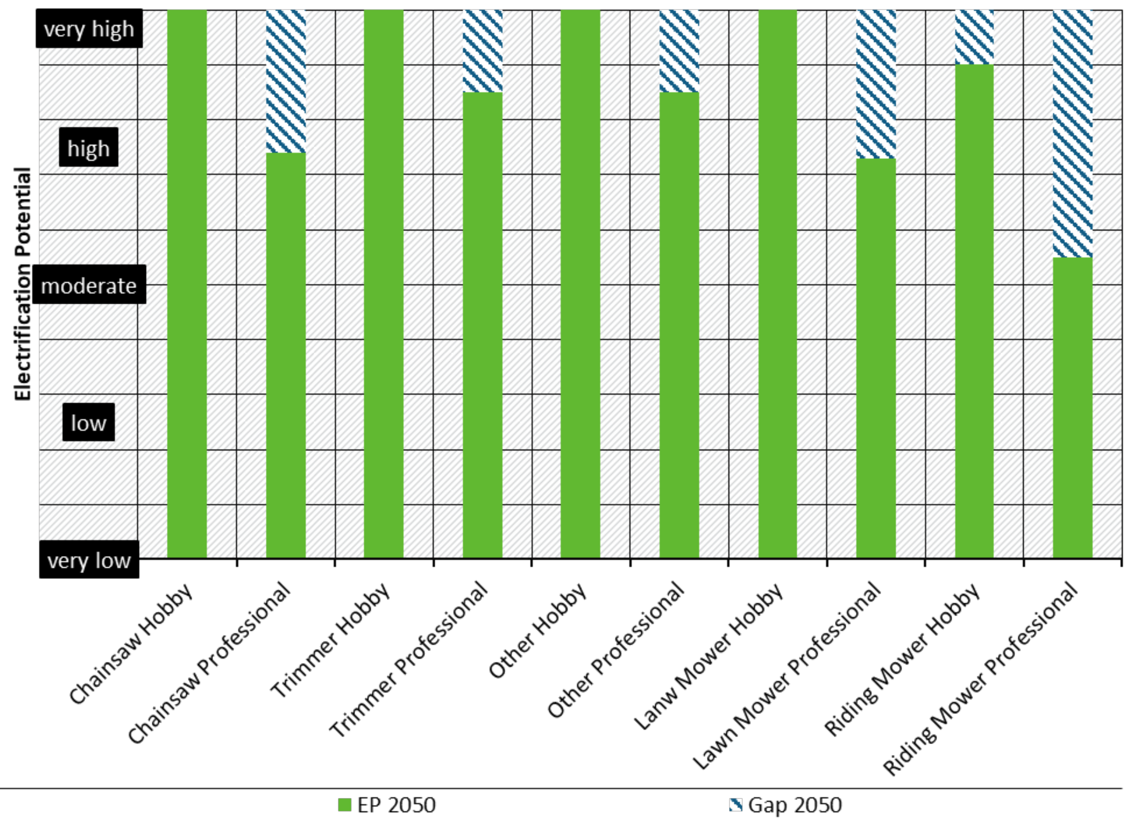
Figure 33: Gap for NRS and NRSh in 2030



Source: Own illustration by TU Graz

Figure 34 shows the gap for small machinery NRS and hand-held machinery NRSh in 2050. The EP increases from 2030 to 2050, but still a gap remains that cannot be covered by electrification. Based on the simplified H_2 potential analysis, hydrogen will cover a bigger part than in 2050 than in 2030. However, the combination of hydrogen and electrification, which is higher than solely electrification, will still leave a considerable share of the CO_2 emissions of the machines uncovered. Thus, other CO_2 neutral options like biofuels or synthetic fuels are needed to reach CO_2 neutrality in the sector NRS and NRSh machinery in 2050.

Figure 34: Gap for NRS and NRSh in 2050



Source: Own illustration by TU Graz

4.3.3.4 Interpretation, discussion and limitations

The results show a high diversity of electrification potential (EP) across different types of application, ranging from low to very high. Therefore, no clear or straightforward grouping of applications into “high” or “low” EP categories is possible.

Despite this heterogeneity, some general trends can be identified for all applications. Those with higher installed power, usually in the operation profile “professional”, tend to show lower electrification potential. Similarly, applications with high daily operating hours generally show lower EP.

Looking ahead from 2030 to 2050, an increase in electrification potential is observed across all applications. These increases are significant but some applications have still an EP of only moderate to high in 2050.

For certain applications and operation profile substantial gaps remain. This highlights the continued need for alternative low-carbon technologies beyond direct electrification.

4.3.4 Powered two-wheelers

This Chapter shows results for the categories two-wheeler with the result for EP. The methodology for powered two-wheelers follows the one for NRS with one exception for the calculation of the factor charging, were there are the additionally to the battery mass the battery volume has to be considered.

Therefore, in the following the calculation methodology for the factor battery is showcased for 2030 for two classes of powered two-wheelers, the small mopeds (L1e-B) and the mid-size motorcycles (L3e-A2) for interrupted operation.

4.3.4.1 Example Calculation factor battery powered two-wheeler

The factor battery depends on the feasibility to use swappable batteries which depends on the battery mass (4.1.1.4). This mass is calculated from the energy demand for maximum trip distance and the specific energy of the battery.

Table 73: Factor battery example calculation two-wheeler

Data	L1e-B	L3e-A2
$E_{trip\ max}$	0.87	13.05
$C_{batt\ trip\ max}$	1.09	16.31
m_{batt}	4.85	72.48
$f_{batt\ mass\ 2W}$	0.81	1.00
$f_{batt\ vol\ 2W}$	0.39	1.81
$f_{Battery}$	1.00	0.55

$E_{trip\ max}$ ... Energy demand for maximum trip distance [kWh]

$C_{batt\ trip\ max}$ ... Battery capacity for maximum trip distance [kWh]

m_{batt} ... Mass of battery for maximum trip distance [kg]

$f_{batt\ mass\ 2W}$ ... Battery mass factor [%]

$f_{batt\ vol\ 2W}$ ... Battery volume factor [%]

$f_{battery}$ ... Factor Battery [-]

Following the same methodology as NRS for the other factors the EP can be calculated (Table 74).

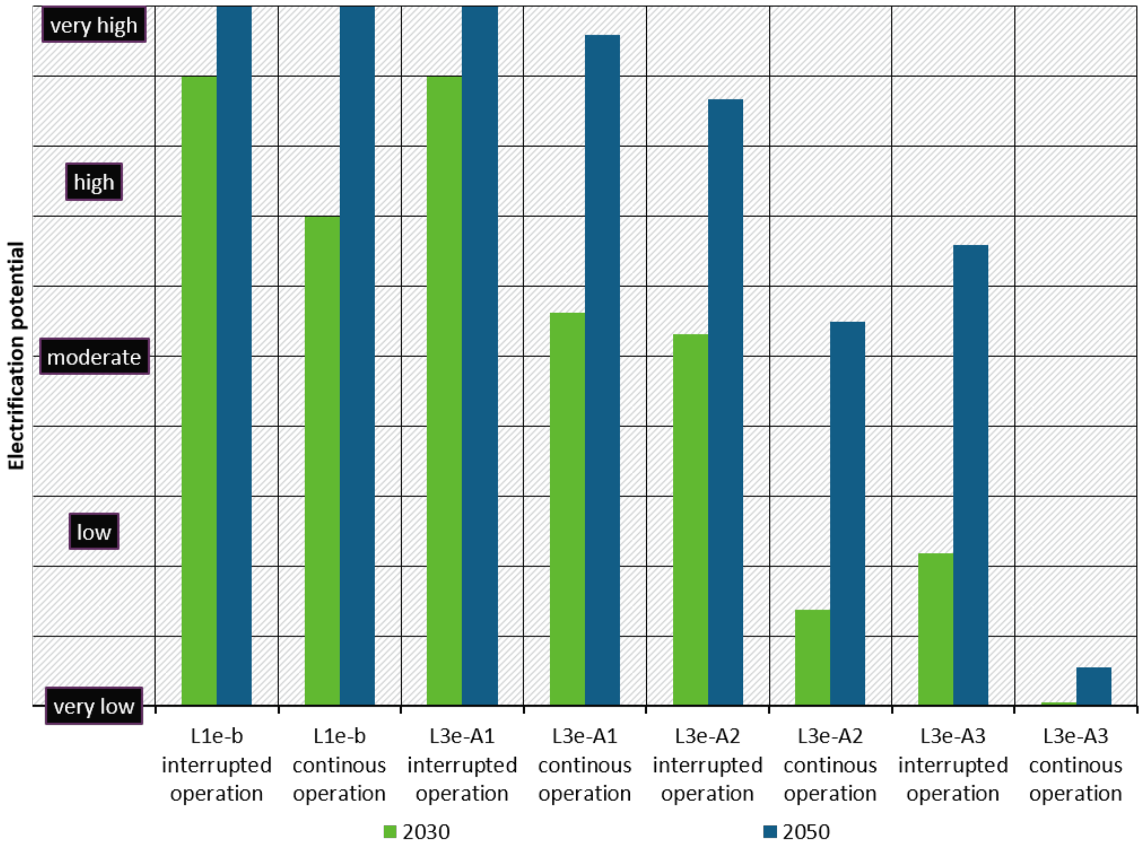
Table 74: Electrification potential example calculation powered two-wheeler

Data	L1e-B	L3e-A2
$f_{battery}$	1.00	0.55
f_{power}	1.00	1.00
$f_{charging}$	1.00	1.00
$f_{infrastruture}$	0.90	0.70
Electrification potential	0.90	0.39

4.3.4.2 Results for powered two-wheelers

The EP for two-wheeler was calculated for the scenarios interrupted operation and continuous operation, which differ by the trip distance between charging (Table 52). In Figure 35 the EP for 2030 and 2050 for the two operation scenarios are shown.

Figure 35: Electrification potentials for BEV category powered two-wheeler

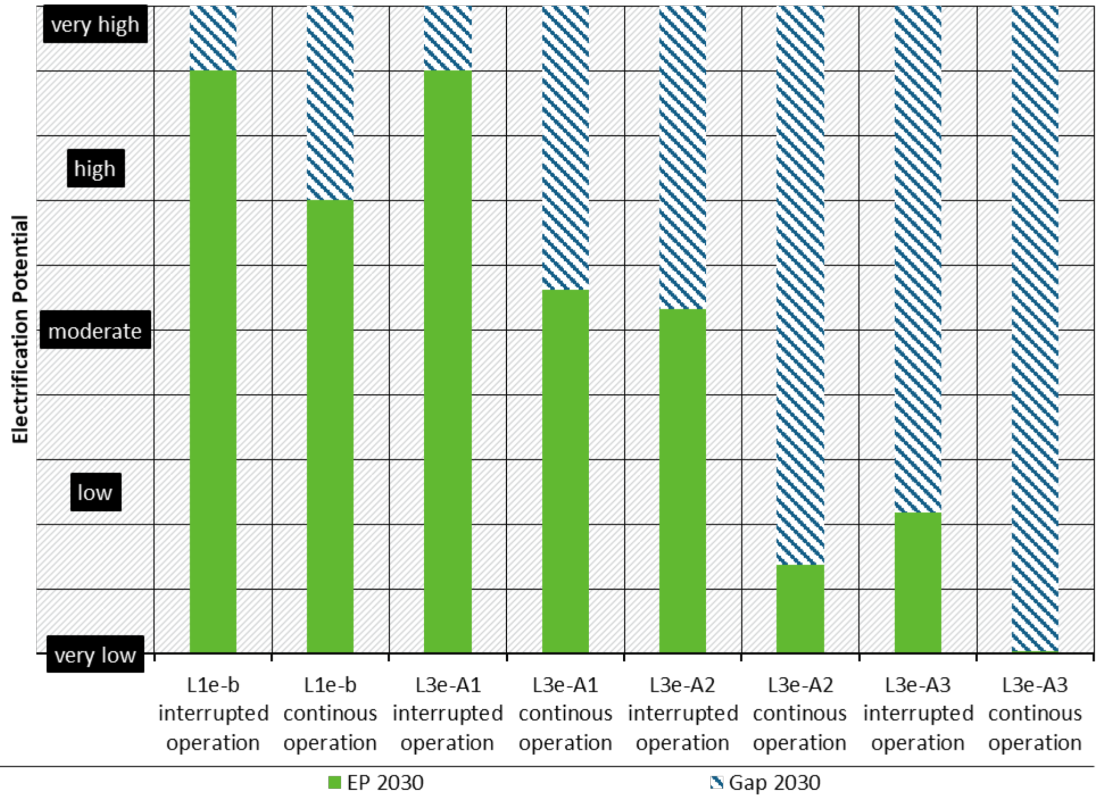


Source: Own illustration by TU Graz

4.3.4.3 Gap for powered two-wheelers

Figure 36 shows the EP results for powered two-wheelers in 2030. The blue striped bars illustrate the remaining gap, which cannot be covered by electrificatsion. This gap is especially high in applications with high engine power. A simplified analysis of the hydrogen potential shows that this technology can cover only a few percent of this gap in 2030 (4.1.2.3). Other CO_2 neutral solutions like biofuels or synthetic fuels can also not replace fossil fuels completely due to limited availability at this time. Thus, fossil fuels will play an important role for these machine categories in 2030.

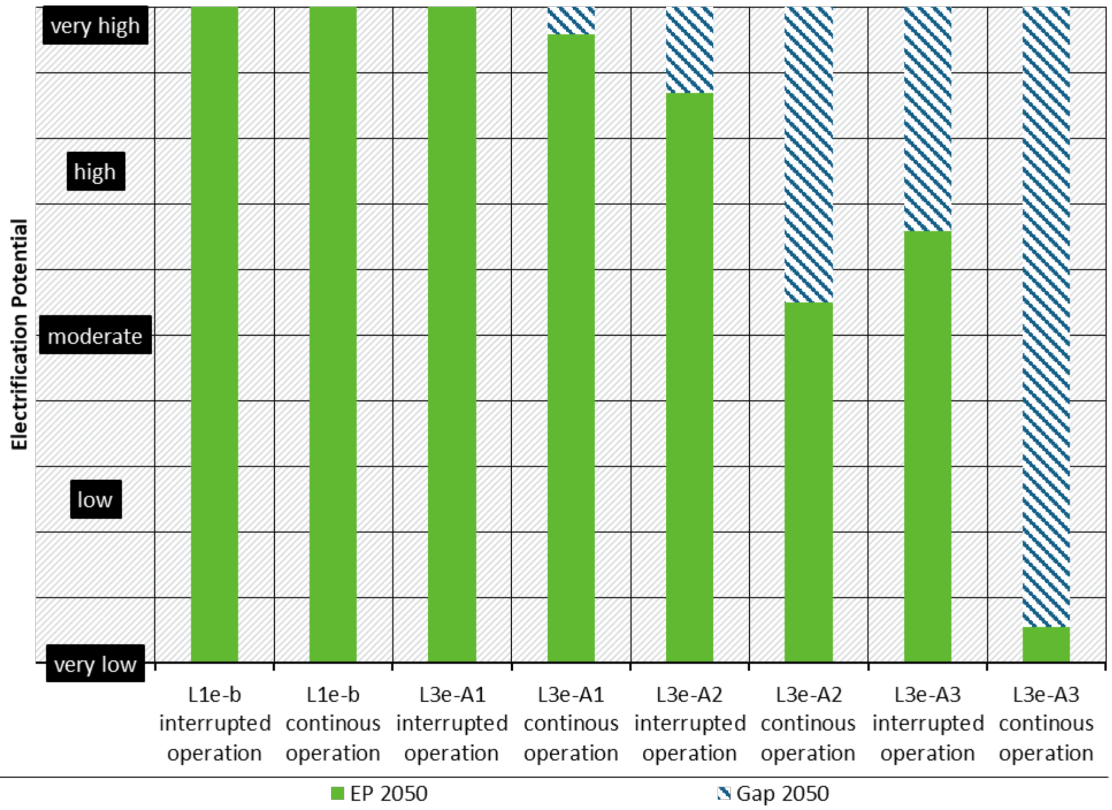
Figure 36: Gap for powered two-wheeler in 2030



Source: Own illustration by TU Graz

Figure 37 shows the gap for powered two-wheelers in 2050. The EP increases from 2030 to 2050, but still a gap remains that cannot be covered by electrification. Based on the simplified H_2 potential analysis, hydrogen will cover a bigger part than in 2050 than in 2030. However, the combination of hydrogen and electrification, which is higher than solely electrification, will still leave a considerable share of the CO_2 emissions of the machines uncovered. Thus, other CO_2 neutral options like biofuels or synthetic fuels are needed to reach CO_2 neutrality in the sector two-wheeler application in 2050; especially for the biggest motorcycles and the use case continuous operation.

Figure 37: Gap for powered two-wheeler in 2050



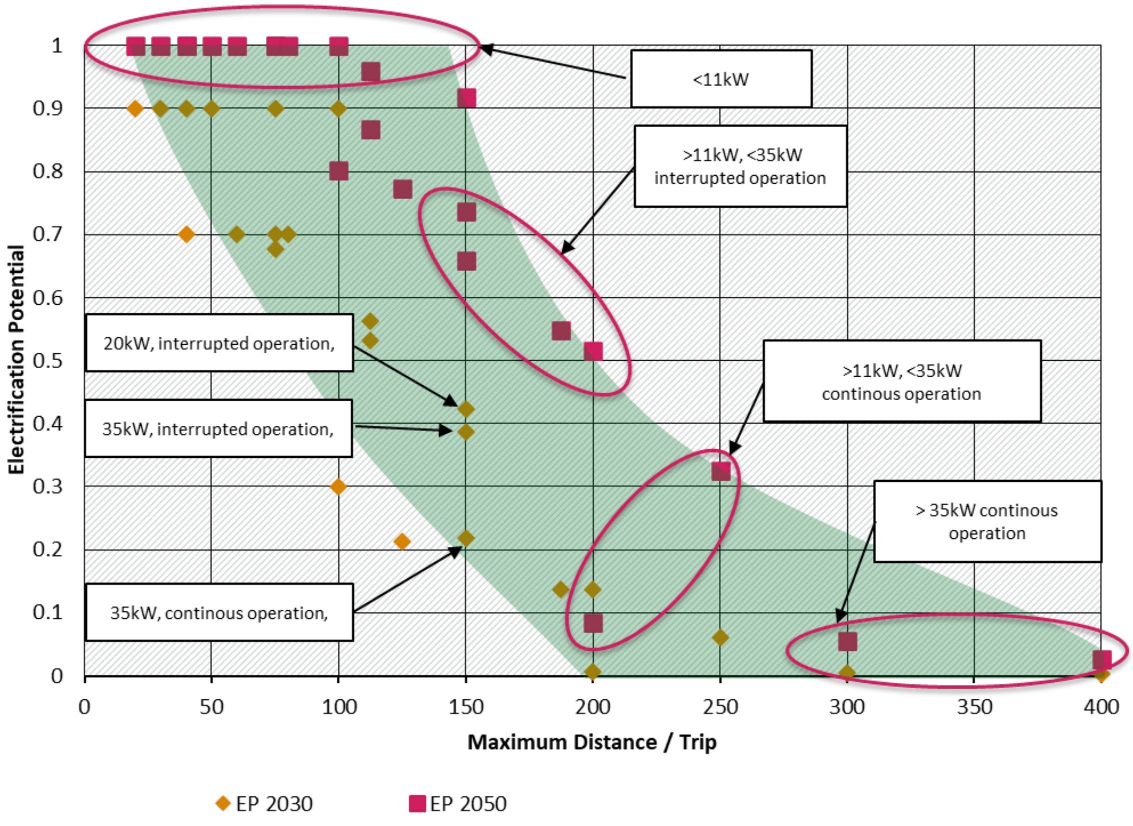
Source: Own illustration by TU Graz

4.3.4.4 Interpretation, discussion and limitations

Similar to other segments, the results show a high diversity of electrification potential (EP) across different vehicle classes, ranging from low to very high. Therefore, no clear or straightforward grouping of vehicle classes into "high" or "low" EP categories is possible.

Despite this heterogeneity, some general trends can be identified for all vehicle classes. Those with higher installed power tend to show lower electrification potential. Similarly, applications with continuous operation profile generally show lower EP. Also, a dependency of the electrification potential on the maximum trip distance can be observed which is shown in the scatter band in Figure 38. Although several other parameters like the type of operation (continous / interrupted) influence the electrification potential, the general tendency "the higher the maximum trip distance the lower the electrification potential" is visible.

Figure 38: Scatter band for electrification potential of powered two-wheelers



Source: Own illustration by TU Graz

Looking ahead from 2030 to 2050, an increase in electrification potential is observed across all applications. These increases are significant but some applications have still an EP of very low to moderate in 2050.

For certain applications and operation profile substantial gaps remain, especially for high-powered two-wheelers with continuous operation. This highlights the continued need for alternative low-carbon technologies beyond direct electrification.

4.3.5 Recreational Crafts

This chapter shows results for the category recreational craft with the result for EP. The methodology for recreational craft follows the one for powered two-wheelers.

4.3.5.1 Results for Recreational Crafts

The EP for recreational crafts was calculated for application types according 4.2.4. For the mapping of the used craft types (CT) for EP to the CO_2 calculation in Chapter 3 the following table was used (Table 75).

Mapping of craft types for EP with craft categories from chapter 3

Table 75: Mapping of craft types for EP with craft categories from chapter 3 (%)

Data	CT 1	CT 2	CT 3	CT 4	CT 5	CT 6	CT 7	CT 8	CT 9	CT 10	CT 11
Motorboat outboard engine ≤ 3kW									100		
Motorboat outboard engine 3 ≤ 12kW										100	
Motorboat outboard engine 12 ≤ 50kW	25		25		25			25			
Motorboat outboard engine > 50kW			50					50			
Motorboat inboard engine SI		100									
Motorboat inboard engine CI < 15kW							100				
Motorboat inboard engine CI 15-50kW								100			
Motorboat inboard engine CI >50kW			100								
PWC's > 12kW				100							
Other boats inboard engine < 15kW							50			50	
Other boats outboard engine 3-12kW						50	50				
Other boats outboard engine >12kW	50							50			

CT ... Craft Type see Table 76

Table 76: Craft type abbreviations

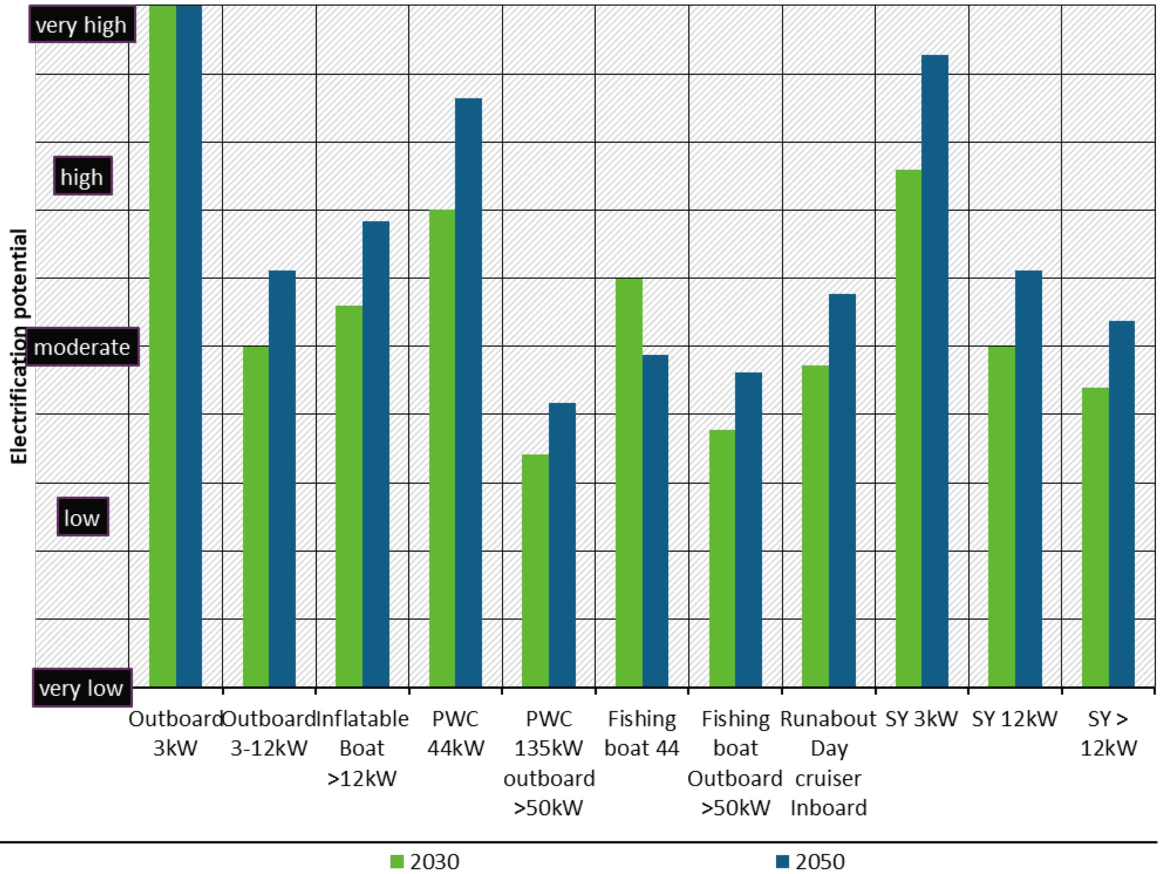
Craft Type (CT)	Description
1	Inflatable Boat 20kW
2	Runabout / day cruiser 260kW
3	Fishing Boat 135kW
4	PWC 44kW
5	PWC 135kW
6	Sailing Boat 3kW
7	Sailing Boat 12kW
8	Sailing Boat 21kW

Craft Type (CT)	Description
9	Outboard 0-3kW
10	Outboard 3-12kW
11	Fishing Boat 44kW

In Figure 39 the EP for 2030 and 2050 for Recreational Crafts are shown. For very low powered outboard and sailing yacht crafts (3kW) the electrification potential is very high to high. For the other craft types and power classes no clear trend is visible as the boundary conditions and restrictions depend strongly on the craft type. For example, in contrast to other sectors, in the medium power sector of outboard and PWC (>3kW–44kW) the EP rises with the power. This is due to the available load and volume capacity for the battery; increased craft power is related to increased craft size and therefor increased load and volume capacity. This is shown also in the Ricardo Study (Zenié et al. 2023) using volume and mass factors for the various craft types. High power leads to high mass and volume factors; in some cases, 5.5 times larger electric powertrain systems than the ICE baseline.

For sailing yachts this trend is contrary as the medium power SY have a very restricted space and load situation. In general, very high power leads to high demand on battery volume and mass and the EP is low to medium for these craft types.
Except for the lowest power category with 3kW, which is at very high in 2030 already, all craft types and power classes show a considerable increase of the EP of ~ 10 % from 2030 to 2050. However, most crafts stay in the medium to high EP range even in 2050.

Figure 39: Electrification potentials for BEV category Recreational Crafts

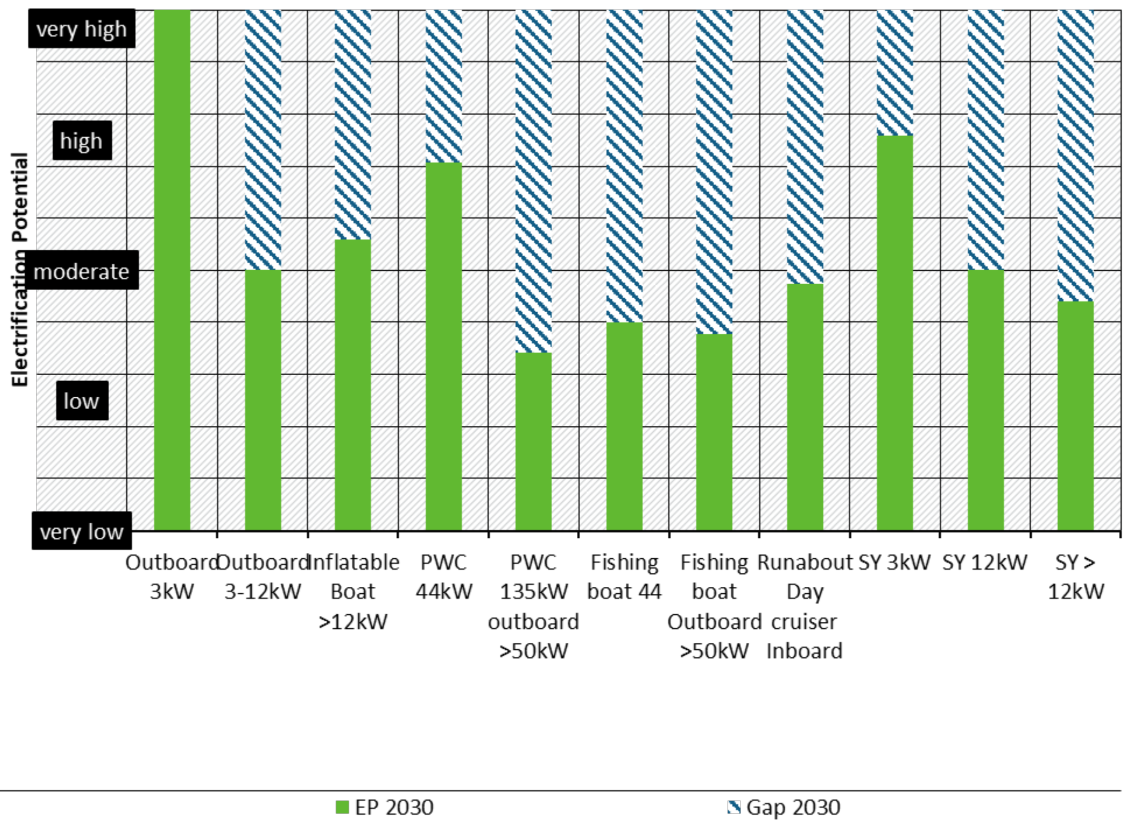


Source: Own illustration by TU Graz

4.3.5.2 Gap for BEV category Recreational Crafts

Figure 40 shows the EP results for recreational crafts in 2030. The blue striped bars illustrate the remaining gap, which cannot be covered by electrification. This gap is especially high in applications with high engine power. A simplified analysis of the hydrogen potential shows that this technology can cover only a few percent of this gap in 2030 (4.1.2.4). Other CO_2 neutral solutions like biofuels or synthetic fuels can also not replace fossil fuels completely due to limited availability at this time. Thus, fossil fuels will play an important role for these categories in 2030.

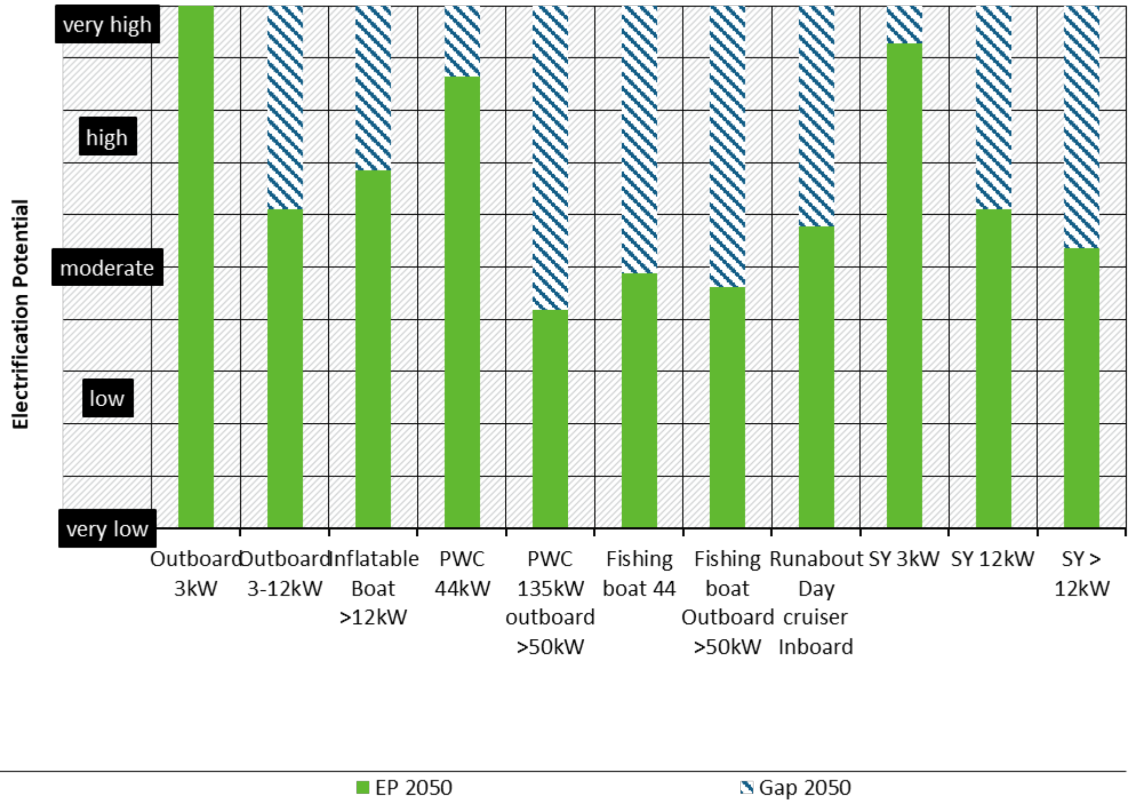
Figure 40: Gap for Recreational Crafts in 2030



Source: Own illustration by TU Graz

Figure 41 shows the gap for recreational craft in 2050. The EP increases from 2030 to 2050, but still a gap remains that cannot be covered by electrification. Based on the simplified H_2 potential analysis, hydrogen will cover a bigger part than in 2050 than in 2030. However, the combination of hydrogen and electrification, which is higher than solely electrification, will still leave a considerable share of the CO_2 emissions of the machines uncovered. Thus, other CO_2 neutral options like biofuels or synthetic fuels are needed to reach CO_2 neutrality in the sector recreational craft in 2050.

Figure 41: Gap for Recreational Crafts in 2050



Source: Own illustration by TU Graz

4.3.5.3 Interpretation, discussion and limitations

Except for very low powered recreational craft types the EP in 2030 is low to moderate with some types being high. No clear or straightforward grouping of crafts into "high" or "low" EP categories is possible.

The EP depends strongly on the operation duration, the possibility for swappable battery use and the feasible battery volume and mass. In contrast to other segments and applications, there is no clear trend regarding the installed power visible.

Looking ahead from 2030 to 2050, an increase in electrification potential is observed across all applications. These increases are rather moderate therefore some applications have still an EP of moderate to high in 2050.

For certain applications and operation profile substantial gaps remain, especially for crafts with long operation duration or with restricted available battery volume and mass. This highlights the continued need for alternative low-carbon technologies beyond direct electrification.

4.4 Sensitivity analysis

Different available data sources and the outcomes of discussions with the consortium partners, industry, other organisations and different experts showed a possible range for specific base values. The final values depend on the source which one uses. This study tries to take the most representative values, but an uncertainty remains, of course. This is especially the case regarding the developments until 2050. To take that into account, the following Chapter shows a sensitivity analysis according to known uncertainties due to ranges in the available values.

The sensitivity analysis conducted for the input data for the model proposed in Chapter 4.1.1 is done regarding the following points:

- The influence of the factor infrastructure
- The influence of available charging power
- Improvement of battery technology
- Adoption of user behaviour
- Three different scenarios regarding the Factor Special solution
- Two different scenarios for the machinery with NRS and NRSh engine categories, powered two-wheelers and recreational craft

Quantifying the effects of these parameters has been done by comparing the average EP for machinery in the Engine categories NRE and NRG. This means all machine sizes are covered by this analysis. The baseline EP for 2030 and for 2050 are 0.58 and 0.60 respectively.

Additionally, a sensitivity analysis has been done for machinery in Engine categories IWA and IWP regarding an increase in available charging power. This work was initialized and supported by an expert discussion with CCNR, which has a comprehensive overview on the inland waterway navigation sector. The experts propose different values than used for the NRE and NRG Sectors.

For the engine categories NRS and NRSh as well as powered two-wheelers and recreational craft two different technology scenarios were calculated, showing the effects of a progressive technology ramp up in contrast to a conservative technology ramp up.

4.4.1 Influence of the factor infrastructure

As mentioned in Chapter 4.1.1.6, available data for the Factor Infrastructure is limited. Thus, an uncertainty remains for this factor. To illustrate the effect of under- or overestimating the availability of infrastructure following steps were taken: For each Segment, the factor infrastructure is increased (scenario “Infrastructure +”) and lowered (scenario “Infrastructure -”) by 0.25.

Table 77 shows the results for the sensitivity analysis done on the Factor Infrastructure. Adjustment of the Infrastructure factor leads to changes in the EP reaching from -28.02 % to 6.55 % depending on the scenario. Thus, a possible overestimation of the Factor Infrastructure would have higher effect than an underestimation.

Table 77: Sensitivity analysis of the Factor Infrastructure

Year	Baseline EP	EP scenario "Infrastructre -"	EP scenario "Infrastructure +"
2030	0.58	0.42	0.61
2050	0.60	0.43	0.64

4.4.2 Influence of available charging power

To illustrate the effect of limited or improved availability of charging power, two scenarios for 2030 and 2050 are calculated for the Sectors NRE and NRG. Scenario "Charging –" limits charging power at 11kW and 20kW for 2030 and 2050 respectively, whereas scenario "Charging +" improves the maximum available charging power by 20 %. The limitation to 11 kW is set according to available charging power in private households, which could be a solution in some use cases, e.g.: a small excavator working on a private ground.

Table 78 shows the effect of these adjustments, which lead to changes in the EP reaching from -31.35 % to 1.32 %. Thus, the effect of a reduction of the charging power (example for 2030: base value: 43 kW, reduction to 11 kW) has a remarkable effect on the Electrification potential, much more than an increase by 20 %.

Table 78: Sensitivity analysis on charging power for Engine categories NRE and NRG

Year	Baseline EP	EP scenario "Charging -"	EP scenario "Charging +"
2030	0.58	0.40	0.59
2050	0.60	0.49	0.60

For the Engine categories IWA and IWP the charging power was increased to 300 kW for 2030 and 2050. The base values are 50 kW for 2030 and 80 kW for 2050. The results can be seen in Table 79. The increases are 25 % for 2030 and about 15 % for 2050. However, the absolute increase is only about 2 % due to the low base values.

Table 79: Sensitivity analysis on charging power for Engine categories IWA and IWP

Year	Baseline EP	EP scenario "IWW Charging +"
2030	0.09	0.11
2050	0.11	0.13

4.4.3 Influence of improved battery technology

To showcase the effect of improvements in battery technology one scenario is calculated for 2030 and 2050. It improves the specifications for specific energy and energy density found in Chapter 4.1.1.4 by 10 %. This leads to an improvement of the EP of 2.89 % for 2030 and 2.10 % for 2050 for the scenario "Battery +", which can be seen in Table 80. Thus, the effect of a possible improvement of the battery specifications of 20 % is low. This can be mainly explained by the high-powered machines, which have such a large power demand, that even improved batteries cannot be installed, due to the high mass and volume.

Table 80: Sensitivity analysis on battery technology

Year	Baseline EP	EP scenario "Battery +"
2030	0.58	0.60
2050	0.60	0.61

4.4.4 Influence of adopted user behaviour

Despite the boundary condition set in chapter 4.1.1.1 requiring the usage of BEM & BEV shall not differ to the original ICE counterpart, one scenario is calculated to showcase the effect of e.g., a lower number of working hours per day. Scenario "Adopted user behaviour" assumes a reduction of 20 % for daily operation. This leads to an increase in EP of 4.17 % for 2030 and 6.3 % for 2050, which can be seen in Table 81. However, the impact is low compared to other measures.

Table 81: Sensitivity analysis on user behaviour

Year	Baseline EP	EP scenario "Adopted user behaviour"
2030	0.58	0.60
2050	0.60	0.64

4.4.5 Influence of the Factor Special solution

The Factor Special solution is assumed to be the same value for all machine Segments, for which the factor is applied. The application of the factor is dependent on the availability of infrastructure and if special solutions exist in principle for a machine Segment (e.g.: catenary operation). A detailed analysis to elaborate separate values for different machine categories is not included in the project capacity. Thus, the effect of the uncertainty coming along with the applied method is analysed in the following.

For analysing the influence of the Factor Special solution, three scenarios are calculated:

- "Special solution –": The Factor Special solution is set to 0.05 instead of 0.1. This leads to a decrease in EP of -0,37 % for 2030 and -0.25 % for 2050. The effect is quite low, since the factor is not applied for all machine Segments.
- "Special solution +": The Factor Special solution is set to 0.2 instead of 0.1. This leads to an increase in EP of 0.82 % for 2030 and 0.59 % for 2050.
- "Special solution all": The Factor Special solution is applied to all Segments. This leads to an increase in EP of 3.46 % for 2030 and 3.14 % for 2050. The effect of applying the factor for a broader number of Segments is higher than increasing the factor itself. However, the effect remains on a low level compared to other measures.

The results can be seen in Table 82.

Table 82: Sensitivity analysis on factor special solution

Year	Baseline EP	EP scenario "Special solution -"	EP scenario "Special solution +"	EP scenario "Special solution all"
2030	0.58	0.58	0.58	0.60
2050	0.60	0.60	0.60	0.62

4.4.6 Scenarios for NRS and NRSh engine machinery

For the machinery equipped with NRS and NRSh engine categories two different scenarios with modified technology parameters were calculated, the conservative scenario which is shown in the chapter 4.3.3 and a progressive scenario with parameters assuming a faster technology increase (Table 83). Additionally, to the technology factor increase an increase in infrastructure availability was assumed, this is shown in Table 84 with the factor infrastructure for the maximum operational variant.

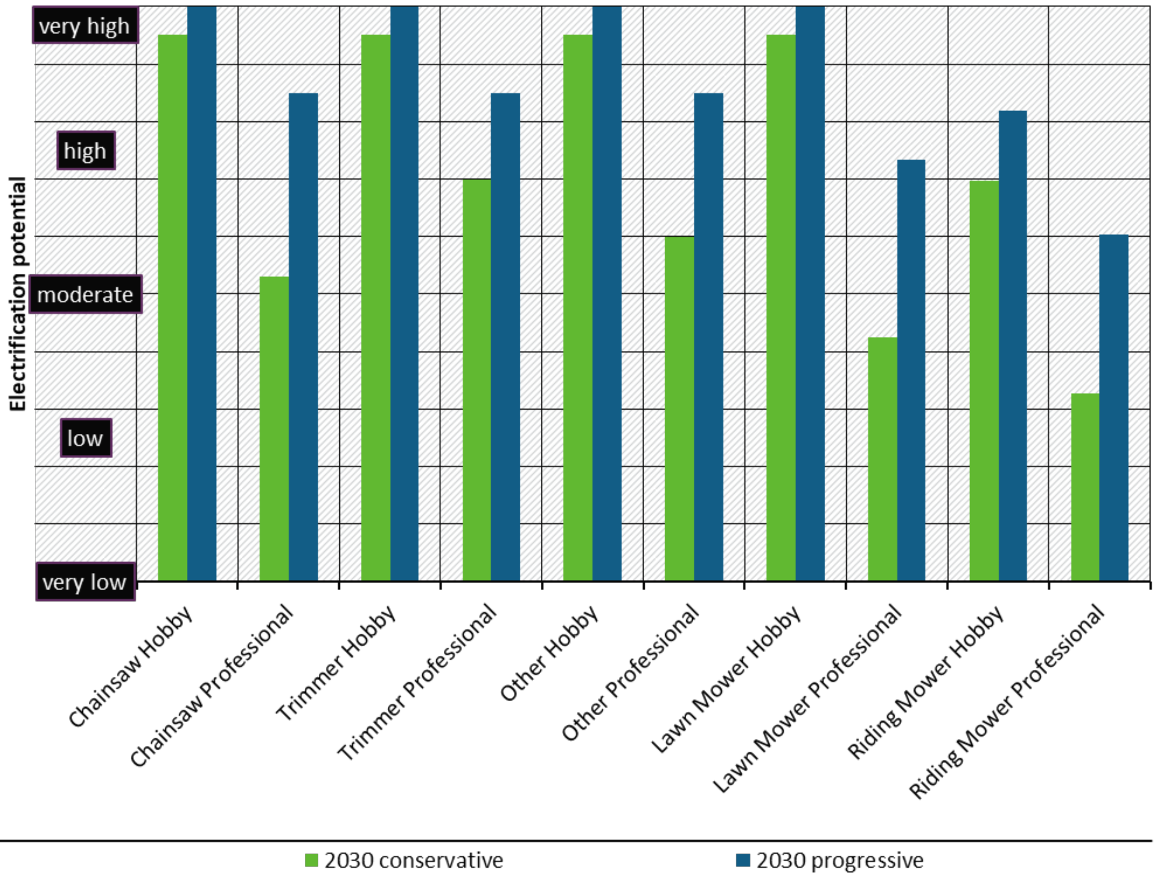
Table 83: Technology data scenario comparison NRS and NRSh

Data	Specific energy battery [kWh/l]	Specific energy battery [kWh/kg]	C-rate charging [h^-1]	C-rate discharging [h^-1]
2030 conservative	0.30	0.23	2.3	13.3
2050 conservative	0.40	0.28	4.0	23.3
2030 progressive	0.45	0.34	3.4	20.0
2050 progressive	0.60	0.42	6.0	35.0

Table 84: Factor infrastructure scenario comparison NRS and NRSh

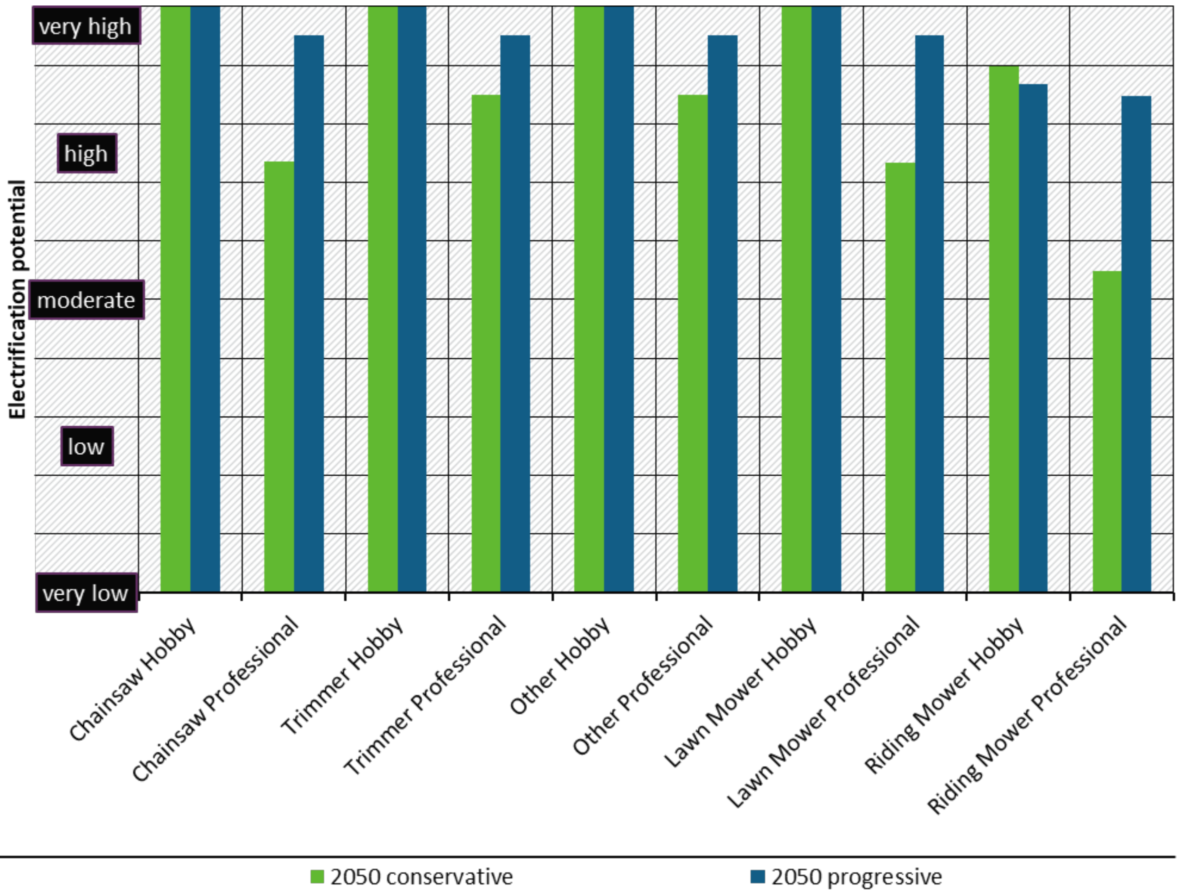
Data	$f_{infrastructure}$ 2030 conservative	$f_{infrastructure}$ 2050 conservative	$f_{infrastructure}$ 2030 progressive	$f_{infrastructure}$ 2050 progressive
Chainsaw Hobby	0.90	1.00	1.00	1.00
Chainsaw Professional	0.50	0.70	0.70	0.90
Trimmer Hobby	0.90	1.00	1.00	1.00
Trimmer Professional	0.50	0.70	0.70	0.90
Other Hobby	0.90	1.00	1.00	1.00
Other Professional	0.50	0.70	0.70	0.90
Lawn Mower Hobby	0.90	1.00	1.00	1.00
Lawn Mower Professional	0.50	0.70	0.70	0.90
Riding Mower Hobby	0.90	1.00	1.00	1.00
Riding Mower Professional	0.50	0.70	0.70	0.90

Figure 42: Electrification potentials for machinery in Engine categories NRS and NRSh sensitivity analysis scenario conservative and progressive for 2030



Source: Own illustration by TU Graz

Figure 43: Electrification potentials for machinery in Engine categories NRS and NRSh sensitivity analysis scenario conservative and progressive for 2050



Source: Own illustration by TU Graz

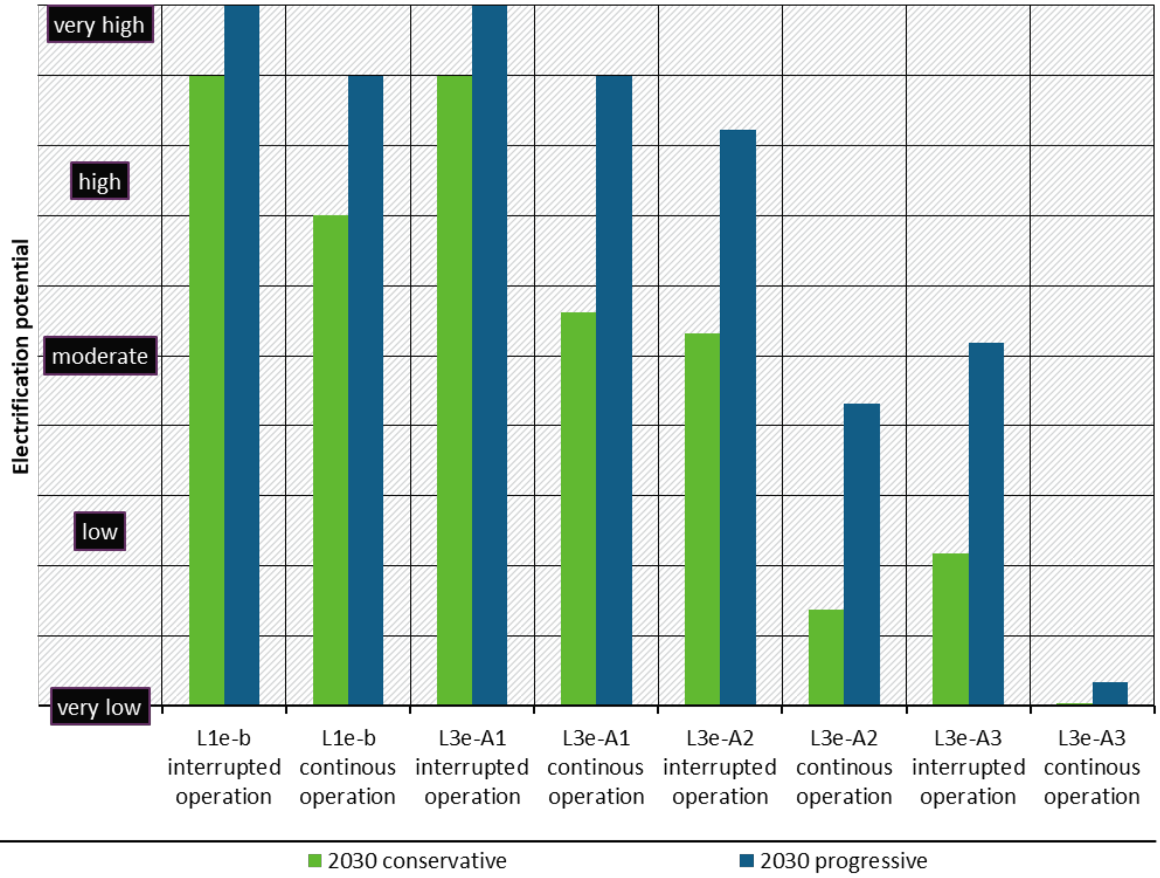
4.4.7 Scenarios for powered two-wheelers

For the two-wheeler category two different scenarios with modified technology parameters were calculated, the conservative scenario which is shown in the chapter 4.3.4.2 and a progressive scenario with parameters assuming a faster technology increase. Additionally, to the technology factor increase an increase in infrastructure availability was assumed, this is shown in Table 85 with the factor infrastructure for the maximum operational variant.

Table 85: Technology data scenario comparison powered two-wheelers

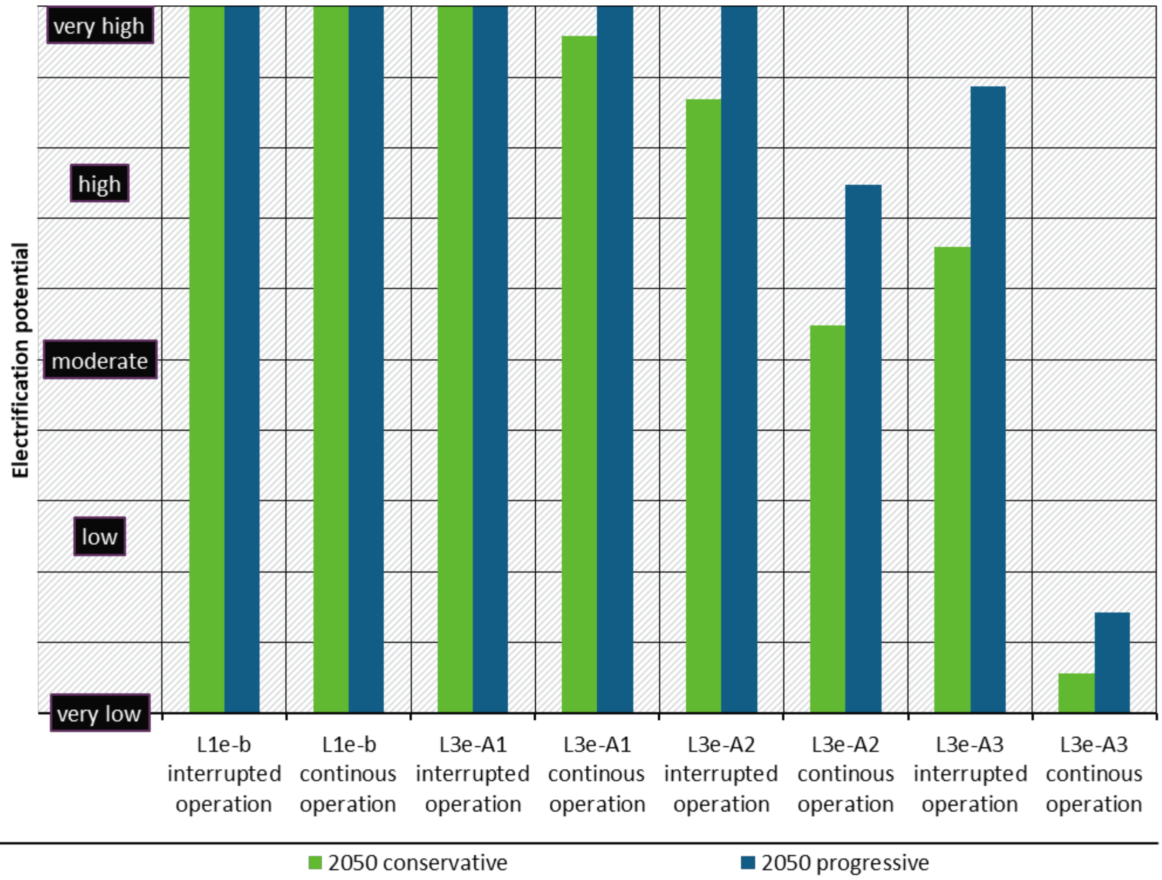
Data	Specific energy battery [kWh/l]	Specific energy battery [kWh/kg]	C-rate charging [h^-1]	C-rate discharging [h^-1]
2030 conservative	0.30	0.27	6.4	12.9
2050 conservative	0.40	0.33	7.9	15.7
2030 progressive	0.45	0.45	9.6	19.3
2050 progressive	0.60	0.60	11.8	23.6

Figure 44: Electrification potentials for powered two-wheelers scenario conservative & progressive for 2030



Source: Own illustration by TU Graz

Figure 45: Electrification potentials for powered two-wheelers scenario conservative & progressive for 2050



Source: Own illustration by TU Graz

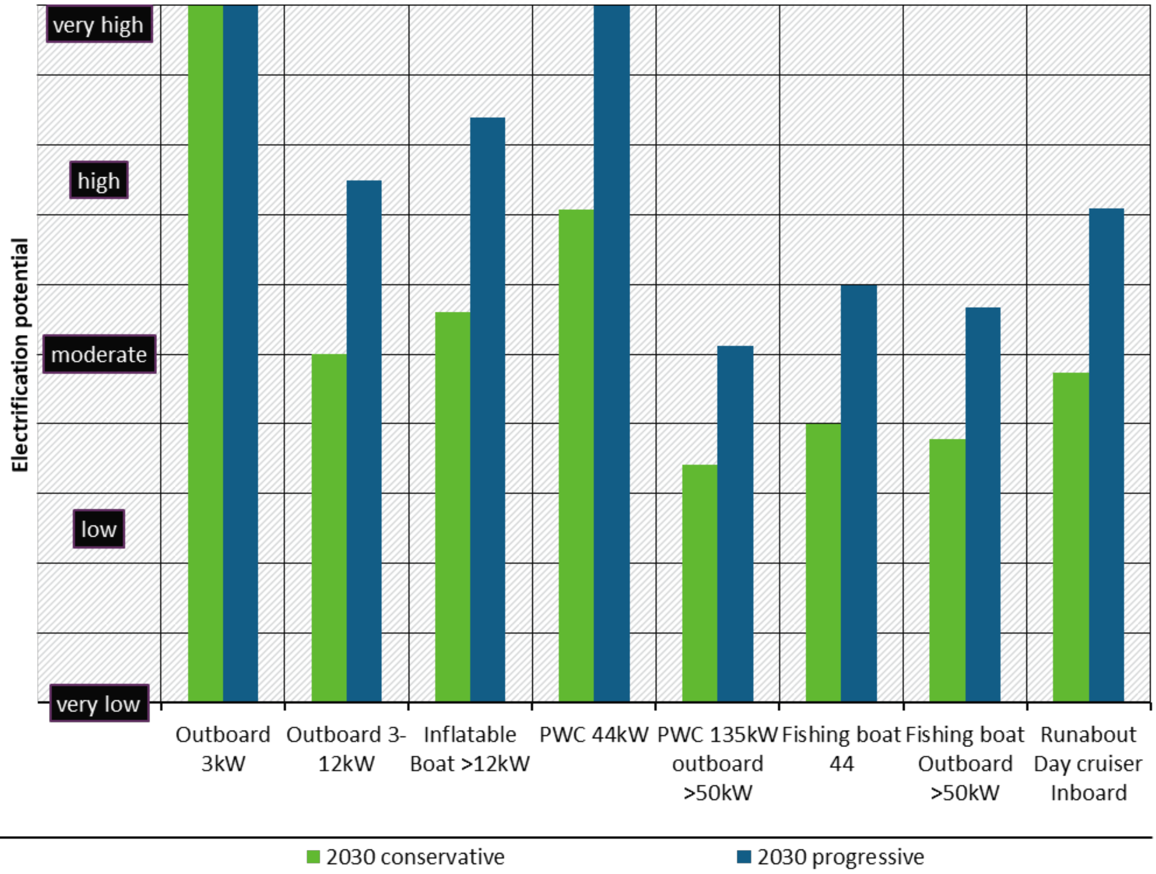
4.4.8 Scenarios for Recreational craft

For recreational crafts two different scenarios with modified technology parameters were calculated, the conservative scenario which is shown in the chapter 4.3.5.1 and a progressive scenario with parameters assuming a faster technology ramp up. The major technology data are shown in Table 86.

Table 86: Technology data scenario comparison Recreational craft

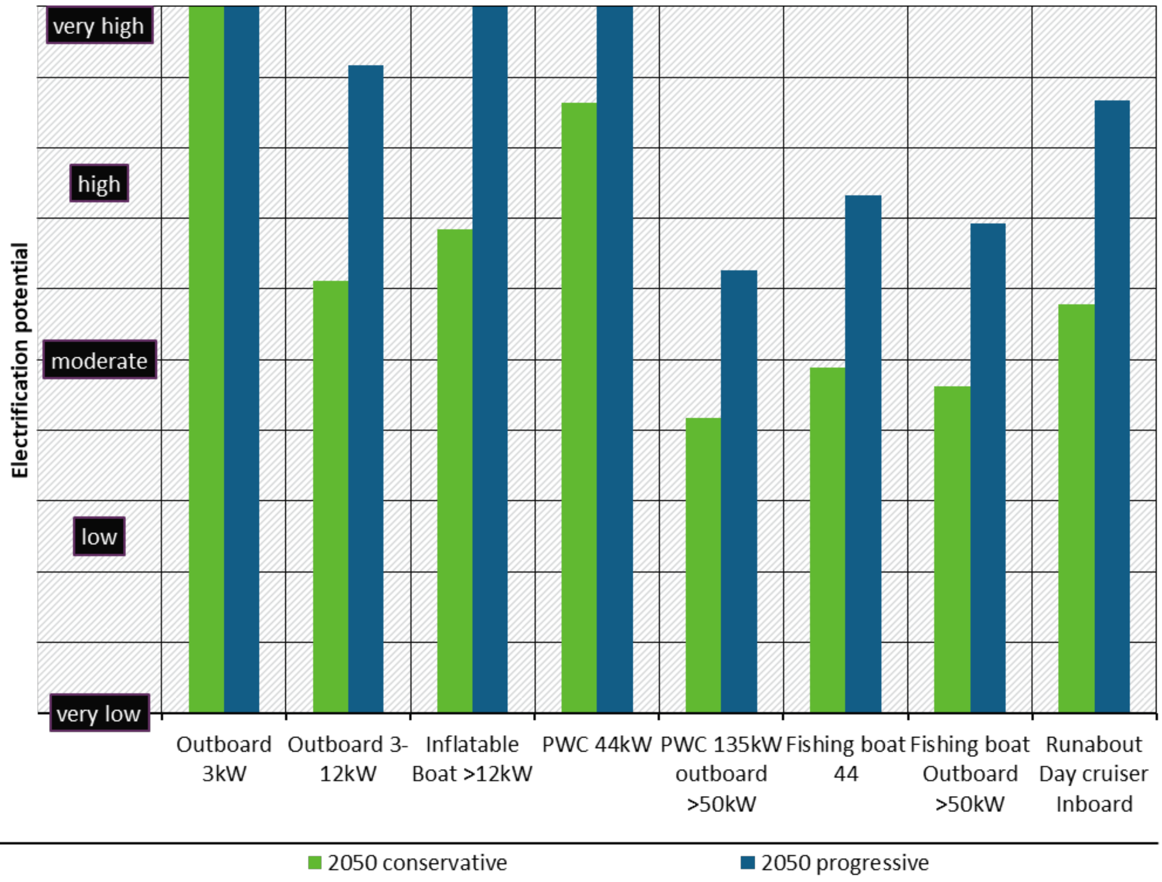
Data	Specific energy battery [kWh/l]	Specific energy battery [kWh/kg]	C-rate charging [h^-1]	C-rate discharging [h^-1]
2030 conservative	0.30	0.18	2.0	12.9
2050 conservative	0.40	0.22	3.5	15.7
2030 progressive	0.45	0.27	3.0	19.3
2050 progressive	0.60	0.33	5.3	23.6

Figure 46: Electrification potentials for recreational craft scenario conservative & progressive for 2030



Source: Own illustration by TU Graz

Figure 47: Electrification potentials for recreational craft scenario conservative & progressive for 2050



Source: Own illustration by TU Graz

4.5 Excurse: Rail

The rail Sector deviates from the typical methodology applied for calculation of the EP applied to other Sectors. Rail infrastructure and rolling-stock investments are expensive, planned over long time horizons (more than ten years), and often led or co-funded by governments in national wide infrastructure plans.

From a technical perspective, the rail Sector can be electrified principally. Using catenary systems is the common approach and is well-approved in many European regions without limitations in the range. Electrification remains the most efficient decarbonization option for most rail use cases. The International Energy Agency (IEA) identifies rail as the “most electrified transport mode” globally and states that high-throughput and intercity corridors will “have to be electric” to align with net-zero pathways (IEA 2025). Countries with established rail systems already demonstrate this pattern: for example, over 90 % of rail traffic (measured in train-kilometres) in Austria is powered by electricity despite only ~74 % of the track being electrified, showing the strong preference for electric traction on the busiest routes (Minarik, Walch 2021).

However, Diesel traction is present and remains an option on regional or rural lines. A short-term change of these systems towards electrification is challenging due to long-term planning periods for such infrastructure projects. This effect of long-term planning must be taken into account for the calculation of the electrification potential in the rail Sector in addition to the technological feasibility.

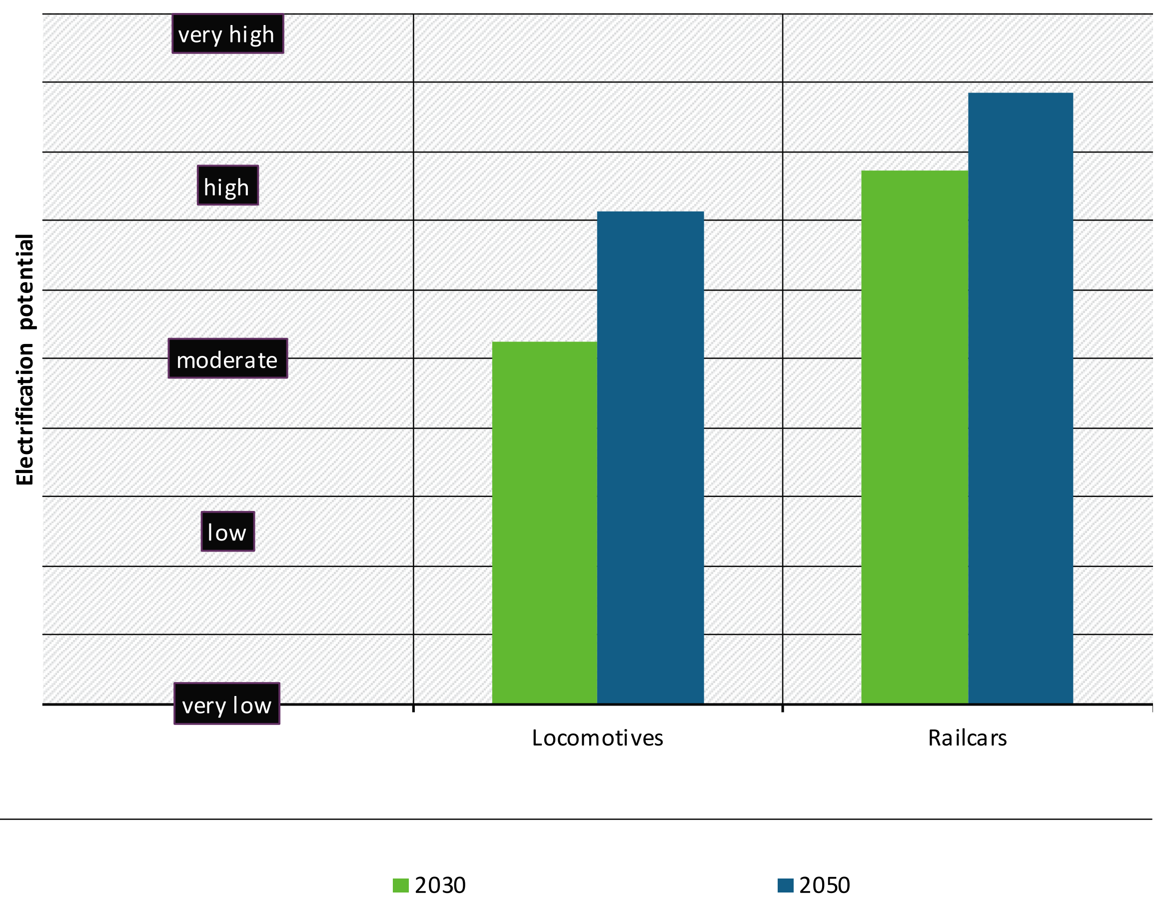
For these reasons, EP of the rail Sector is determined by looking at the share of new registrations for diesel and electric locomotives and railcars, which represent the long-term plans for the rail Sector. UNIFE states a share of 20 % for diesel and 80 % for electric machinery until the end of 2029. IEA forecasts a share of 20 % for diesel and 80 % for electric machinery for 2030 and a share of 10 % for diesel and 90 % for electric machinery in 2050 (IEA 2019). These trends (relative change from 2025 to 2030 and relative change from 2025 to 2050) are applied to the current share of new registrations in EU27 for 2025, leading to the results for 2030 and 2050.

Other alternative propulsion technologies such as hydrogen or battery-electric trains can serve as viable replacements for diesel propulsion. However, studies consistently show that their deployment potential is limited to specific, low-density Segments of the network. For instance, European analyses estimate that hydrogen trains could replace roughly 10–40 % of diesel operations by 2030 depending on utilisation and infrastructure conditions (Ruf 2019).

Results for Engine categories RLL and RLR

Figure 48 shows the EP results for the Engine categories RLL and RLR in 2030 and 2050.

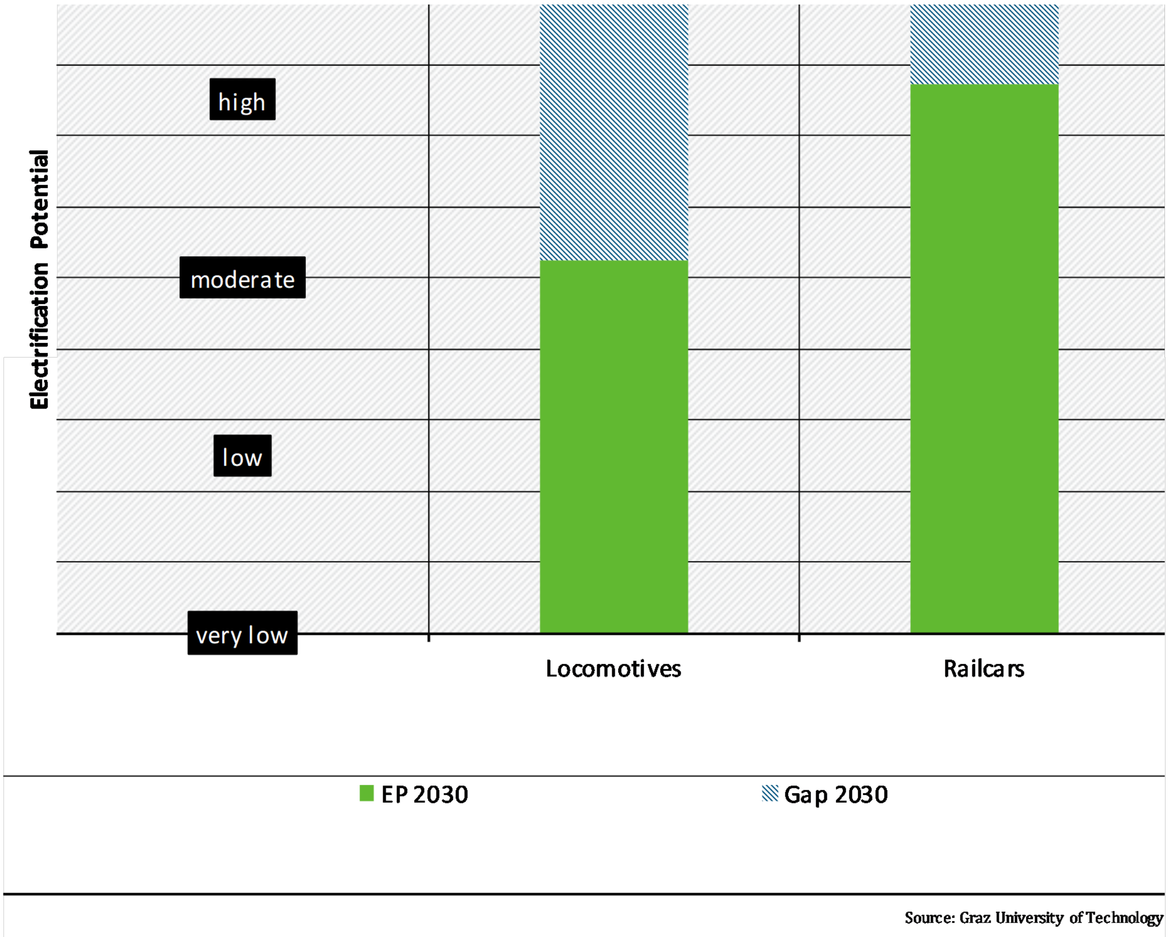
Figure 48: Electrification potentials for machinery in Engine categories RLL and RLR



Source: Own illustration by TU Graz

Figure 49 shows the EP results and remaining gap for the Engine categories RLL and RLR in 2030.

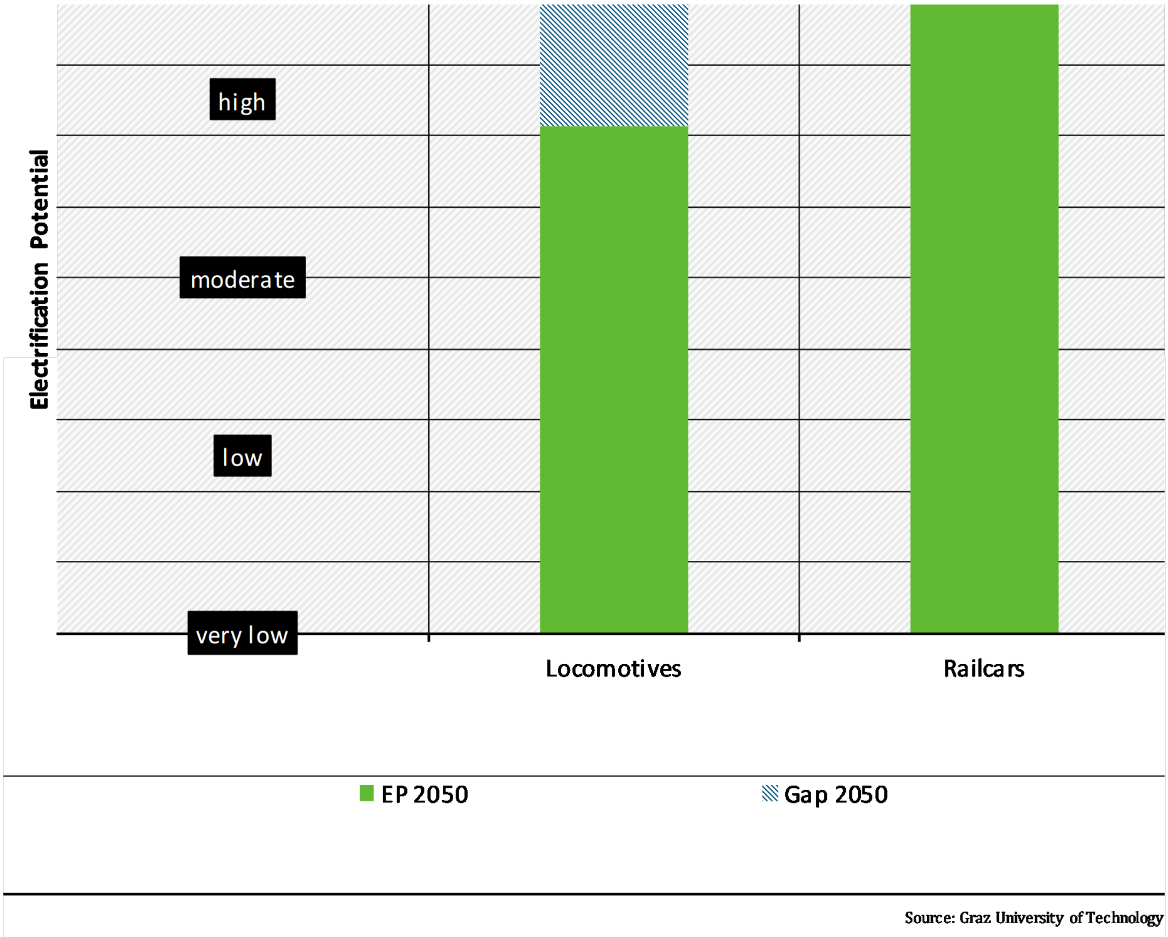
Figure 49: Gap for machinery in the Engine categories RLL and RLR in 2030



Source: Own illustration by TU Graz

Figure 50 shows the EP results and remaining gap for the Engine categories RLL and RLR in 2050.

Figure 50: Gap for machinery in the Engine categories RLL and RLR in 2050



Source: Own illustration by TU Graz

4.6 Excurse: Total cost of ownership (TCO) analysis

As the aim of this study is to analyse the technological feasibility, economic factors are not considered when determining the EP or H_2 potential. To get a principal idea on this very crucial topic for market acceptance, a TCO analysis for a few select examples is done.

Main aspects considered in the TCO are:

- Initial purchase value (IPV) of the machinery. At this point the resale value is uncertain for electrified machines, because there is no market existing. For this reason, the resale value is not considered.
- Fuel and energy costs for the usage phase of the machine
- Maintenance and insurance costs
- Charger installation costs (for BEM & BEV)

The TCO analysis is conducted for three machines:

- A mini excavator, 14.8 kW

- A crawler excavator, 110 kW
- A wheel loader, 228 kW

Energy demand is calculated using the same operational data gathered in Chapter 4.2.

The depreciation period is set to seven years. This value is based on expert discussions. Expert discussions show that in these seven years no battery change is needed. Thus, this point is not included in the calculation.

For results of the TCO analysis see Chapter 4.6.2.

Depreciation and second/third life for NRMM

While depreciation and resale value are a deciding factor when acquiring conventional NRMM machinery, it is difficult to predict how the second-hand market for electric options will behave. Currently, there is no second-hand market for eNRMM and thus no evaluation is possible. In addition, for users acquiring used machinery, it becomes important to consider the costs of setting up charging infrastructure to operate electric machinery.

Key points for initial owners and second/third life are:

- Higher initial purchase value compared to conventional NRMM
- Possible differences in depreciation
- Costs for setting up charging infrastructure

4.6.1 Fuel and energy prices

Predicting energy and fuel prices for 2030 and 2050 respectively lies out of the scope for this study. For this reason, the prices (for fuel and energy) used in the TCO analysis are derived from literature sources and current fuel and energy prices. The prices for scenario "UBA" stem from (Prognos 2025).

The prices used for the calculation can be seen in Table 87.

Electricity:

For 2030 electricity prices in scenario A and C are based on current rates for energy in Germany seen as representative for Europe. Scenario A represents the industrial electricity price as a best case and scenario C prices at a public supercharging station as a worst-case scenario.

For Electricity prices it is assumed, that increased production capacity and availability lead to a constant price of electricity when adjusted for inflation.

Fuel:

Fuel prices for 2030 in scenario A and C are derived from current market prices for diesel fuel in Europe (Benzinpreis-Aktuell 2025).

For 2050 only carbon-neutral diesel fuel are eligible for use in any traditional ICE in accordance to the climate goals set out by the European commission in Regulation (EU) 2021/1119[6]. This

[6] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')

can be bio- or synthetic fuels. The range for the costs in 2050 is high due to high uncertainty regarding market developments.

Table 87: Fuel and energy price scenarios

Technology	Unit	Scenario A	Scenario C	Scenario UBA
Diesel 2030	[2030 EURO/L]	€ 1.95	€ 2.54	€ 2.57
Diesel* 2050	[2030 EURO/L]	€ 1.52	€ 2.90	€ 2.91
Electricity** 2030	[2030 EURO/kWh]	€ 0.23	€ 1.21	€ 0.50
Electricity** 2050	[2030 EURO/kWh]	€ 0.23	€ 1.21	€ 0.50

*Carbon-neutral diesel fuel

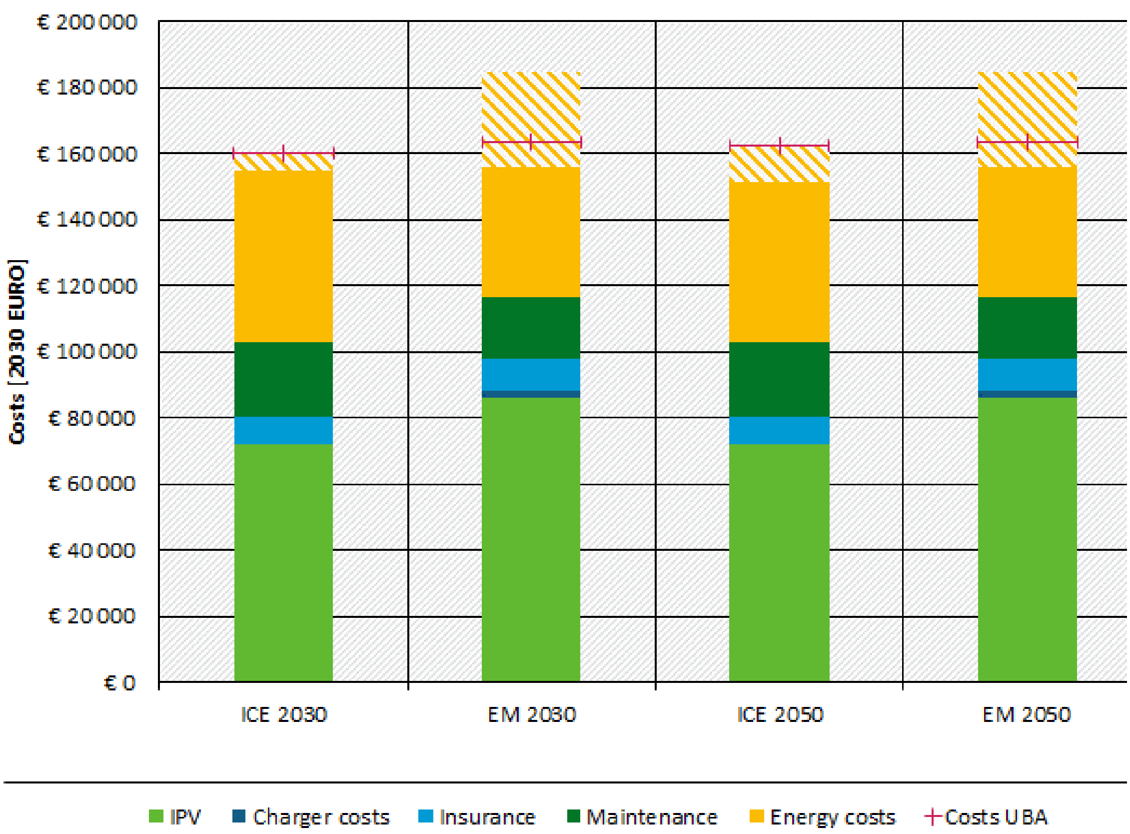
**Prices for purchased energy, no production

4.6.2 Results

As discussed in Chapter 4.6, a TCO analysis is done for three different machines. The results of the TCO analysis can be seen below.

Figure 51 shows the results of the TCO analysis done for a mini excavator with an installed engine power of 14.8 kilowatts.

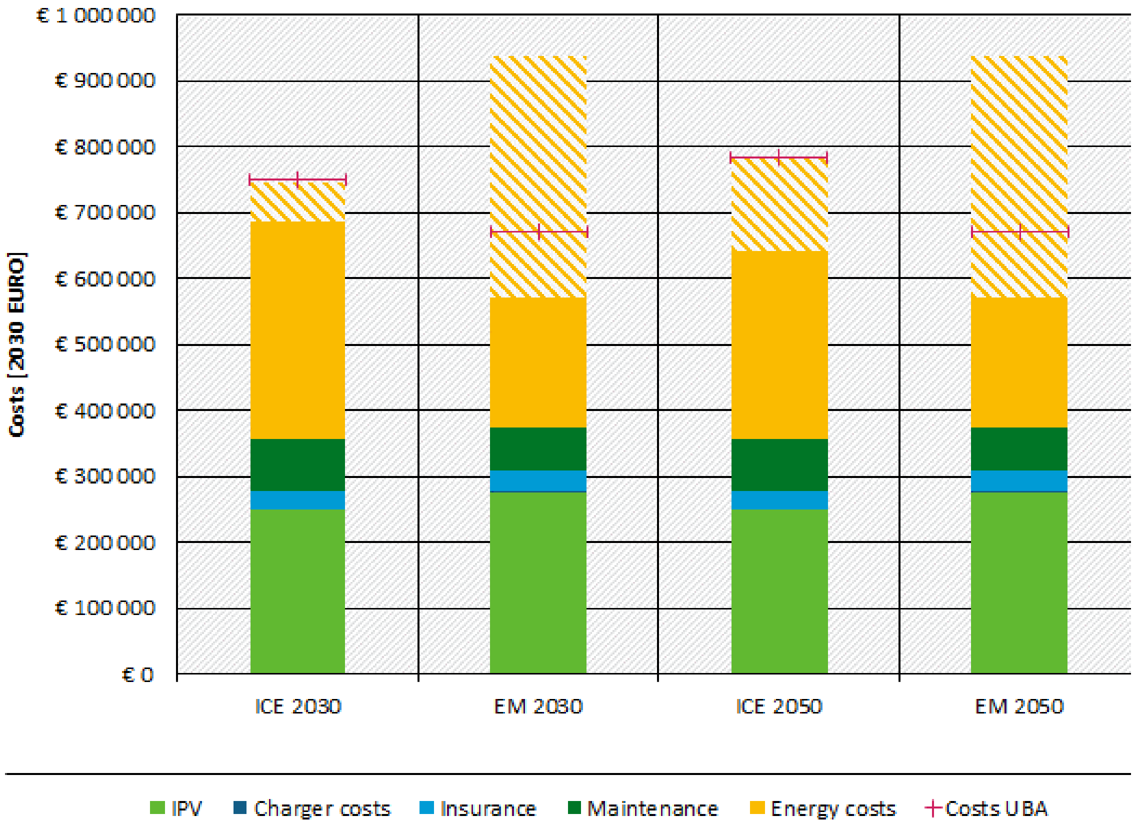
Figure 51: TCO Analysis for Mini Excavator 14.8 kW



Source: Own illustration by TU Graz. Costs UBA refers to TCO with energy prices by the UBA scenario (see previous section)

Figure 52 shows the results for the TCO analysis done for a crawler excavator with an installed engine power of 110 kilowatts. Compared to the mini excavator, energy costs make up a larger portion of the total costs. This is due to higher engine power and a higher utilization, both leading to a higher energy demand.

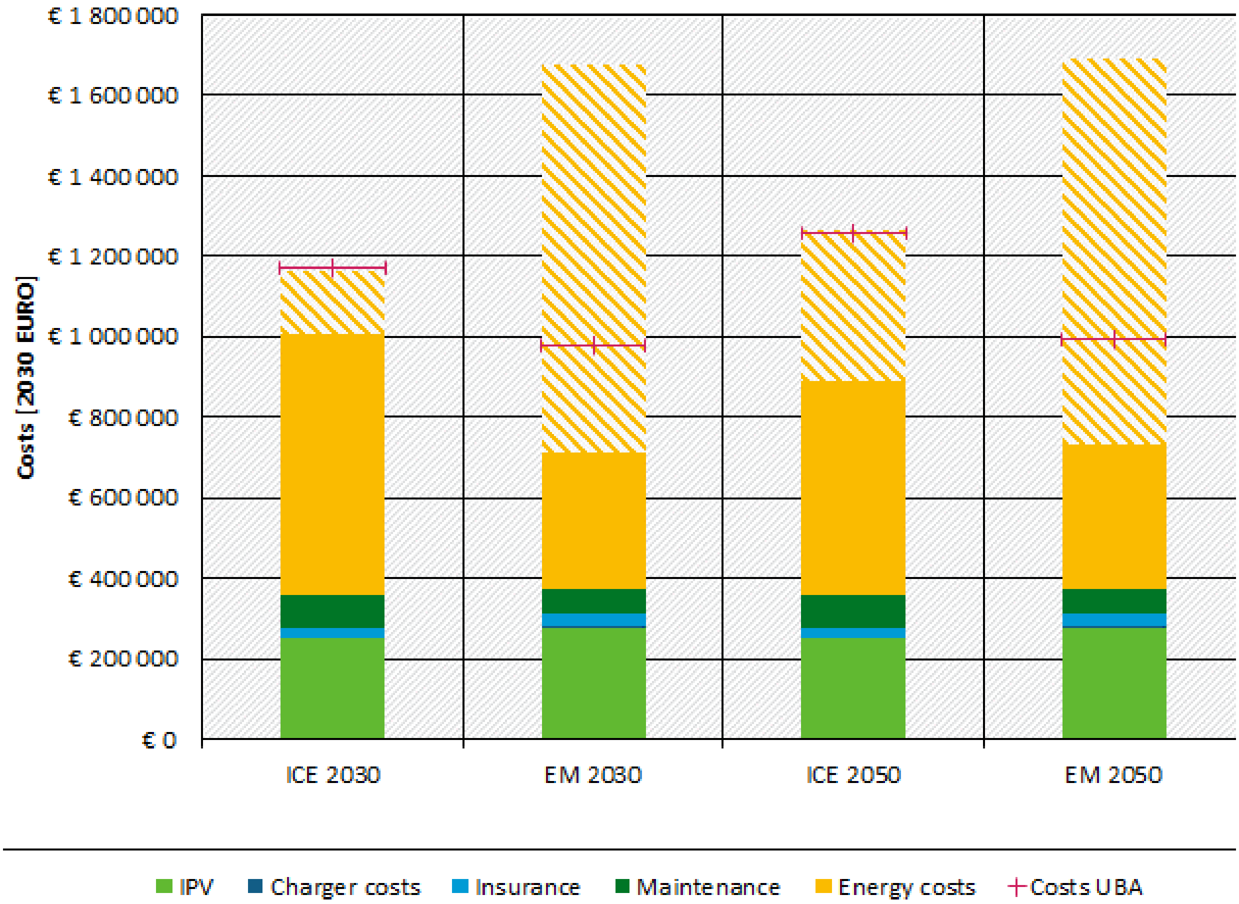
Figure 52: TCO Analysis for Crawler Excavator 110 kW



Source: Own illustration by TU Graz. Costs UBA refers to TCO with energy prices by the UBA scenario (see previous section)

Figure 53 shows the results for the TCO analysis done for a wheel loader with an installed engine power of 228 kilowatts. Comparatively, the energy costs make up for an even larger portion than for the crawler excavator.

Figure 53: TCO Analysis for Wheel Loader 228 kW



Source: Own illustration by TU Graz. Costs UBA refers to TCO with energy prices by the UBA scenario (see previous section)

5 Policy options for electrification

5.1 Supply side regulations related to NRMM in Europe

There are no supply side regulations aimed at reducing the greenhouse gas emissions of NRMM in the EU at present. Such regulations are not commonplace globally, with limited examples only available in California.

Despite this, regulations currently exist which lay out requirements of on the level of pollutant emissions under regualtion (EU) 2016/1628[7]. – Stage V – specifically carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM) and particulate numbers (PN).

Regulations also exist regarding the type-approval procedures for certain road-going NRMM as well as requirements on the health and safety procedures for non-mobile machinery.

To ease the regulatory burden on manufacturers, a future regulation aimed at reducing GHGs and/or increasing the share of zero-emission NRMMs could be considered to be created through amendments to some of these pre-existing regulations. As such, a description of the existing regulations as they relate to NRMMs is presented here.

5.1.1 Stage V

The first emission standards for NRMM engines in the EU were adopted in 1997 under Stage I Directive 97/68/EC[8]. Stage I established the initial pollutant limits for non-road internal combustion engines and formed the regulatory foundation for all subsequent stages, including Stage II, IIIA/IIIB, IV, and most recently Stage V. Stage I originally applied to engines with a rated power between 18 kW and 560 kW and set limits on the emission of carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and particulate matter (PM).

Over the proceeding amendments, the NRMM regulatory framework introduced stricter limits on these pollutants, expanded the scope to engines below 18 kW and above 560 kW, and introduced particulate number. The current commanding regulation, Stage V established by Regulation (EU) 2016/1628, was adopted in 2016.

The Stage V-requirements began to apply from 1 January 2019, with phased implementation depending on engine power categories[9] and application timelines. A list of the emission limits for the NRE engine category, the most common in the NRMM sector, is presented in Table 88. By comparison, the limits for CI engines in on-road heavy-duty applications under the latest Euro 7 regulation are 0.2 g/kWh for NOx, 0.008 g/kWh for PM, and 1.5 g/kWh for CO according to Regulation (EU) 2016/1628.

[7] Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013, and amending and repealing Directive 97/68/EC.

[8] Directive 97/68/EC of the European Parliament and of the Council of 16 December 1997 on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery

[9] Stage V applies to engines in non-road spark-ignition engines below 56 kW (NRS), hand-held spark-ignition engines below 19 kW (NRSh), generating sets above 560 kW (NRG), inland waterway vessel propulsion engines (IWP), inland waterway vessel auxiliary engines (IWA), railway locomotive engines (RLL), railcar engines (RLR), spark ignition snowmobiles (SMB), spark ignition all-terrain vehicles (ATS) and general non-road engines that fall outside of these categories (NRE).

Table 88: Emission limits for NRE within Stage V. Note: v = variable-speed engine, c = constant-speed engine, CI = compression ignition.

Engine Subcategory	Power Range (kW)	Ignition Type	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	PM (g/kWh)	PN (#/kWh)	A
NRE-v-1 / NRE-c-1	0 < P < 18	CI	8.00	$HC+NO_x \le 7.50$		0.40	—	1.10
NRE-v-2 / NRE-c-2	18 ≤ P < 19	CI	6.60	$HC+NO_x \le 7.50$		0.40	—	1.10
NRE-v-3 / NRE-c-3	19 ≤ P < 37	CI	5.00	$HC+NO_x \le 4.70$		0.015	1×10^{12}	1.10
NRE-v-4 / NRE-c-4	37 ≤ P < 56	CI	5.00	$HC+NO_x \le 4.70$		0.015	1×10^{12}	1.10
NRE-v-5 / NRE-c-5	56 ≤ P < 130	All	5.00	0.19	0.40	0.015	1×10^{12}	1.10
NRE-v-6 / NRE-c-6	130 ≤ P ≤ 560	All	3.50	0.19	0.40	0.015	1×10^{12}	1.10
NRE-v-7 / NRE-c-7	P > 560	All	3.50	0.19	3.50	0.045	—	6.00

While greenhouse gases such as CO_2 are not regulated under Stage V, CO_2 concentrations are still measured during both the transient and steady-state engine test cycles. This measurement is a required part of the emission test methodology as CO_2 is used to determine key parameters such as exhaust mass flow, fuel consumption, and the calculation of pollutant emission levels during the official ISO 8178 test procedures (International Organization for Standardization 2020).

Article 43 of Stage V requires engine manufacturers to make this information on CO_2 measurements available to the OEM who must then communicate that information, together with explanatory information on the test conditions, to the end-user of the NRMM in which the engine is intended to be installed.

Europe has never set CO_2 emission limits at the engine level for on-road or non-road applications. Instead, EU climate policy regulates CO_2 at the vehicle level through fleet-average performance standards. For example, Regulation (EU) 2019/631[10] establishes CO_2 standards for new passenger cars and vans (light-duty vehicles), and Regulation (EU) 2019/1242[11] sets CO_2 standards for new heavy-duty vehicles. Despite this, there is evidence of other jurisdictions which have considered applying CO_2 limits on non-road engines globally, as discussed in Section 5.2.

The responsibility on the implementation of Stage V falls within the Directorate General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) who are also responsible for

[10] Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011.

[11] Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC

conducting a review of the standards. According to the existing regulation a report was due by the 31 December 2020 to be sent to the European Parliament and to the Council regarding:

a) the assessment of further pollutant emission reduction potential, on the basis of available technologies and a cost-benefit analysis.

b) the identification of potentially relevant pollutant types that do not fall within the scope of this Regulation.

This report has not yet been published. When contacted, the European Commission explained the delay due to the ongoing work on in-service monitoring of NRMM emissions. However, initial analyses and recommendations for possible further development already exist from a study conducted for the German Federal Environment Agency (Heidt et al. 2023).

A future revision of Stage V could be harnessed to set limits on the CO_2 emissions from non-road engines, or could promote the uptake of electric vehicles through increase limits on the level of air pollutants currently in place.

5.1.2 Type approval legislation

Type-approval legislation has played a key role in the determination of CO_2 emissions and air pollutants from on-road vehicles, which in turn has allowed standards to be set limiting these emissions. For example, regulation (EU) 2018/858[12] lays down the requirement for on-road vehicles of category N (i.e., goods vehicles) and M (passenger vehicles) to follow the CO_2 determination legislation as laid out by regulation (EC) 595/2009[13] and (EC) 715/2007[14]. Limits on the CO_2 emissions of these vehicles are then set through regulations (EU) 2019/1242 for heavy-duty vehicles and (EU) 2019/631[15] for light-duty vehicles.

Type-approval legislation are more complex in the NRMM sector. Some NRMM categories are required to follow type-approval legislation, while others are not: EU-wide type approval procedures are in place for agricultural and forestry vehicles, two- and three-wheelers, and for certain NRMM which are used partially on public roads.

- Regulation (EU) 167/2013[16] is the type approval legislation for agricultural and forestry vehicles which applies to vehicles of category T and C (tractor), R (trailers), and S (interchangeable towed equipment).

[12] Regulation (EU) 2018/858 of the European Parliament and of the Council of 30 May 2018 on the approval and market surveillance of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles, amending Regulations (EC) No 715/2007 and (EC) No 595/2009 and repealing Directive 2007/46/EC (Text with EEA relevance.).

[13] Regulation (EC) No 595/2009 of the European Parliament and of the Council of 18 June 2009 on type-approval of motor vehicles and engines with respect to emissions from heavy duty vehicles (Euro VI) and on access to vehicle repair and maintenance information and amending Regulation (EC) No 715/2007 and Directive 2007/46/EC and repealing Directives 80/1269/EEC, 2005/55/EC and 2005/78/EC (Text with EEA relevance)

[14] Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information (Text with EEA relevance).

[15] Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011 (recast) (Text with EEA relevance.)

[16] Regulation (EU) No 167/2013 of the European Parliament and of the Council of 5 February 2013 on the approval and market surveillance of agricultural and forestry vehicles Text with EEA relevance

- Regulation (EU) 168/2013[17] is the type approval legislation two- or three-wheel vehicles and quadricycles which applies to vehicles of category L that are intended to travel on public roads.
- Regulation (EU) 2025/14[18] is the type-approval legislation for NRMMs that are intended for circulation on public roads. However, it does not apply to vehicles with a maximum design speed above 40 km/hour or below 6 km/hour. It applies from 2028 but Member States can continue to grant their own national type approval until 2036.

Many different NRMM categories covered in the scope of this project are not covered by type approval legislation, but rather by (EU) 2023/1230[19], also known as the Machinery Regulation. The Machinery Regulation repealed the previous Machinery Directive (2006/42/EC)[20] and applies from 2027. This Regulation establishes health and safety requirements for machinery placed on the EU market and applies to machinery defined as an assembly, fitted with or intended to be fitted with a drive system other than directly applied human or animal effort, consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application

Part of the Machinery Regulation requires manufacturers to draw up for each machine a declaration of conformity which must include references to the harmonised standards referred, for example to Stage V. Part of this declaration requires also the name of the machine to be declared.

While there is no CO_2 regulation currently in place for the NRMM sector in Europe, the legal framework for introducing a declaration and certification of the CO_2 emissions from vehicles and machines may be introduced through a combination of the type approval legislation and the Machinery Regulation described above. For NRMM which have type-approval legislation in place, a similar procedure as with on-road vehicles could be adopted. For those which do not have a type-approval legislation, CO_2 certification and declaration could be established as a requirement of the declaration of conformity.

5.1.3 Registration Procedures in Member States

CO_2 regulations for on-road vehicles in Europe require input from both the vehicle manufacturer and the national authorities in each Member State. Manufacturers are required to monitor and report directly to the European Commission the CO_2 emissions of their vehicles. The national authorities are then required to report a comprehensive list of all vehicles registered in a given period in their Member State to the European Commission.

[17] Regulation (EU) No 168/2013 contains a number of exemptions from its scope set out in Article 2, including, inter alia, vehicles with a maximum design speed not exceeding 6 km/h; vehicles intended exclusively for use by persons with disabilities; vehicles intended exclusively for competition or for use by the armed services, emergency or public-order services; certain agricultural, forestry and non-road machinery covered by other EU approval frameworks; vehicles primarily intended for off-road use; electrically assisted pedal cycles (pedelecs) with a maximum continuous rated power not exceeding 250 W; and self-balancing vehicles.

[18] Regulation (EU) 2025/14 of the European Parliament and of the Council of 19 December 2024 on the approval and market surveillance of non-road mobile machinery circulating on public roads and amending Regulation (EU) 2019/1020 (Text with EEA relevance)

[19] Regulation (EU) 2023/1230 of the European Parliament and of the Council of 14 June 2023 on machinery and repealing Directive 2006/42/EC of the European Parliament and of the Council and Council Directive 73/361/EEC (Text with EEA relevance)

[20] Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast) (Text with EEA relevance)

The two direct reports are normally matched using the Vehicle Identification Number. This provides a guarantee that all vehicles first registered in a given period are covered under the scope of a CO_2 standard.

A significant challenge arises when attempting to follow this same procedure in the NRMM sector. Normally, only vehicles that have a type approval procedure in place and are intended for use on public roads are required to register with national authorities. However, many NRMM categories covered in the scope of this report are not monitored by national authorities. There are no evident requirements by any Member States to monitor sales of non-mobile sectors such as generators and hand-held machines, while the monitoring of mobile categories is limited.

A review of five countries — Austria, Germany, Spain, Italy, and France — showed that there is no uniform procedure across Member States (Table 89).

Table 89: Summary of registration procedures for NRMMs in Austria, Germany, Spain, Italy, and France.

Country	Tractors	Mobile machinery	Non-mobile machinery	2/3 wheelers	PWC/IWW	Legislation
Austria	Only if used more than 20 % on public roads	Self-propelled work machines (including forklifts, excavators, wheel loaders, dump trucks, and transport carts) are exempt	No	Yes	Yes	Kraftfahrgesetz 1967 and Schifffahrts-gesetz
Germany	Yes	Self-propelled work machines (including forklifts, excavators, wheel loaders, dump trucks, and transport carts) are exempt	No	Light motor cycles, two- and three wheeled mopeds are exempt	Yes PWC >2.21 kW and IWW >10cc	Fahrzeug-Zulassungs-verordnung and KlFzKV-BinSch
Spain	Yes – owners must register in public database	Machines >750kg	No	Yes	Yes for PWC, but IWW less clear	Royal Decree 448/2020 and 2822/1998 and 1435/2010
Italy	Yes, if above 1.5 tonnes	Forklifts and road-going machinery are exempt	No	Yes	Registration depends on hull size	Codice della Strada
France	Yes	Yes, if design speed is above 25 km/hr	No	Yes	Yes for hull length >2.5m.	Code de la route

To implement an EU-wide regulation aimed at CO_2 emission reduction, it may be necessary to establish a harmonized approach to monitoring the sale of NRMMs within EU Member States.

While this may be possible for certain road-going vehicles that already have a type-approval system in place, it will be more challenging for non-road going vehicles and stationary machinery.

California, one of the only jurisdictions globally to have set zero-emission requirements on NRMMs, have adopted standards that do not require state-wide registration information.[21] For their Zero-Emission Forklift Regulation (discussed below), they require reporting from all regulated entities including manufacturers, dealers, rental agencies, and fleets. All forklifts are then linked using an equipment identification number.

To create a fleet-wide regulation In Europe, a similar mechanism that has been proposed in California could be employed. This would face potential difficulties as uniform implementation would be necessary across Member States which is currently not in place. European-wide regulation may be needed to create such a uniform procedure.

5.2 Regulations aimed at GHG reduction in California

In September 2020, Governor Gavin Newsom issued an Executive Order, establishing a statewide policy direction to accelerate the transition to zero-emission technologies across California's transportation and equipment sectors (Newsom 2020). In addition to setting the target of ending sales of new gasoline passenger vehicles by 2035, the Executive Order also establishes the aim to achieve 100 % zero-emission off-road vehicles and equipment operations in California by 2035, where feasible.

This Executive Order provides the overarching framework for the subsequent development of CARB's off-road regulatory portfolio, which includes a range of sector-specific regulations, reporting systems, and compliance pathways aimed at reducing air pollutant and greenhouse gas emissions from off-road equipment in the state. This section summarizes the regulations that are under consideration and in place in California.

5.2.1 ZE Forklift Regulation

The Zero-Emission Forklift Regulation applies to cushion-tired forklifts of all lift capacities and pneumatic-tired forklifts of lift capacities 12,000 pounds or less powered by a large spark-ignited (LSI) engine (California Air Resources Board 2024b). The regulation is intended to eliminate emissions from this equipment category by requiring a transition to zero-emission forklifts. Starting in 2026, manufacturers would be subject to sales restrictions for applicable LSI forklifts and fleet operators would be restricted from acquiring LSI forklifts. Existing forklifts are subject to a phased retirement schedule based on model year, with full fleet transition to zero-emission equipment required by 2038. In May 2025, CARB published a notice that it has not yet sought authorization from the U.S. Environmental Protection Agency which is required to enforce this regulation (California Air Resources Board 2025e).

5.2.2 Small Off-Road Engine Regulations

The Small Off-Road Engine regulations govern spark-ignition engines rated at 19 kilowatts or less (California Air Resources Board 2021a). From 2024, all new spark ignition engines – with the exception of power washers above 250cc and generator engines – are required to have zero

[21] The regulating body in California, the California Air Resource Board, has not yet sought authorization from the U.S. Environmental Protection Agency for the Zero-Emission Forklift Regulation pursuant to section 209(e)(2)(A) of the Clean Air Act. This means it is not currently in effect in California, despite being adopted by CARB.

grams of HC+NOx, effectively creating a zero-emission mandate from that year. For generator engines and power washers above 250cc, a date of 2028 applies.

These regulations primarily apply to manufacturers, distributors, and retailers rather than equipment owners. Engines must be certified by CARB, meet exhaust and evaporative emissions standards, and include emissions labels. Existing equipment that was legally sold may continue operating for its useful life, meaning the regulation does not mandate retirement of in-use engines.

5.2.3 Transportation Refrigeration Unit (TRU) Regulation

The pollutant emissions from Transportation Refrigeration Units (TRU) are addressed through the Air Toxic Control Measure which applies to diesel-powered refrigeration units installed on trucks, trailers, railcars, and intermodal containers operating in California (California Air Resources Board 2022a).

CARB are developing requirements to transition diesel-powered TRUs to zero-emission technology in two parts. Part 1 consists of amendments to the TRU ATCM, which were approved in 2022. The amendments include requirements for the transition of diesel-powered truck TRUs to zero-emission, a particulate matter emission standard for newly-manufactured non-truck TRUs, lower global warming potential refrigerant, facility registration and reporting, expanded TRU reporting and labeling, and fees. CARB are assessing zero-emission options for non-truck TRUs and plan to take a second rulemaking (Part 2) to the Board for consideration.

5.2.4 Upcoming technical assessment to zero-emission Cargo Handling Equipment

The Cargo Handling Equipment regulation applies to diesel-powered equipment used at ports, rail yards, and intermodal facilities, including yard tractors, top handlers, reach stackers, and large forklifts (California Air Resources Board 2011). Existing requirements mandate cleaner diesel engines and reporting of equipment activity. CARB is currently developing a zero-emission technology assessment for cargo handling equipment (California Air Resources Board 2025a).

5.2.5 Upcoming On-Ground Aircraft Operations Regulation

CARB is developing regulatory measures aimed at reducing emissions from on-ground aircraft operations, particularly airport ground support equipment such as baggage tractors, belt loaders, aircraft tugs, and ground power units. Although no finalized regulation has yet been adopted, this sector has been identified as a priority under CARB's Mobile Source Strategy (California Air Resources Board 2021c). The anticipated regulatory approach would include fleet reporting, operational controls, and a phased transition from diesel and gasoline-powered equipment to zero-emission alternatives. Regulatory development and stakeholder engagement are expected to occur in the mid-2020s, with phased compliance extending into the 2030s.

5.2.6 Marine Vessel Regulations

The Marine Vessel regulations, formally known as the Commercial Harbor Craft Regulation, apply to diesel-powered commercial vessels such as ferries, tugboats, crew boats, dredges, and workboats operating in California waters (California Air Resources Board 2021b). The regulation establishes engine replacement and repower schedules to reduce diesel particulate matter, nitrogen oxides, and greenhouse gas emissions. Amendments adopted in 2022 expanded the regulation to include zero-emission and near-zero-emission requirements for certain vessel categories. Compliance milestones begin in the mid-2020s and extend through the 2030s, with many vessel categories required to transition to zero-emission propulsion by approximately 2035.

5.2.7 Upcoming Phased Advanced Clean Equipment Regulation

The Phased Advanced Clean Equipment regulation is a proposed manufacturer-focused rule designed to increase the availability of zero-emission off-road equipment in California (California Air Resources Board 2025b). Rather than regulating fleet owners directly, the regulation would require equipment manufacturers to meet minimum production or sales targets for zero-emission off-road machinery across construction, industrial, and agricultural sectors. CARB has conducted workshops and released discussion documents outlining a phased approach beginning in the late 2020s, with increasingly stringent zero-emission equipment sales requirements through the 2030s. This regulation is intended to complement in-use fleet rules by ensuring sufficient market availability of compliant equipment.

5.3 Regulation design

There are several design elements that should be considered in setting a requirement for NRMM. Many of these are standard decisions that would have pros and cons, for example whether to set a CO_2 regulation or a zero-emission mandate. However, there are some essential elements of regulatory design that render a regulation challenging to establish today. Particularly, there is no uniform procedure for registration of NRMM across Europe. In the absence of such a procedure, setting a regulation for the sector may not be possible. This is discussed in more detail in Section 5.1.3.

5.3.1 Regulation type

A European-wide regulation which requires a reduction in CO_2 emissions could be established either through setting a CO_2 emissions standard, which would allow manufacturers to focus on efficiency improvements in combustion engines as well as an increased deployment of zero-emission NRMMs, or it could be set through a zero-emission mandate where manufacturers or fleets are required to sell or purchase an increasing share of zero-emission vehicles. The EU has so far focused on CO_2 standards as the primary mechanism for reducing GHG emissions for the on-road vehicle sector.

For light-duty vehicles, CO_2 emissions are certified as part of the type approval process through a dynamometer test using the Worldwide Harmonised Light Vehicles Test Procedure. Vehicle manufacturers are then required to reduce their fleet average CO_2 emissions in line with the CO_2 standards. For heavy-duty vehicles a different method is employed due to the wide variations of truck configurations sold. CO_2 emissions are certified through a simulation program, VECTO, where manufacturers are required to measure the performance of their components (e.g., aerodynamic performance, engine performance, tyres) and then simulate the CO_2 emissions of the combination of components through VECTO.

Due to the wide variety of NRMMs, establishing a CO_2 certification procedure would be significantly challenging for the full vehicle or machine. CO_2 emissions are already determined as part of the engine pollutant standards set under Stage V, but verifying the CO_2 emissions at the full vehicle or machine level would require a vast array of harmonized test procedures to be established which would be onerous and time consuming – work commenced on the development of VECTO in the early 2010’s and was only first adopted through regulations in 2017.

The advantage of a CO_2 standard over a ZEV mandate is that it allows for CO_2 emissions reductions through the improvement of the combustion engine or the efficiency of a hydraulic system to be used to assist in compliance, while a zero-emission mandate can only be complied with through increasing the share of zero-emission vehicles or machines sold.

NRMMs offer the possibility for improvements regarding CO_2 emissions to the engine and to the vehicle or machine design. Of course, improvements in the aerodynamics of a vehicle are best utilized by vehicles travelling at high speeds, such as for on-road vehicles while NRMMs usually operate at much lower speeds comparatively. Tires in the on-road sector can contribute towards reduced CO_2 emissions by lowering the rolling resistance while tires for NRMM vehicles are designed for increased traction rather than lower resistance due to the rough terrain they operate in. Nevertheless, the overall efficiency of NRMMs can be improved by optimizing the hydraulic system, which is used for working. This can be done not only by efficiency improvements of the hydraulic system, but also by hybridization or even total electrification of the system. However, due to the heterogeneous nature of the sector and the complexity of creating a system, which takes the CO_2 savings of the entire machine into account, we do not recommend the establishment of a CO_2 certification procedure as part of a future regulation. Furthermore, the energy saving potential of NRMM goes far beyond engine and vehicle design and also includes operational and process efficiency. Due to the heterogeneous nature of the sector and the complexity of creating such a system, a full vehicle certification procedure would not be reasonable and rather a separate standard could be set using the CO_2 emissions values monitored in Stage V as a baseline.

5.3.2 Regulation scope

A key challenge in designing a European-wide CO_2 regulation for NRMMs lies in defining a scope that has a significant emissions coverage and is also administratively feasible. Compared to the on-road vehicle sector—where regulatory frameworks can focus on relatively well-defined vehicle categories and a limited number of manufacturers—the NRMM sector is characterised by a far larger diversity of equipment types, operating conditions, and supply chains. NRMMs spans many industries and applications, from construction and agriculture to inland waterways and niche sectors, each with distinct technical constraints and decarbonisation potentials. As such, a single regulation applied uniformly across the whole sector risks either being overly burdensome for some segments, or too weak to drive meaningful emissions reductions in others.

This diversity is already reflected in existing Stage V pollutant regulations, where the scope is primarily defined through engine categories and power bands rather than by machine type. However, the current sectoral disaggregation in Stage V remains limited for the purposes of GHG regulation. In particular, some regulatory groupings – particularly the group NRE, NRS, and NRSh – encompass a very wide array of engines and applications, combining machinery that may be relatively straightforward to electrify with machinery that is substantially more difficult due to high power demand, long operating hours, or limited infrastructure availability. This lack of granularity creates a significant challenge for any regulation that seeks to impose CO_2 requirements across broad categories, as the decarbonisation potential within each group is highly heterogeneous.

Establishing a new regulation focused on GHG emissions may divert from the groupings laid out in Stage V and focus instead on new groupings more relevant for the decarbonization of the sector. This could include creating a grouping based on electrification potential, power ratings, sectoral categories (e.g., agricultural, construction, marine, etc.), and daily use profiles. This would allow for more ambitious targets being set for easy to electrify categories and less stringent targets set for the harder to electrify.

5.3.3 Targets and timelines

There is a wide variation in decarbonisation potential across machine types, power ranges, and use cases as shown in Section 4. As such, setting targets for a future NRMM CO_2 regulation should reflect the diversity in this sector.

Targets could be set by utilizing the well-established Stage V regulation. Either the pollutant emissions limits for certain categories could be set to zero, thus creating a proxy zero-emission mandate, or the emissions limits could be strengthened to encourage a shift towards zero-emission technologies. One challenge with this approach would be on the timelines – Stage V applies to all non-road engines sold on the European market and there is no possibility to include an averaging framework under the existing regulation. As such, if a zero-emission mandate was introduced through this method, it should only be applied to categories where a high degree of electrification is already feasible.

Alternatively, targets could be set through a new regulation where NRMMs are grouped into tiers based on their electrification potential and targets could be applied to these sets. This is the approach under consideration by California in its upcoming Phased Advanced Clean Equipment regulation.

Another key design question is how targets are structured over time. One option is to set milestone targets at fixed intervals (e.g., every five years), which is consistent with many EU regulatory approaches and provides manufacturers flexibility to adjust deployment strategies within each compliance period. An alternative is to adopt annual step increases, which can accelerate early deployment by preventing delayed compliance but reduces flexibility and requires continuous scaling of zero-emission production. Given the early stage of market development for many NRMM categories, a milestone-based approach could offer a more practical starting point, especially if combined with interim review clauses that allow timelines to be adjusted in response to technology progress and infrastructure availability.

5.3.4 Compliance flexibilities

A regulation which requires reductions in CO_2 emissions from NRMM—whether through a CO_2 standard or a zero-emission mandate—will likely need flexibility mechanisms to account for differences in technology readiness, duty cycles, and the highly diverse nature of the sector. While the EU has relied heavily on fleet-based compliance approaches for on-road CO_2 standards, the existing Stage V framework is designed as an engine-based pollutant regulation with per-engine limit values and limited category granularity. As such, many of the flexibility tools used in on-road regulations would not be directly transferrable to an NRMM regulation implemented through Stage V without major structural reform.

Stage V already includes limited flexibility mechanisms, mainly via its transitional provisions and special cases. For example, the EU amended the Stage V transition timetable in 2020 to address COVID-19 supply-chain disruption, postponing certain deadlines for producing and placing on the market NRMM with “transition engines” by 12 months. In addition, Stage V provides longer transition timelines for “small volume” OEMs (defined as OEMs with total yearly production of fewer than 100 units of NRMM equipped with ICEs), as well as certain niche categories (e.g., mobile cranes, snow throwers). Finally, Stage V explicitly regulates replacement engines (i.e., engines placed on the market to replace engines in existing machines), allowing these to be placed on the market for extended periods after the Stage V start dates (with no time limit to sell/install once placed on the market within the relevant deadlines).

5.3.4.1 Averaging, banking and trading

Averaging, banking and trading (ABT) is widely used in fleet-average CO_2 standards and ZEV mandates to provide flexibility and reduce compliance costs, but it would not function effectively under Stage V as currently structured. Stage V is based on engine families meeting fixed emission limit values rather than a fleet-average approach, and therefore does not create a compliance space where manufacturers can overcomply on one product line and compensate for underperformance elsewhere. Implementing ABT would require a fundamental redesign of Stage V into a fleet-based framework, including the establishment of a harmonised method for aggregating CO_2 performance across an extremely diverse product portfolio. Without such structural revision, a Stage V-based approach could only apply fixed caps to each engine category, eliminating the flexibility that ABT is designed to provide.

5.3.4.2 Weighting system for credits

A key risk of unweighted credit systems is that compliance can be driven primarily by smaller machines that are easier to electrify but contribute relatively little to total CO_2 emissions, while larger and higher-emitting equipment remains largely unchanged. To avoid this outcome, credit systems would need to be weighted to reflect the expected emissions impact of a machine over its operational lifetime, rather than simply counting unit numbers. Weighting could be based on power, energy consumption, duty cycle proxies, or expected lifetime use, with the objective of ensuring that decarbonising higher-emitting segments produces proportionally greater compliance value. Such an approach would help align the regulation with real-world emissions reductions and reduce the risk that the regulation achieves nominal compliance without addressing the highest-emitting categories of NRMM. Creating such a monitoring mechanism is arduous and would require careful research into the real-life performance of the various NRMM categories regulated.

5.3.4.3 Credit inflation for earlier adoption

Credit inflation mechanisms—where early deployment of zero-emission equipment generates enhanced compliance value—can help overcome the “first mover” disadvantage in a market where technologies are immature and uptake remains low. In the NRMM sector, such mechanisms may be particularly important in the early compliance periods, where uncertainty over technology scale-up and infrastructure availability is high, and where incentives may be needed to stimulate supply chain investment. However, inflated credits must be carefully calibrated to avoid undermining the regulation’s environmental integrity by allowing compliance to be achieved through limited early deployment without corresponding long-term market transformation. Credit multipliers should therefore be time-limited, decline predictably over successive compliance periods, and be paired with tightening targets to ensure early incentives accelerate—not replace—progress toward decarbonisation.

5.3.4.4 Exemptions

Exemptions may be necessary to avoid imposing disproportionate burdens on niche segments or applications where decarbonisation pathways are currently infeasible, but they introduce risks of erosion of ambition and regulatory loopholes if too broadly defined. In the NRMM context, exemptions could be considered for low-volume manufacturers, specialised machinery with extreme operational requirements, or certain remote-use cases where charging or hydrogen infrastructure is unavailable.

5.3.5 Monitoring and reporting

Monitoring and reporting is an essential component for any future regulation, although one that comes with an increased level of administrative burden on national authorities and manufacturers of equipment. A key requirement is the establishment of a robust certification procedure to define what constitutes a “zero-emission” NRMM and to ensure that compliance claims can be verified consistently across Member States. While engine-level CO_2 emissions values already exist under Stage V, these do not provide an equivalent framework for certifying whole machines as zero-emission or for validating the technology pathways used (e.g., battery-electric, fuel cell, hybrid configurations). A dedicated certification procedure for zero-emission NRMMs would therefore be required to support enforcement, avoid inconsistent interpretation, and ensure that compliance is tied to verifiable technical performance.

Monitoring and reporting for NRMMs is further complicated by the lack of comprehensive machine registration data across the EU, as mentioned in Section 5.1.3. Unlike on-road vehicles—where registration systems provide a clear and harmonised basis for tracking fleets, sales, and compliance—many NRMMs are not registered with national authorities, and where registration exists it is often fragmented, inconsistent, or limited to specific sub-sectors. This makes it difficult to establish reliable baselines, track the deployment of regulated equipment, or verify market shares of zero-emission machinery at the Member State or EU level. As such, any future regulation may need to introduce new reporting obligations, including harmonised reporting of sales and machine characteristics by manufacturers, or the development of a dedicated NRMM registration or tracking framework to support compliance monitoring. Without such measures, enforcing targets based on deployment shares would be highly challenging.

5.4 Policy scenarios

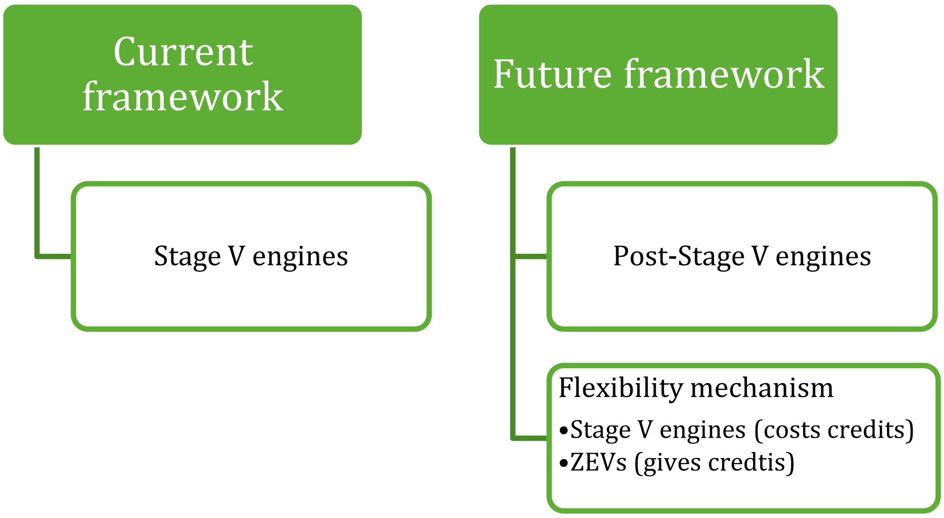
We only consider policy scenarios here that require an increase in the deployment of zero-emission NRMMs. We explore these policy scenarios through adopting changes to Stage V (Scenario 1) and through setting a separate standard, such as the proposed Phased Advanced Clean Equipment regulation in California (Scenario 2).

5.4.1 Scenario 1: Amending Stage V to promote zero-emission NRMMs

Amending Stage V to tighten emission standards and compliance could be combined with a zero-emission vehicle (ZEV) crediting mechanism to encourage electrification of non-road mobile machinery (NRMM). This hybrid approach could continue to regulate engine manufacturers while providing compliance flexibility to address segment-specific barriers to electrification, potentially reducing certain administrative burdens compared to direct ZEV quota mandates.

Policymakers evaluating options for tightening Stage V could consider several complementary approaches for strengthening emission requirements.

Figure 54: Possible policy framework for amending Stage V



Source: Own illustration by ICCT

5.4.1.1 Lowering Pollutant Limits

California's proposed Tier 5 standards for new compression-ignition engines, though developed for a different market, provide a reference point for assessing technical feasibility of tighter emission limits(California Air Resources Board 2024a). Table 90 compares current EU Stage V limits with California's Tier 5 proposals.

Table 90: Comparison of EU Stage V and California Tier 5 Proposed Emission Limits for Compression-ignition Engines

Power Category	Pollutant	EU Stage V	CA Tier 5 Proposed
< 19 kW	HC+NOx	7.5 g/kWh	4.0–5.0 g/kWh
	PM	0.40 g/kWh	0.1–0.2 g/kWh
	PN	No limit	1x10^12/kWh
19–56 kW	NOx	4.7 g/kWh*	2.5 g/kWh
	PM	0.015 g/kWh	0.008 g/kWh
56–560 kW	NOx	0.40 g/kWh	0.040 g/kWh
	PM	0.015 g/kWh	0.005 g/kWh
	NMHC	0.19 g/kWh (HC)	0.80 kWh
< 560 kW	NOx	3.5 g/kWh	0.35 g/kWh (Generator sets); 3 g/kWh (Mobile)
	PM	0.045 g/kWh	0.008 g/kWh (Generator sets); 0.04 g/kWh (Mobile)

*Stage V 19-56 kW limit is combined HC+NOx; Tier 5 separates these pollutants.

California Tier 5 values are presented as a technical feasibility reference, not as recommendations for amended EU Stage V limits. The appropriate level of stringency for tightened EU standards would depend on technical feasibility assessments under European market and regulatory conditions, cost-effectiveness analysis, stakeholder consultation, among others. For additional context, Euro 7 limits for heavy-duty on-road CI engines – NOx at 0.200 g/kWh (WHTC) and 0.175 g/kWh (WHSC), PM at 0.008 g/kWh – demonstrate that significantly lower emission levels are technically achievable with modern diesel aftertreatment.

California's Tier 5 is not yet finalized and may change. Under California's Tier 5 proposal, these standards apply differently depending on engine type. For variable-speed engines up to 560 kW, certification testing must be conducted using both the transient cycle and a steady-state duty cycle. For engines above 560 kW and all constant-speed engines, the standards apply only when tested using a manufacturer-selected steady-state duty cycle, and transient cycle testing is not required for these categories.

Small engines below 19 kW currently have no PN limits, higher CO limits and, especially the hand-held NRSh, have HC+NOx limits much higher than large engines.

There are currently no proposals to tighten the standards for NRS/NRSh category engines beyond Stage V. A comparison of the emission standard for HC+NOx of small L-category vehicles L1e-b (Mopeds) and NRSh shows that latter have higher emission limits for CO, NOx and HC when compared in g/kWh than L-category vehicles (Heidt et al. 2023). However, this is due to the different boundary conditions and requirements of the small hand-held machinery NRSh. Main drivers are installed power and operation duration with one tank filling which goes hand in hand with weight and handling requirements. This leads to different combustion and exhaust gas aftertreatment technologies of NSRh compared to L1e-b.

Meeting tightened PM, HC and NOx limits would require electronic fuel injection and integrating advanced aftertreatment systems. For small engines that currently use simpler mechanical control architectures, integrating complete electronic control systems would require substantial redesign and development costs In the very small power class of NRSh with engines up to ~ 3kW, which are used in non-professional operation mainly, a transition to electric powered machinery is already ongoing which corresponds to the electrification potential. In this category, for the decision pro electric, cost seems not the major reason considering higher costs for the electric machinery and additional costs for the required battery packs. Applicability or useability along with reduced impact on the environment in terms of noise, smoke and smell are relevant factors.

For higher power demands in the NRS and NRSh segment of professional use the major drawbacks of electrification are low operation duration, increased weight and worse handling. Stricter emission limits and consequently advanced ICE technology with higher cost would certainly reduce the environmental impact but might not reduce these drawbacks and the effect of reduced emission limits would be there but of minor scale.

For large engines above 56 kW, Stage V already requires advanced aftertreatment. These engines use electronic control systems and sophisticated aftertreatment, so further tightening would bring incremental cost increases rather than fundamental system redesign. While tightened emission standards alone may not fundamentally shift manufacturer economics in these categories, the incremental compliance costs would improve the relative total cost of ownership position of electrific alternatives. However, electrification of large engine applications is progressing.

The combination of tightened standards with ZEV crediting (described below) could accelerate zero-emission deployment by enabling manufacturers to continue supplying combustion engines for applications with genuine electrification constraints while requiring corresponding zero-emission powertrain placements in segments where electric alternatives are viable.

5.4.1.2 Introducing In-Service Conformity (ISC)

Tightened standards could build on Stage V's in-service monitoring (ISM) by introducing enforceable in-service conformity (ISC) requirements. Stage V's ISM collects real-world emission data but does not carry enforceable consequences for exceeding type-approval values. Introducing enforceable ISC limits would strengthen the incentive for manufacturers to optimize in-use emission performance and ensure real-world emission performance matches type-approval values throughout the equipment's useful life as defined under a post-Stage V standard (see durability discussion below).

California's Tier 5 proposal provides one model for structuring in-use requirements. For engines 56–560kW, Tier 5 proposal requires compliance with in-use thresholds evaluated using a moving average window (MAW) approach, similar to CARB's on-road Heavy-Duty Omnibus regulation which uses a 3-bin structure (idle, low-load, and medium/high load). For smaller engines below 56 kW and very large engines above 560 kW, Tier 5 proposes to apply not-to-exceed (NTE) limits.

California's proposed Tier 5 also follows a phased approach: an initial pilot screening program followed by enforceable ISC requirements once testing protocols are refined.

5.4.1.3 Strengthening Durability Requirements

Stage V requires manufacturers to establish deterioration factors demonstrating emission control effectiveness over defined useful life periods. Tightened standards could strengthen these requirements in several ways which may create a more favourable case for electrification. These measures primarily aim to improve real-world emission performance rather than directly drive electrification; incremental aftertreatment replacement costs may not alone shift equipment TCO decisively toward electric alternatives, though they contribute to the broader cost differential. Extended useful life periods improve effectiveness of emission control systems over equipment lifetimes, which often exceed certification periods. California's Tier 5 proposes using an accelerated diesel aftertreatment aging method designed to provide more representative assessment of real-world aftertreatment deterioration. Enhanced warranty requirements tied to extended useful life periods would ensure manufacturers design for durability, while strengthened defects reporting would enable regulators to identify systematic emission control failures in the field.

5.4.1.4 Introducing Low-Load Cycle Certification

A new certification test cycle targeting low-load operating conditions could address a recognized gap between certification and real-world performance. Aftertreatment systems – particularly SCR catalysts – often exhibit reduced efficiency at low exhaust temperatures associated with low-load operation(DieselNet 2025; Rodríguez, Badshah 2021). At moderate stringency levels, compliance costs for such solutions are unlikely to drive electrification directly. However, very stringent low-load limits could narrow the compliance pathway for combustion engines, effectively functioning as a de facto zero-emission requirement for certain operating conditions. California's Tier 5 introduces a low-load cycle for variable-speed engines between 56 and 560kW. Machines outside of this power range could also be included, but a separate set of provisions may have to be considered.

5.4.1.5 Idle Emission Reduction Provisions

Extended idling contributes to urban emissions, particularly for equipment operating in ports, construction sites, and distribution facilities. Tightened standards could introduce idle-specific emission limits or require automatic engine shutoff systems after specified idle durations. Such provisions would reduce unnecessary emissions during periods when equipment is not performing useful work.

California's Tier 5 proposes idle-specific NO_x standards for certain variable-speed engine categories: engines 19-56 kW would face an idle NO_x limit scaled to engine power, while mobile machinery above 560 kW would face a flat 50 g/hr limit. Manufacturers could comply either through engine testing or by demonstrating that engines are equipped with automatic shutoff systems during idling.

5.4.1.6 Transport Refrigeration Units

Transport refrigeration units (TRUs) represent a significant regulatory gap. TRUs typically use engines below 19 kW, which face no PN limits and weaker NO_x/PM limits under current NRMM legislation. Research found that a single diesel auxiliary TRU fitted to a Euro VI heavy goods vehicle produces two to three times the NO_x emissions of the truck engine, five times the PM2.5, and approximately 1,000 times the particle number (Robinson, Fraser 2021).

Given their operation in urban distribution settings with direct health impacts, TRUs represent a priority category. While infrastructure for electric standby at parking and rest areas remains limited, many TRUs operations are depot-based, which enables return-to-base operation, and shore power connections at loading facilities. For non-depot operations, phased infrastructure requirements could accompany a transition timeline. A key regulatory design question is how to target TRU engines specifically without imposing requirements on all NRMM below 19 kW. Options include defining TRUs as a distinct sub-category within the NRMM framework, or addressing TRUs through a separate regulatory instrument, as California has done with its zero-emission TRU regulation (California Air Resources Board 2025c; d).

5.4.1.7 ZEV Crediting Flexibility Mechanism

While the measures described above would strengthen emission standards and compliance requirements, a complementary ZEV crediting system could enable compliance flexibility. Engine manufacturers could continue placing Stage V-compliant engines on the market if manufacturers simultaneously place a specified number of zero-emission powertrains on the market. Machine manufacturers who face genuine barriers to electrification – such as limited grid access, high power requirements, or challenging operating profiles – would retain access to combustion engines.

In California's proposed Tier V pollutant standards, a ZEV crediting mechanism was proposed whereby an equipment manufacturer that sells a zero-emission machine may earn zero-emission credits to be transferred to the engine manufacturer. Credits are only earned for ZE machines above 130 kW but may be used by the engine manufacturer on all machines. These credits can then be used by the engine manufacturer to comply with their emission limits.

This mechanism relied on an emissions averaging mechanism which is not present in the European system. Instead, it may be possible to follow a similar procedure as outlined by the transitional provisions outlined in Article 58 of the Stage V regulation.

Under this transitional provision, machine manufacturers were allowed to install a limited number of transition engines – meeting the previous stage but not Stage V standard – after Stage V took effect.

A ZEV crediting mechanism could allow for a credit to be generated by equipment manufacturers that place ZE machines on the market. As we find there is already a high degree of electrification potential for small machines, these credits should be limited to machines above 130 kW, following the Tier V proposal in California. Under a post-Stage V standard, each credit could then be transferred to an engine manufacturer which would grant them the authority to produce a transitional engine in line with the provision laid out in Article 58 of 2016/1628.

In California's proposed Tier V, the ZE equipment manufacturer would be required to provide a valid California equipment identification number dating back at least three years, or other proof of prior California sales presence and operations, the actual number of ZE equipment sold in California via End of Year Reporting by equipment type, model year, power category, and diesel equivalent engine family and an attestation to the accuracy of ZE equipment credit numbers and credit calculations via a signed letter of accountability by the ZE equipment manufacturer.

A similar monitoring mechanism would be required in the EU to perform such a check that ZE equipment has been placed on the European market and to grant an engine manufacturer the allowance to produce a transitional engine.

5.4.1.8 Two- and Three- Wheelers and Recreational Craft

Two- and three-wheelers (L-category vehicles) and recreational craft are not regulated under the NRMM framework (Regulation (EU) 2016/1628) but fall under separate EU legislation: Regulation (EU) 168/2013 for L-category vehicles and Directive 2013/53/EU for recreational craft. While these categories are addressed under other scenarios in this project, several of the emission standard tightening measures discussed above – PN limits, in-service conformity, durability provisions – could, in principle, be adapted to strengthen these frameworks as well.

L-category vehicles are currently subject to Euro 5 emission limits (Regulation (EU) 168/2013), tested on the WMTC laboratory cycle. Euro 5 does not include particle number (PN) limits, in-service conformity testing, or real-world emission requirements. The Commission's 2018 report on the effects of the Euro 5 environmental step examined, among other findings, the feasibility of introducing these elements, but no subsequent Euro 6 proposal has been tabled to date (European Commission 2018). Analogous to the measures discussed above for NRMM, tightening L-category emission standards could include introducing PN limits (as discussed for small NRMM engines below 19 kW), enforceable in-service conformity requirements using portable emission measurement systems, and strengthened durability provisions. The electrification potential for urban-use L-category vehicles – particularly mopeds and light motorcycles – is high, though the applicability of ZEV incentive mechanisms would depend on the specific regulatory structure of the L-category framework.

Recreational craft engine emission limits under Directive 2013/53/EU are substantially less stringent than current NRMM Stage V standards. For spark-ignition outboard and personal watercraft engines, CO and $HC+NO_x$ limits are set separately and can collectively reach several hundred g/kWh. Compression-ignition marine engines face limits ($HC+NO_x$ 4.7–5.8 g/kWh, PM 0.11–0.3 g/kWh, organized by engine displacement per cylinder) that are also well above Stage V levels for comparable power categories. The directive does not include PN limits, in-service conformity, or durability requirements. Aligning recreational craft standards more closely with the NRMM framework – including tightened pollutant limits, PN requirements, and durability provisions – could yield meaningful emission reductions, particularly in inland waterways and coastal areas where recreational craft contribute to local air quality impacts.

Recent evidence from the Horizon Europe project L-vehicles Emissions and Noise mitigation Solutions (LENS) further supports the case for strengthening the L-category framework ('LENS - L-vehicles Emissions and Noise mitigation Solutions' no date). Based on extensive laboratory, on-road and roadside testing, the project found that real-world pollutant emissions and noise levels frequently exceed type-approval values under typical operating conditions. In its final report (D6.5: Recommendations for Quieter and Cleaner L-Vehicles), LENS recommends broadening test procedures to better reflect real-world use, introducing limits for currently unregulated pollutants such as particle number (PN), expanding real-world emission testing with portable measurement systems, and strengthening anti-tampering provisions. These findings provide a technical foundation for future revisions of Regulation (EU) 168/2013 aimed at improving real-world environmental performance.

5.4.2 Scenario 2: Establishing a tiered zero-emission mandate

Scenario 2 considers the laying of a new regulation to require the reduction of CO_2 emissions from the NRMM sector. The European Commission has the powers to set new legislation of this sort under article 192(1) of the Treaty on the Functioning of the European Union which forms the basis for all CO_2 standards for the on-road sector.

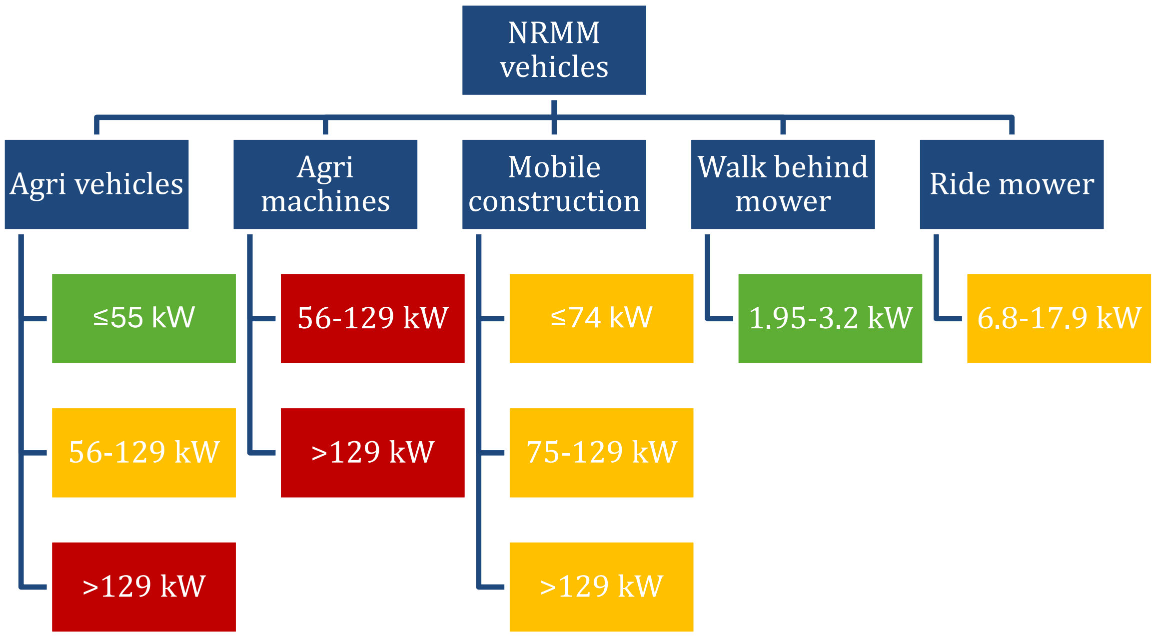
This scenario assumes the setting of tiered targets for the entire NRMM sector with higher targets for categories with a high electrification potential and vice versa for categories with a low electrification potential. The electrification potential is calculated in accordance the methods detailed in Section 4.

For this scenario we establish three tiers to which these targets apply:

- Low: Machines with an electrification potential less than 33 %
- Medium: Machines with an electrification potential between 33 % and 66 %
- High: Machines with an electrification potential above 66 %

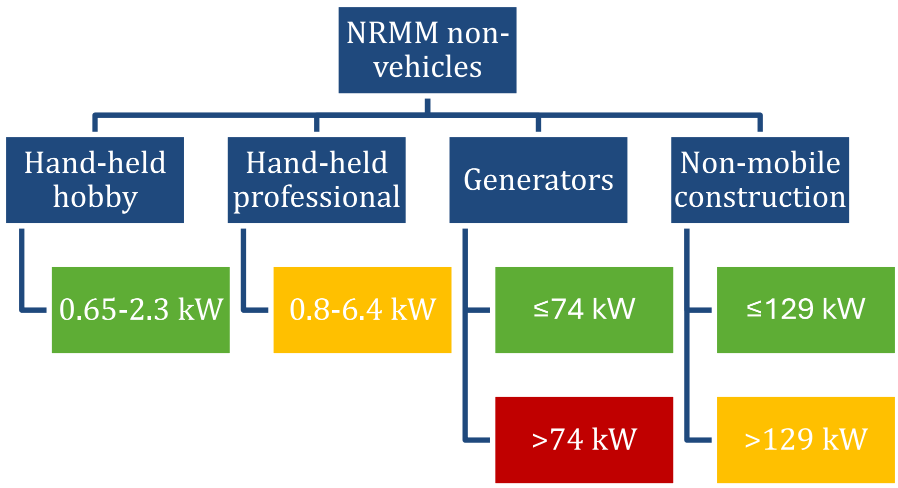
The figures below show the grouping of machines by tier. Boxes coloured red fall under the "Low" tier, boxes coloured yellow fall under the "Medium" tier, and boxes coloured green fall under the "High" tier. A full list of all NRMM machines included in these groups is presented in Section A.3.

Figure 55: Tiered category for NRMM vehicles. Note: green denotes high electrification potential, yellow is medium electrification potential, red is low electrification potential.



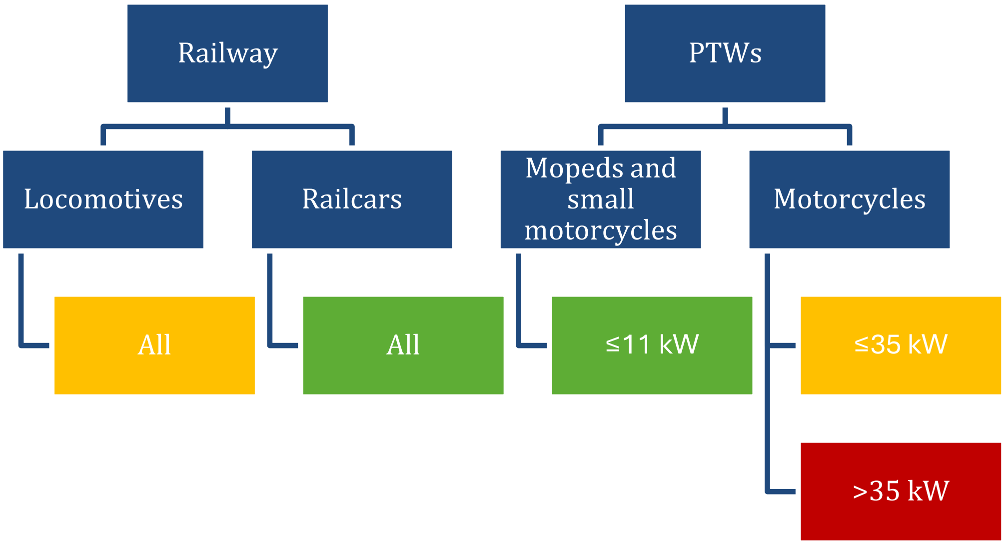
Source: Own illustration by ICCT

Figure 56: Tiered category for NRMM non-vehicles. Note: green denotes high electrification potential, yellow is medium electrification potential, red is low electrification potential.



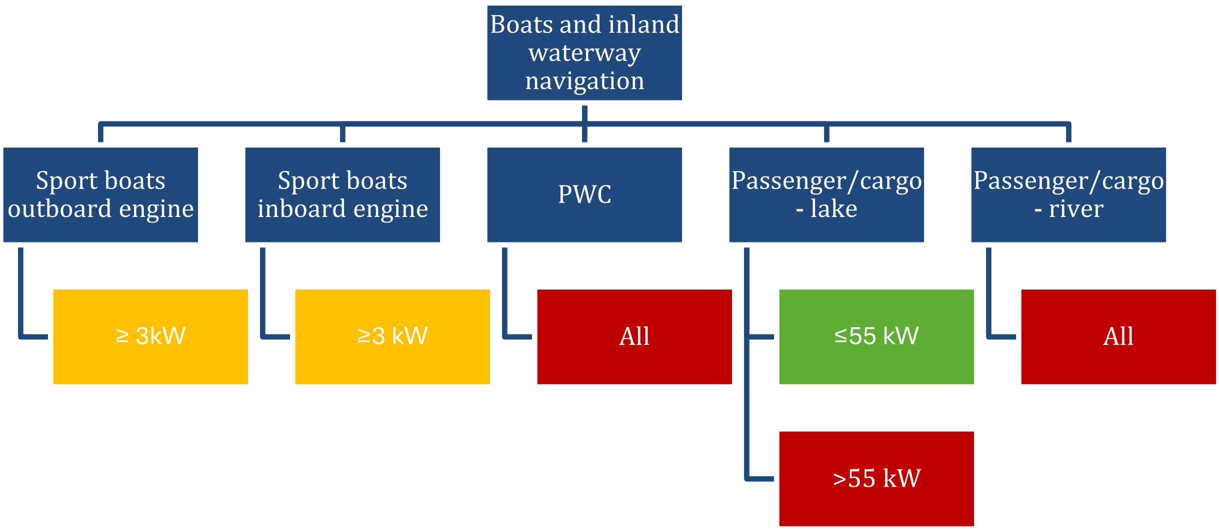
Source: Own illustration by ICCT

Figure 57: **Tiered category for Railway and powered two-wheelers. Note: green denotes high electrification potential, yellow is medium electrification potential, red is low electrification potential.**



Source: Own illustration by ICCT

Figure 58: **Tiered category for boats and inland waterway navigation. Note: green denotes high electrification potential, yellow is medium electrification potential, red is low electrification potential.**



Source: Own illustration by ICCT

For this scenario, we apply no targets to the “Low” tier, as the potential of electrification is particularly low for these machines.

- For the "Medium" tier we apply a 30 % zero-emission target in 2035 chosen as all of the machines that fall within this tier have a minimum electrification potential of 30 % in 2035. This target rises to 50 % in 2050.
- For the "High" tier, we apply a 70 % zero-emission target in 2035 increasing to an 85 % target in 2050.
- For all NRMM where a registration procedure is uncommon in the EU, we apply a five-year delay to the introduction of the targets to accommodate the establishment of Union-wide registration procedure. This applies to NRMM non-vehicles and NRMMM which do not operate on public roads.

This scenario would have a wider reaching scope than Scenario 1, with machines representing 74 % of all energy consumption in the NRMM sector regulated: machines representing approximately 57 % of energy consumption in the NRMM sector in the EU would be covered under the "Medium" tier category while 17 % of NRMM energy consumption would be covered under the "High" tier.

Flexibilities could be included in such a regulation, as discussed in Section 5.3.4, to ease the effort of compliance for manufacturers. These could include an averaging, banking, and trading system to allow manufacturers to overcompensate in certain sectors to offset under-compliance in harder-to-abate sectors, exemptions for small scale manufacturers and manufacturers of machinery that is particularly hard to transition to zero-emission, and a weighting mechanism that account for the CO_2 contribution of certain machines. While we do not quantify the impact of such flexibilities in this scenario, a future regulation should take these flexibilities into consideration.

The issues with the lack of a uniform registration procedure poses a significant issue for this scenario. In the on-road sector, CO_2 reduction targets are set based on the new registrations of vehicles. As no such procedure for registration exists for NRMM, this poses a large challenge in the establishment of such a regulation.

Under the Machinery Regulation, a manufacturer is required to provide a declaration of conformity with every machine put on the market. Market Surveillance authorities are entitled to ask for these declarations to be produced up to 10 years after the last unit has been placed on the market. One potential solution would be to create a centralized database at the Member State level which gathers information from every declaration of conformity relevant to NRMM for the fuel type to be included in declarations. This would allow for the monitoring of the production of NRMM and could establish a requirement in the shift towards zero-emission powertrains under this scenario. This process would deviate from the on-road sector standards which are set by new registrations and instead be based on the number of machines produced in a given year.

5.5 Demand side regulations related to NRMMs

The focus of this project is to highlight possible supply-side regulations to drive decarbonisation in the NRMM sector, i.e., regulations requiring manufacturers to improve or transition their technologies. However, there are many examples of action that can be taken at the demand side by national and local authorities to spur the deployment of zero-emission technologies.

Below is a sample of four different such measures globally, each which used a distinctive approach: Oslo through public procurement rules, London through establishing a low-emissions zone for construction equipment, The Netherlands through providing access to public funding, and New York City through pilot programs.

5.5.1 Oslo

As a means of incentivizing the adoption of zero-emission construction equipment, the City of Oslo amended their procurement strategy to put a greater weighting on the emissions contribution of publicly procured machinery and vehicles (Hepsø, Mortensen 2024). From 2025, the city requires all municipal construction projects to be emission-free at a minimum. From 2030, all construction work should be zero-emission. By 2023, 77 % of the machinery deployed in municipal construction sites was zero-emission. This has been achieved through approximately €1–2 billion in annual investment spending, including on schools, care facilities, roads, metro infrastructure, and water and sewage works.

Oslo's approach has been deliberately phased, combining procurement mandates with market dialogue and international collaboration. The City began requesting fossil-free construction sites in 2016, moved municipal projects to fossil-free in 2017, and introduced common tender criteria and pilot projects in 2019. By 2022, Oslo reported over 60 projects using electric construction equipment, demonstrating that the policy has successfully progressed from limited trials to scaled deployment.

In parallel, Oslo has proposed an urban planning regulation extending the approach beyond municipal procurement, requiring that at least 50 % of energy use in all private and public construction projects be zero emission, and that all construction work be zero emission from 2030, signaling an intention to embed zero-emission construction as a city-wide standard. The City identifies remaining challenges as ensuring equipment supply, industry capacity, energy supply solutions, grid impacts, and cost management, supported by enabling measures such as quantified emissions targets, R&D missions, incentives, and emissions regulations

5.5.2 Greater London Area

The Greater London Authority operates a Low Emission Zone (LEZ) for NRMMs that applies to construction sites across Greater London (Mayor of London 2024). The NRMM LEZ is implemented through the Mayor of London and borough planning powers, meaning compliance is tied to planning requirements for construction sites rather than road-use enforcement, and is intended to address NRMM as a significant contributor to local air pollution in London.

The scheme sets minimum engine emission stage requirements for NRMM operating on sites in Greater London. From 1 January 2025, NRMM between 37 kW and 560 kW must meet EU Stage IV as a minimum, while the requirement for generators remains Stage V. The standards are uniform across Greater London and are designed to tighten over time: from 1 January 2030, the requirement becomes Stage V across London, and from 1 January 2040, only zero-emission machinery will be allowed.

Compliance is supported through an online NRMM register, which site operators must use to log machinery within the regulated power range. The register is also the mechanism through which exemptions and retrofit approvals are managed. Exemptions can be granted where compliant machinery cannot be sourced or where machines are retrofitted with approved emissions-reduction systems, but requests must be supported by evidence and are assessed case-by-case.

5.5.3 The Netherlands

In 2023, the Netherlands established a program for Zero Emission Construction Equipment (ZECE) (Schoon en Emissieloos Bouwen 2024). This voluntary program brings together governments, industry stakeholders, and knowledge institutions to increase the deployment of zero-emission construction equipment. The ZECE program establishes 2030 emission reduction targets relative to 2018, including a 60 % reduction in NO_x, a 75 % reduction in PM10, and a reduction of 0.4 Mt CO_2 through advancing the deployment of zero-emission equipment.

The transition is supported by over €1 billion in public funding for equipment purchase support, retrofits, charging infrastructure, and implementation guidance, alongside workstreams on monitoring, bottleneck identification, and maintaining a level playing field. Participation is voluntary, but to benefit from this funding industry stakeholders and local authorities are required to follow the emission reduction targets set by ZECE.

Stakeholders that have agreed to take part in this scheme must follow a tiered ambition structure. Under the basic tier, participants of the scheme must ensure all zero-emission mobile machinery between 19 and 56 kW is zero-emission from 2028. Machinery between 56–560 kW transitions to zero-emission from 2035, and machinery above 560 kW follows between 2035 and 2040 depending on application.

5.5.4 New York City

In 2022, Mayor Eric Adams published Executive Order number 23 which requires NYC capital project agencies to develop and implement measures to reduce emissions associated with municipal construction, explicitly including emissions from construction equipment combustion, as well as embodied emissions from major materials such as concrete, steel, and asphalt (Office of the Mayor of the City of New York 2022). The Order directs agencies to integrate tools such as environmental product declarations, life-cycle assessment approaches, and the adoption of low-emission vehicles and equipment.

In 2023, PlaNYC was published, the city's climate and sustainability plan, which includes a commitment to reduce the climate and air quality impacts of construction by using the City's procurement and capital investment leverage (Binder 2025). The plan sets out actions to lower both operational and embodied emissions from municipal construction, including advancing performance-based standards for low-carbon construction materials and cleaner equipment, with implementation milestones intended within the mid-2020s as part of the City's pathway toward carbon neutrality.

In 2025, The Clean Construction Innovation Pilot was launched, a City-led initiative to partner with manufacturers and suppliers of light-, medium-, and heavy-duty electric construction equipment to trial and assess real-world performance in City-run construction projects. As part of the pilot, the city called for companies who can provide their equipment and right-sized charging solutions at no cost for a period of roughly 2–6 months. During the pilot's duration, the City will evaluate how effective the equipment is under real-world conditions.

5.4.3. California

The In-Use Off-Road Diesel-Fueled Fleets Regulation (California Air Resources Board 2022b) applies to self-propelled off-road diesel vehicles with engines rated at 25 horsepower or greater that operate in California, including owned, leased, and rented equipment. The regulation was originally adopted in 2007 to reduce diesel particulate matter and nitrogen oxides emissions from existing off-road fleets and has since been amended to align with California's greenhouse gas reduction goals. Regulated entities are required to report all applicable equipment to CARB, label engines with identification numbers, comply with idling limits, and meet fleet-average or equipment-specific compliance pathways. Amendments adopted in November 2022 and effective October 1, 2023 accelerated engine phase-out schedules. Tier 0 engines are fully prohibited, Tier 1 engines are largely phased out, Tier 2 engines begin phase-out on January 1, 2024, and Tier 3 engines on January 1, 2028. Tier 4 Final engines may continue operating through 2036. Fleets may utilize renewable diesel as a compliance flexibility, but long-term compliance requires transition toward zero-emission equipment.

5.5.5 EU Clean vehicle directive

The Clean Vehicle Directive (Dir. 2014/24/EU and 2014/25/EU) regulates the procurement of road vehicles for public fleets by setting quotas for low-emission or zero-emission vehicles. These quotas can be met, for example, by vehicles with electric, plug-in hybrid, or fuel cell propulsion systems. To date, tractors and mobile machinery have been explicitly excluded from the CVD. However, these could potentially be included, albeit partially, as part of a revision of the CVD. In that case, targets by machine category and criteria for "clean machines" would need to be defined, along with a monitoring approach—similar to that used for ZEV Mandate for manufacturers. The pioneering role of the public sector is also proposed by the European Associations for construction and agriculture machinery manufacturers (CECE, CEMA 2025), or rather, the concrete implementation within the framework of the CVD by KTBL (Eckel et al. 2024). It should be examined what administrative burden a corresponding extension of the CVD would entail, given that the procurement of mobile machinery or its use by public institutions often takes place in many small-scale processes.

5.6 Other policies

In addition to regulatory measures affecting vehicle, machinery, or engine manufacturers and demand-side measures, the literature and individual stakeholders identify further measures. These were not the focus of the eNRMM study, but they are listed here.

5.6.1 CO_2 pricing/fuel taxes

Differentiated energy taxation can also be used to create incentives for ZEVs (or renewable fuels). (Eckel et al. 2024) discuss various levers in this context. At the EU level, it is expected that the Emission Trading System 2 (ETS2) will lead to rising prices for fossil fuels such as diesel and gasoline in the future. Currently, this affects transportation, buildings, and agriculture. In addition, there are national regulations, e.g., currently the Act on a National Emissions Trading System for Fuel Emissions (BEHG[22]) in Germany. The elimination of subsidies for fossil fuels, e.g., the diesel fuel rebate for agriculture in Germany, could also increase the competitiveness of ZEVs or renewable fuels relative to internal combustion engines. However, the technical potential for ZEVs is particularly limited in agriculture.

Energy taxation is also being addressed by the European associations of construction and agricultural machinery manufacturers (CECE, CEMA 2025), though primarily as part of an overall decarbonization strategy that includes other measures as well.

5.6.2 Fuel quotas

The EU Renewable Energy Directive (RED) III, (Directive EU 2023/2413)[23] establishes incentives for the transport sector to use electricity and renewable fuels. Member states can

[22] "Brennstoffemissionshandelsgesetz vom 12. Dezember 2019 (BGBl. I S. 2728; 2022 I S. 2098), das zuletzt durch Artikel 2 des Gesetzes vom 27. Februar 2025 (BGBl. 2025 I Nr. 70) geändert worden ist"

[23] Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652

implement these in national regulations, e.g., a GHG reduction quota in Germany and some other countries. Complementing this are the Refuel Aviation Directive (Regulation (EU) 2023/2405)[24] for aviation and the Fuel EU Maritime (Regulation (EU) 2023/1805)[25] for shipping. They specify minimum quotas per sector and fuel type. However, the GHG quota also specifies an overall percentage reduction for all fuels (with different sectoral scopes, depending on the country), which can be achieved flexibly through electricity, biofuels, or synthetic fuels. In principle, such requirements could also be extended to NRMM (Eckel et al. 2024) and recreational boats. Although fuel distributors are responsible for compliance, the use of electricity in NRMM could be quantified using default values depending on the NRMM equipment type and the corresponding GHG reduction could be brought into the GHG quota market (bound to the ownership of such equipment). This creates a financial "GHG bonus" for the owner and thus an additional incentive for customers to purchase. For an electric passenger car, for example, the GHG quota bonus in 2025 – depending on the vehicle and contracts – typically ranged between 170 € und 330 €.

However, based on the example of the subsidy amount for electric passenger cars compared to their current higher purchase costs, it can be assumed that the additional incentive for purchasing electric vehicles is relatively small. These incentives, however, depend on the level of GHG quota prices, which depend on a variety of factors and thus are hard to predict. This will probably reduce the incentivizing effect for electric NRMM purchase. The administrative effort of integrating electric NRMM into the GHG quota system should also be considered. It would probably be necessary to define a minimum machine size for participation in the GHG quota market.

5.6.3 Expansion of the grid and charging infrastructure

Infrastructure availability is a key factor in the adoption of zero-emission vehicles (ZEVs); without it, market penetration cannot occur. For construction sites that vary in location and duration, for example, access to local power grids through the respective grid operators is crucial. This is called for by (CECE, CEMA 2025), among others. Mobile battery containers or other energy storage devices can also serve as buffers and high-speed chargers in this context and are already being used at some zero-emission construction sites. For other applications, such as trucks and passenger cars, permanent charging options will be necessary. In this regard, the government must ensure the necessary technical regulations for approval, but can also accelerate the expansion through financial subsidies or favorable loan programs. Relevant examples could be drawn from road transport such as the Alternative Fuels Infrastructure Regulation (AFIR), (Regulation EU 2023/1804) or national programs.

The impact assessment examines the environmental effects of zero-emission machinery and equipment. To this end, the energy consumption, greenhouse gas and air pollutant emissions from NRMM, powered two-wheelers and recreational craft in the EU27 are calculated for each of the possible policy scenarios from the previous chapter for the years 2025–2050. In addition, illustrative life cycle assessments (LCA) are carried out to include the impact of energy supply and battery production for electric machinery.

[24] Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation) (Text with EEA relevance)

[25] Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (Text with EEA relevance)

6 Environmental Impact Assessment

6.1 Impact of political scenarios in the EU27

6.1.1 Scenario definition

Based on the 2025 emissions inventory, several scenarios for the period 2025 to 2050 are calculated using the TREMOD-MM emissions model to quantify their impact on fleets, energy consumption, and emissions:

- In the BAU scenario, the ZEV shares of newly sold machines and equipment will remain constant in the future compared to today (2025).
- In the scenario ZEV Mandate, parts of the new fleet will be electrified from 2035 onwards, depending on the EP, i.e., 30 % of the medium EP group and 60 % of the high EP group. All other equipment remains as in BAU.
- In the POT scenario, the technical potential and the additional H_2 potential per EP group are fully exploited. This scenario represents the theoretical maximum market penetration with ZEVs.

A summary of the assumptions can be found in Table 91.

Table 91: Introduction of ZEV in new sales in the different scenarios

Scenario	Groups	2030	2035	2040	2045	2050
BAU	All	Similar to 2025				
ZEV Mandate	0–33 % EP	Similar to 2025				
	33–66 % EP	BAU	30 % ZEV*	Linear interpolation		50% ZEV
	> 66 % EP	BAU	70 % ZEV*	Linear interpolation		85% ZEV
POT	All	ZEV share = EP/H2 2030	Linear interpolation			ZEV share = EP/H2 2050

Note: a start of a ZEV mandate in 2035 applies for NRMM vehicles, boats and PTW. For NRMM machines a start in 2040 is assumed as developing a registration scheme will take more time.

Scenario 1 (see chapter 5.4.1) was not examined because quantification was not possible. The assumptions used for the calculation, e.g., average lifetime/operating hours/energy consumption, are identical to those used for the emissions inventory (chapter 3). The change in fleets for each scenario is described in the next section.

6.1.2 Modelling of the fleet

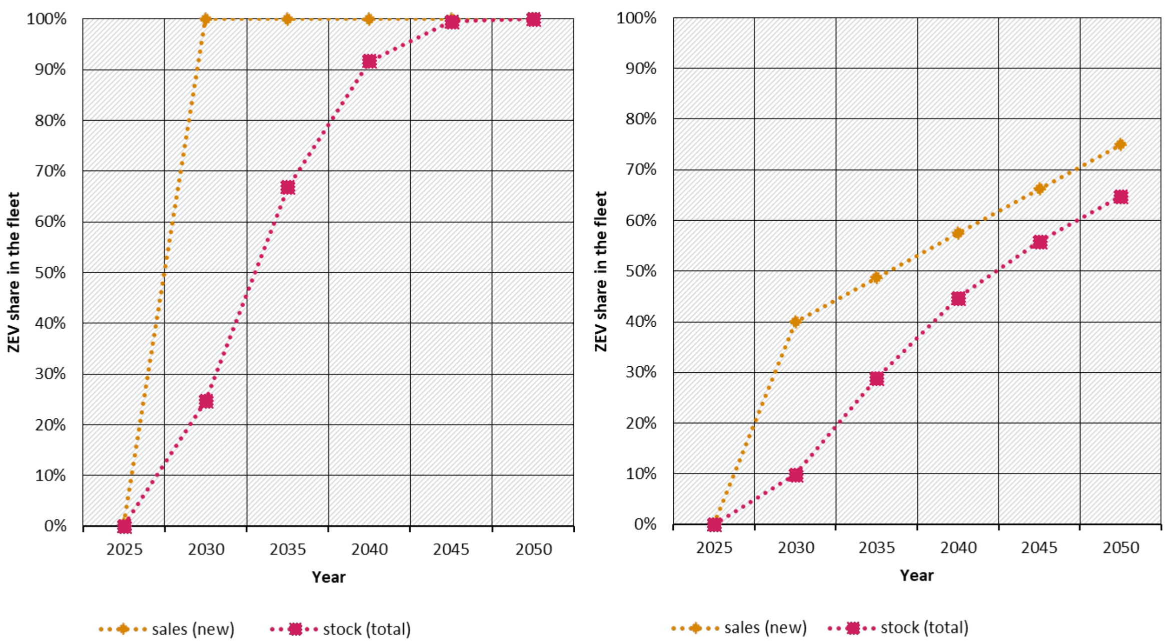
The main variable in the various scenarios is the share of drive types in new registrations and sales figures. The electrification potential for 2030 and 2050 per segment was used as a basis for this share. When target values for a certain year were defined, a linear interpolation is made between those years, e.g. in the POT scenario between 2025 and 2030 and between 2030 and 2050.

Modelling in-use fleet from new sales

The total fleet in use by drive type can be determined based on the age distribution in TREMOD-MM (see appendix and (Heidt et al. 2020)). If, for example, the share of electrical devices in a segment is 10 % of sales figures in 2030 and 0 % in the years before, this 10 % is only applied to devices that are 0–1 year old in 2030. If newly sold devices account for 10 % of the total stock in 2030, the share of electrical appliances in the stock in 2030 would be 1 %.

For the POT scenario, this is illustrated by the example of crawler excavators 18–37 kW and 75–129 kW (Figure 59). For excavators in the 18–37 kW range (left side of the figure), which will already have an EP of 100 % from 2030 onwards, a very steep ramp-up in ZEV shares of sales figures is assumed from 2025 onwards, remaining constant at 100 % from 2030 onwards. The ramp-up will be slower in the existing fleet, reaching approximately 100 % of electric machines only in 2045. For excavators with 75–130 kW, the technical potential for electrification is significantly lower than for smaller excavators. There also will be a sharp increase in ZEV new registrations up to 40 % until 2030, followed by a further slight increase up to 75 % until 2050 in the POT scenario. The stock of ZEV excavators in the 75–130 kW power class will account for just over 10 % in 2030 and increase to almost 65 % by 2050, whereas 50 % of the ZEV are assumed to be electric and 15 % hydrogen-based.

Figure 59: Share of electric equipment in new sales for crawler excavators (left 18–37 kW, right: 75–129 kW) in the POT scenario



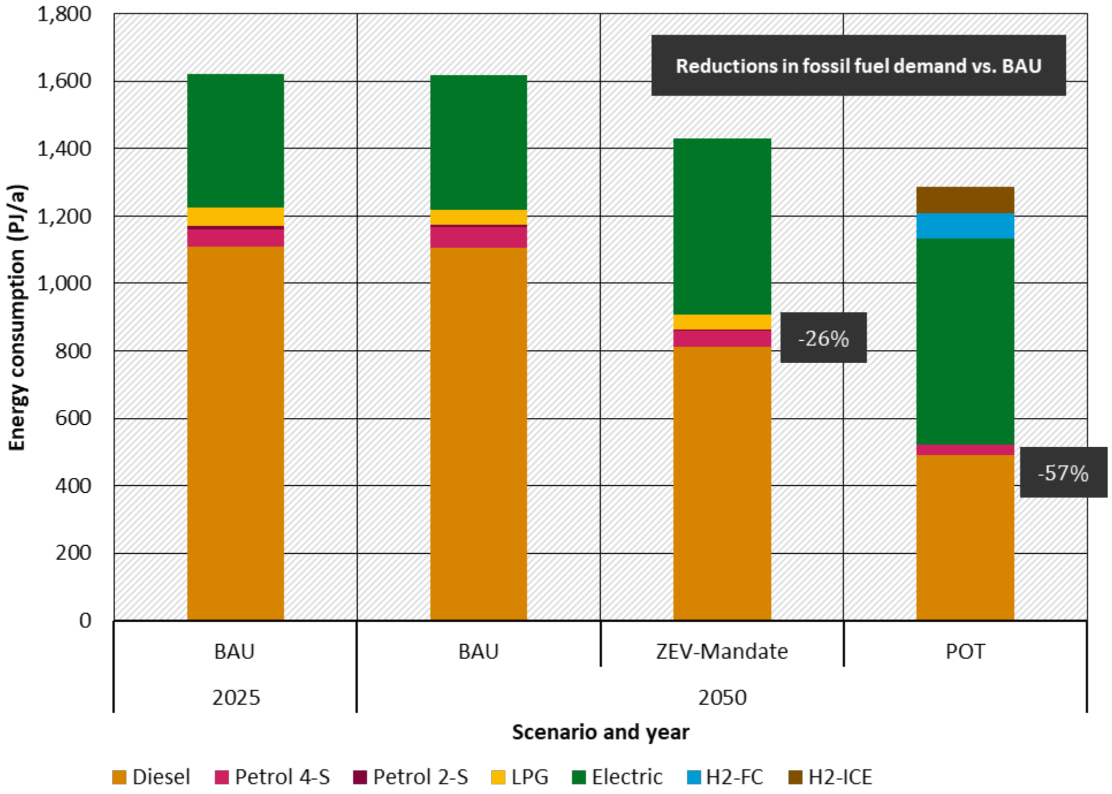
Source: Own illustration by ifeu

The fleet distribution for all product categories was calculated for each scenario. The results on final energy consumption and emissions are presented in the next chapters.

6.1.3 Final energy consumption

The final energy demand of NRMM and recreational boats in the defined scenarios is shown in Figure 60. While the BAU shows almost no decrease until 2050, the other scenarios lead to significant reductions in final energy demand due to the substitution of combustion engines with electric – and in the POT scenario – hydrogen-powered devices. The reduction in fossil fuel demand per scenario compared to the BAU scenarios in the scenario ZEV Mandate is lower as in the POT scenario. At the same time, the demand in electricity and hydrogen increases in the same order.

Figure 60: Final energy demand of NRMM and recreational craft by scenario and fuel type, EU27

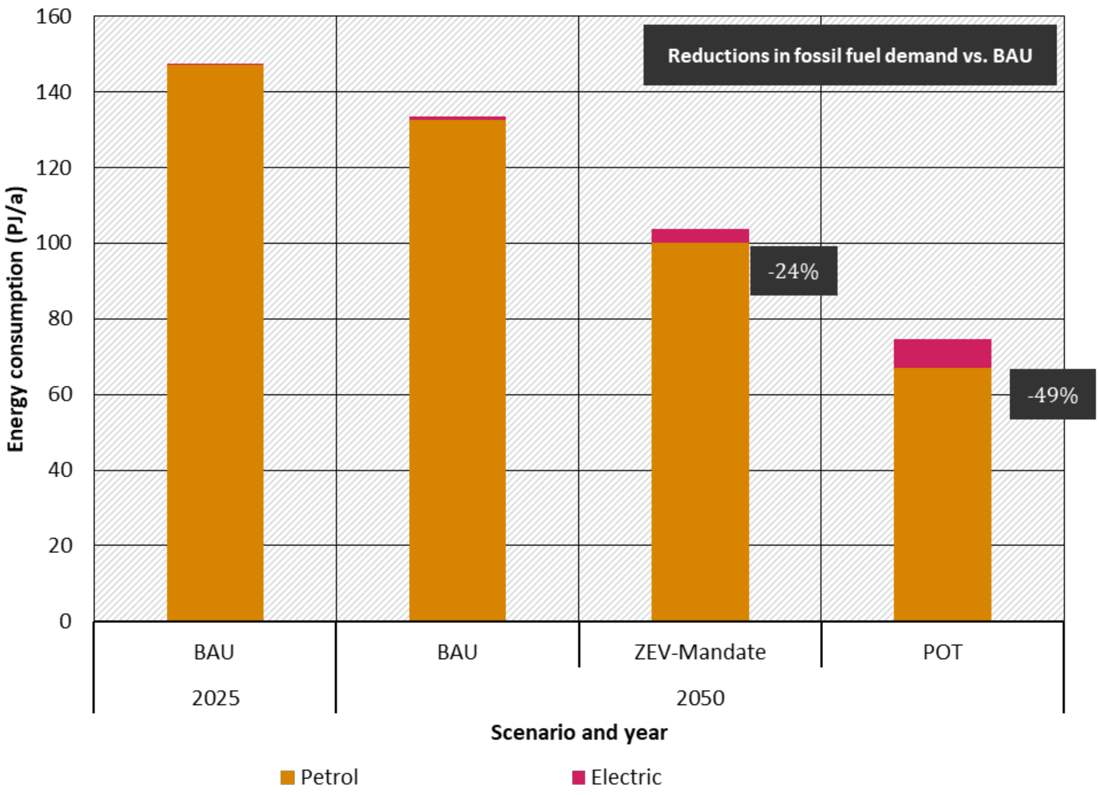


Source: Own illustration by ifeu

Nevertheless, even if the technical potential is fully exploited (POT scenario), a high demand for liquid fuels (mostly diesel) remains in 2050. At around 550 PJ/a, the demand for fuels almost corresponds to the current amount of biofuels used for transport in the EU27. This is partly due to the limited potential for electrification of new machinery, but also to the long service life of the existing fleet, as 9 % of fossil fuel consumption in 2050 will be accounted for by machinery that is 30 years old or older.

In the BAU scenario, a slight decline in final energy demand is assumed for powered two-wheelers, which is only partly due to electrification and largely due to a decline in the number of vehicles and mileage. In the ZEV-Mandate Scenario, final fossil energy consumption will be reduced by additional 24 % and in the POT-scenario by 49 % POT by 2050 due to higher electrification (Figure 61). However, there is still a significant demand for fuels here as well, at around 70 PJ at minimum, as not all powered two-wheelers can be electrified by 2050.

Figure 61: Final energy consumption of powered two-wheelers per fuel type and scenario, EU27

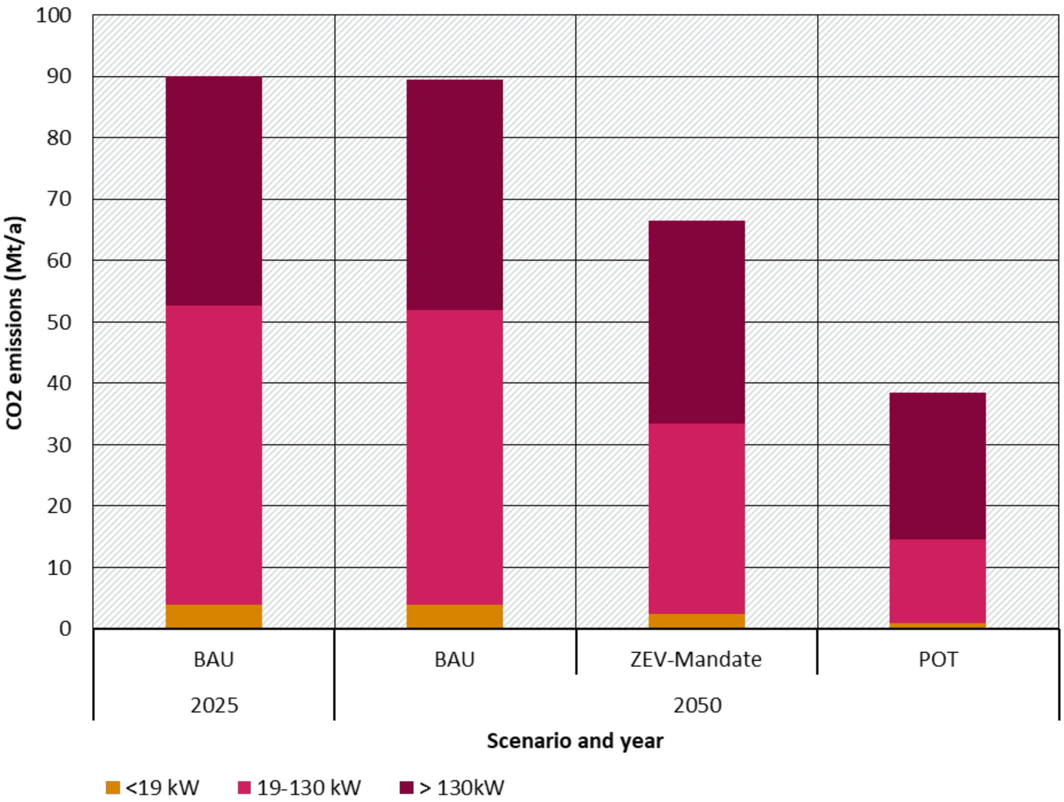


Source: Own illustration by ifeu

6.1.4 Direct CO_2 emissions

Direct CO_2 emissions from NRMM and recreational boats in the EU27 will remain more or less constant between 2025 and 2050 in the BAU scenario, as there will be no drive change, the efficiency of combustion engines will only improve slightly and assuming use of mostly fossil fuels. The emission reductions in the policy scenarios and the POT scenario are similar to the reduction in fossil fuel demand with -26 % for the ZEV Mandate and -57 % for the POT scenario. In the ZEV Mandate scenario the reductions are achieved by the power classes with <130 kW, whereas in the POT scenario the power class > 130 kW also contributes due to individual product categories such as excavators and dump trucks which can be electrified to a small amount and hydrogen engines for a large number of construction machinery as well as for tractors and combine harvesters (Figure 62).

Figure 62: Tailpipe CO_2 emissions of NRMM and recreational craft by scenario and fuel type, EU27



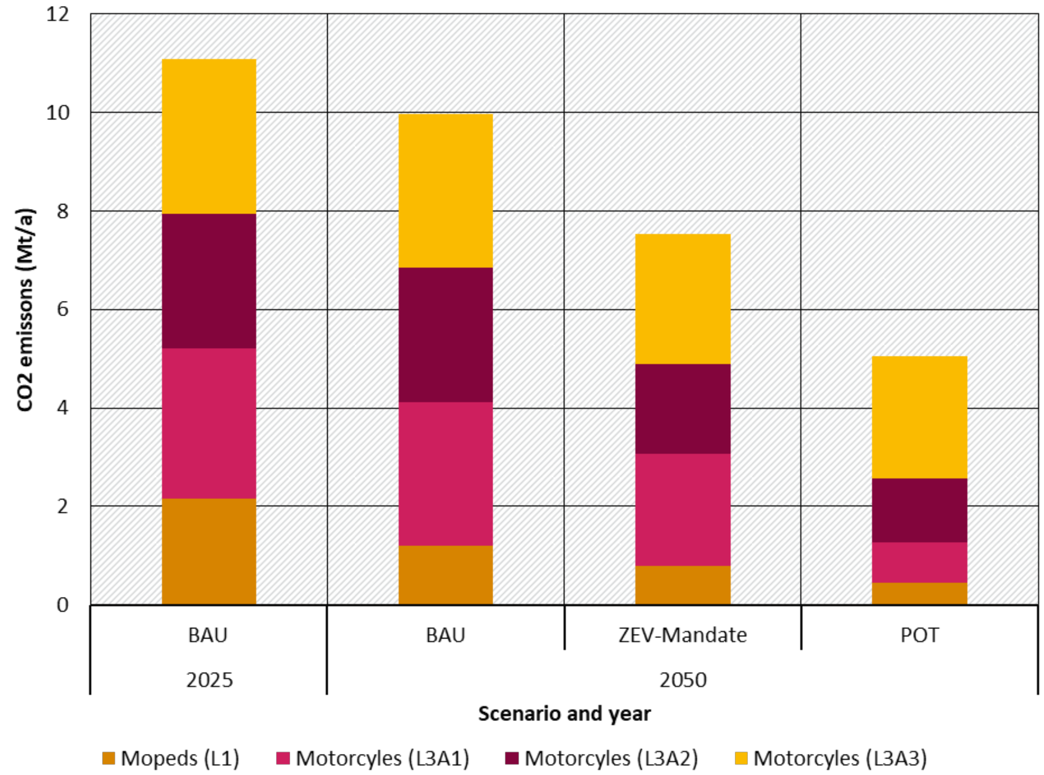
Source: Own illustration by ifeu. Note: Exhaust emissions are calculated using 100 % fossil fuels.

Decarbonisation of combustion engines?

Even in the POT scenario, CO_2 emissions are still around 40 Mt per year. Additional measures would have to be taken to achieve the European GHG target of zero emissions by 2050. One option would be to run the remaining combustion engines on renewable fuels, such as sustainable biofuels or synthetic fuels produced from renewable electricity. These options were not the focus of the eNRMM study but were frequently mentioned in discussions between machine manufacturers in the context of technological openness. If such fuels were available in sufficient quantities and at reasonable costs, they could potentially be used to operate machines that cannot be electrified for technical reasons or to operate older machines.

In the ZEV-Mandate Scenario, direct CO_2 emissions from powered two-wheelers will fall by 24 % and in the POT scenario by 49 % by 2050 as a result of additional electrification (Figure 63). Due to the varying electrification potential, emissions from mopeds (L1) and smaller motorcycles (L3A1+2) will be reduced in particular. For larger motorcycles (L3A3), there will be little to no reduction by 2050 than for smaller vehicles.

Figure 63: Tailpipe CO_2 emissions of powered two-wheelers by scenario and fuel type, EU27



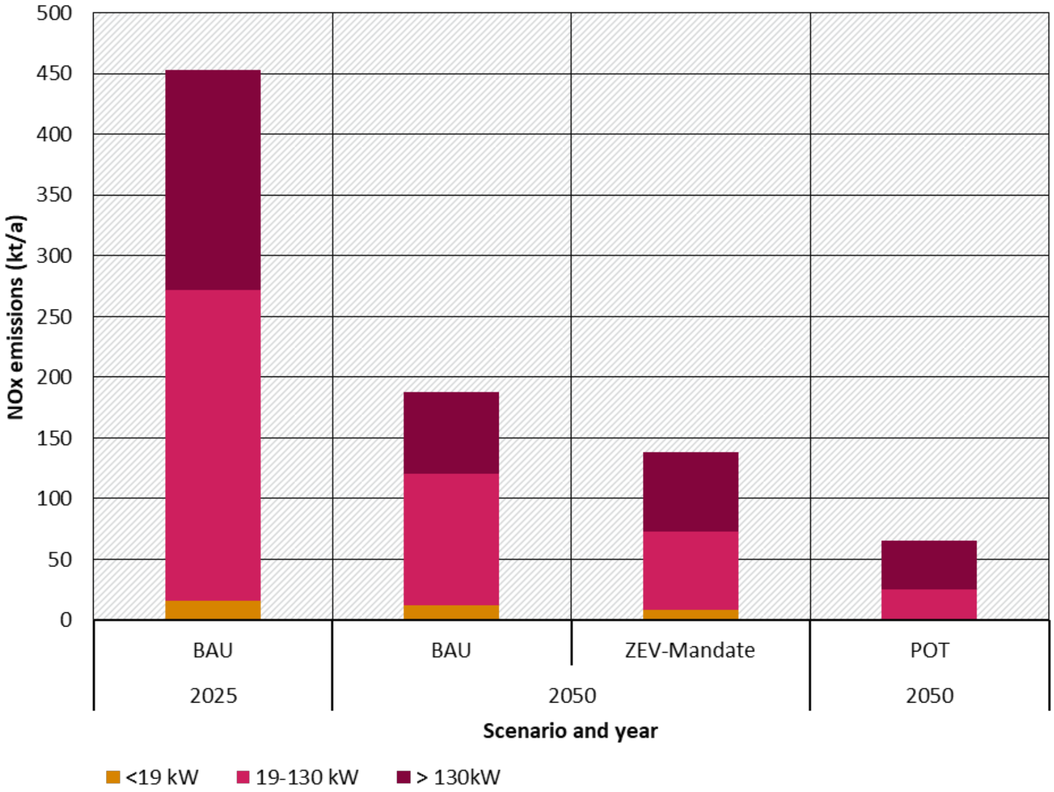
Source: Own illustration by ifeu

6.1.5 Air pollutants

Air pollutants will decrease considerably in all scenarios. Even in the BAU scenario, i.e. without a change in drive systems, nitrogen oxides (NO_x) emissions will fall sharply by 60 % until 2050. The reason for this is that older machinery will be replaced by machinery with modern emission standards, such as NRMM Stage V. The reduction will be greatest in the upper power classes, as this is where the strictest emission limits apply.

In the POT scenario, NO_x emissions will fall by more than 80 % in 2050 compared to 2025, particularly in the smaller and medium power classes. This is 65 % lower than BAU emissions in 2050. The ZEV Mandate scenario also show additional NO_x reductions, but to a lower extend than the POT scenario.

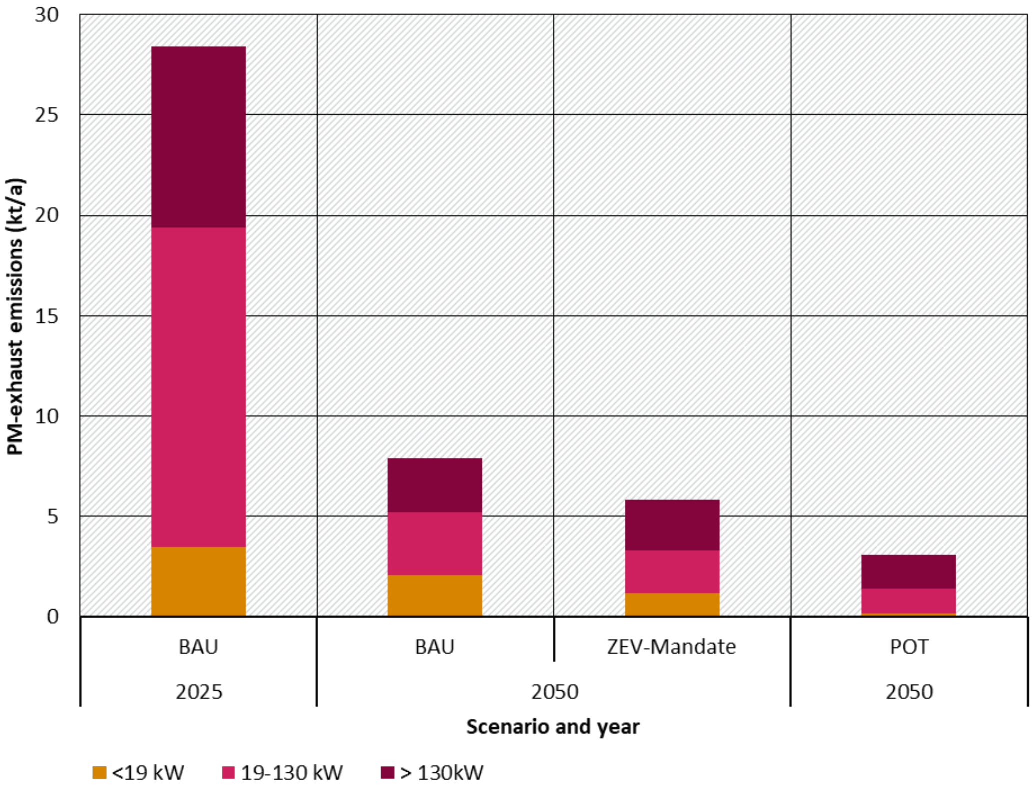
Figure 64: NO_x emissions of NRMM and recreational craft by scenario and fuel type, EU27



Source: Own illustration by ifeu

The picture for particulate matter (PM) emissions is similar to that for NO_x. Existing emission standards and fleet renewal are reducing emissions in all scenarios. In the BAU scenario, they fall by over 70 % by 2050 compared to 2025. Zero-emission powertrains in the POT scenario could halve emissions once again (Figure 65). The EV Mandate scenario also show additional PM reductions, but to a lower extend than the POT scenario.

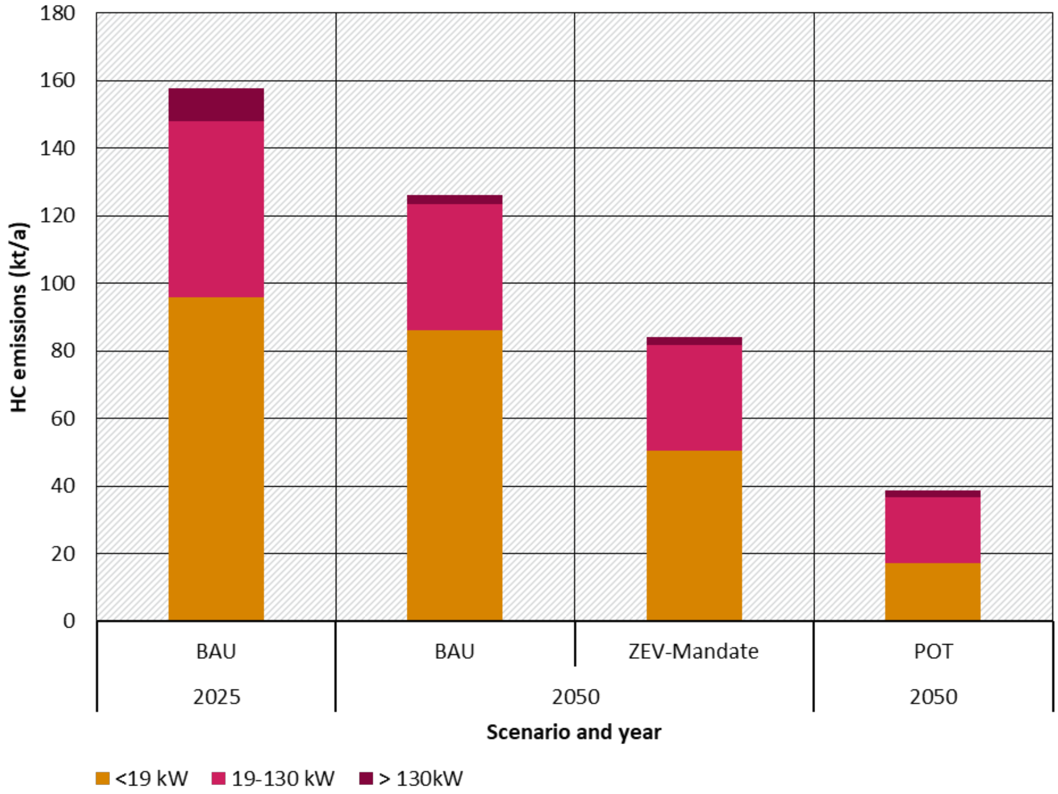
Figure 65: PM10 emissions (exhaust) of NRMM and recreational craft by scenario and fuel type, EU27



Source: Own illustration by ifeu

Unlike NO_x and PM10, hydrocarbons (HC) emissions tend to be produced by smaller devices, which are often powered by gasoline engines today. In these cases, the effects of fleet renewal with the current limit values are significantly lower, which is why HC emissions in the BAU scenario do only fall by ~20 % and thus not as sharply as NO_x emissions. In the POT scenario, on the other hand, the reduction is also very high, as electrification can effectively reduce these emissions, especially in small appliances (Figure 66). The ZEV mandate would also lead to additional HC reductions, as it would result in additional electrification in the area of small and handheld devices (NRS, NRSh) that cannot be 100 % electrified due to fleet targets.

Figure 66: HC emissions of NRMM and recreational craft by scenario and fuel type, EU27



Source: Own illustration by ifeu

6.2 Exemplary life cycle GHG emissions

Electric drivetrains lead to zero tailpipe emissions, as demonstrated above. Nevertheless, upstream emissions for energy production and distribution as well as emissions to produce and dispose machinery can increase on the other hand. Such aspects are examined in so-called life cycle assessments (LCA). As part of the study, a simplified LCA was carried out for selected categories of machinery.

6.2.1 Methodology

The GHG emissions in this screening LCA include:

- use phase (fuel combustion in combustion engines),
- energy supply (upstream), i.e., for the extraction, refining, and transport of diesel, as well as the generation and distribution of electricity for electric machines,
- manufacture of batteries for electric machinery

For the production of machinery thus only the additional emissions from the batteries are considered, while the body and engines or motors are neglected since they are assumed to be roughly comparable between machines with combustion and electric engines. Also maintenance as well as fueling and charging infrastructure are not covered.

Since there have been improvements in upstream emissions from electricity in particular due to the growth of renewable energies in recent years, and since further improvements are planned for the future, we examine the current status (2023) and a scenario for the year 2030. The screening LCA represents average energy/fuel mixes for the EU27. A comparison of purely renewable options, e.g., green electricity, HVO100 and PtL for diesel engines, was not carried out, as there are currently no incentives to bring these to market in larger quantities by 2030. The assumptions are shown in the following two tables.

Table 92: Machine parameters for the LCA

Parameter		Mini excavator	Agricultural tractor	Wheel loader	Crawler excavator
Machine data	Power [kW]	28	100	103	215
	Average load factor	0.30	0.30	0.30	0.30
	Average operating [hours/a]	560	300	1130	1280
	Lifetime [years]	10.0	10.0	8.8	7.8
Energy efficiency	Diesel engine	32 %	37 %	37 %	37 %
	Electric engine	85 %	85 %	85 %	85 %
	Incl. charging losses	73 %	73 %	73 %	73 %
Battery	Capacity [kWh]	36	100	229	542

Source: Machine data from TREMOD-MM, efficiency data see annex, charging losses 17% based on HBEFA 5.1, battery capacity based on simulations by TUG (see chapter 4)

Table 93: Energy and emission factors for the LCA

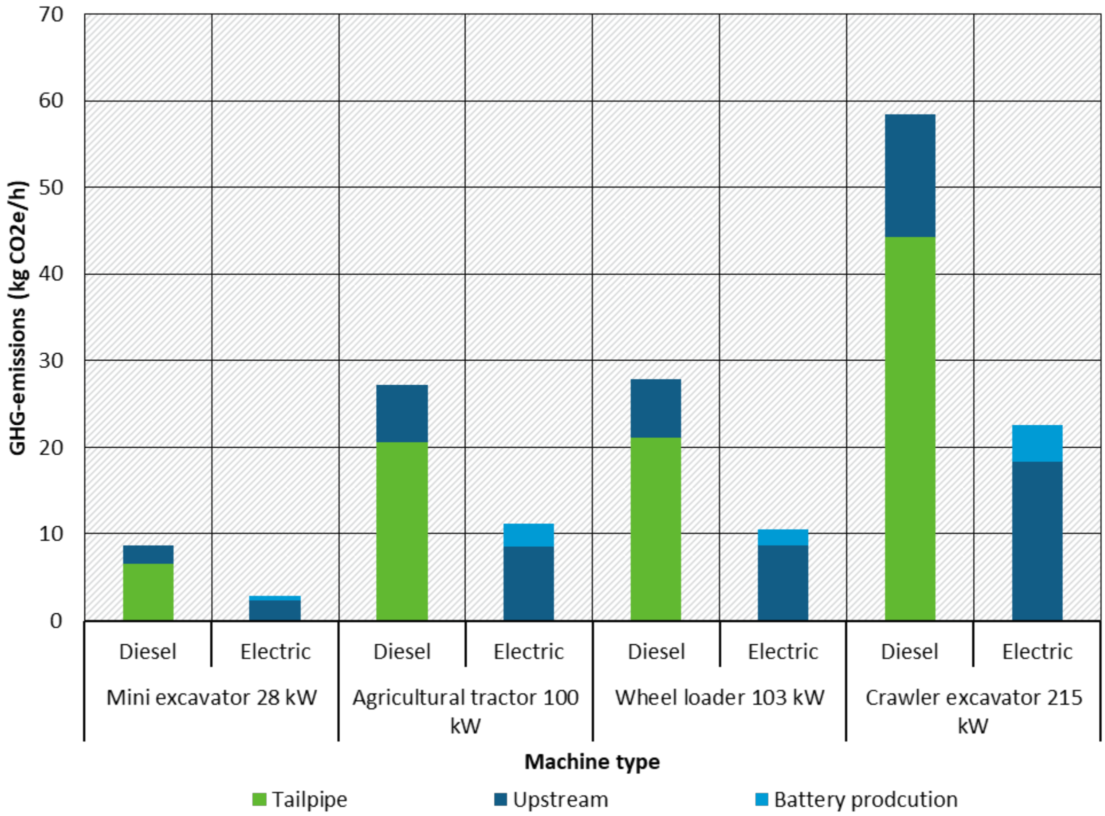
Energy type	Parameter	2023	2030
Diesel	Biofuel share	6.5 %	10.0 %
	Tailpipe [kg CO_{2e}/kWh]	0.254	0.245
	Upstream [kg CO_{2e}/kWh]	0.081	0.080
Electric	Upstream [kg CO_{2e}/kWh]	0.207	0.110
	Battery production [kg CO_{2e}/kWh]	80	80

Source: Biofuel share 2023 EEA data for transport, 2030 own assumption based on the trend scenario for road transport in TREMOD 6.63 in order to comply with the EU RED directive. Tailpipe and upstream emission factors diesel by TREMOD 6.63. Upstream emission factors electricity by (European Environment Agency 2025). Battery production (LFP battery) emission factors by (Biemann et al. 2025).

6.2.2 Results

Figure 67 shows emissions in kg CO_2 per operating hour for the four selected machine types in 2030. Diesel machines mainly show tailpipe emissions and limited additional emissions from fuel supply (upstream). Electric machines on the other hand have no tailpipe emissions but significant upstream emissions for electricity generation and additional emissions from battery production. Overall, all electric machines have over 70 % lower emissions than diesel machines.

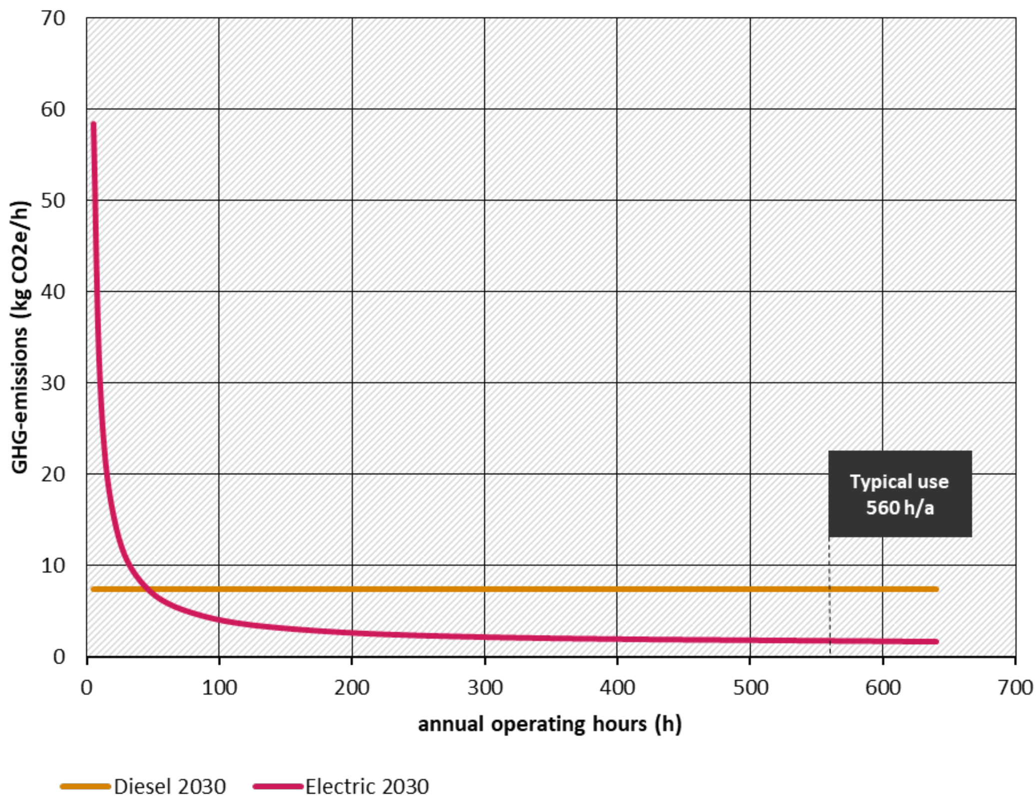
Figure 67: Specific LCA GHG emissions of selected electric vs. diesel machines 2030



Source: Own illustration by ifeu

The example of the mini excavator illustrates GHG emissions depending on annual usage (Figure 68). As shown above, electric machines emit GHG emissions primarily during the usage phase. In order to offset the manufacturing emissions of the battery, the machines must have a sufficient intensity of use. In the case of the mini excavator, the emissions of an electric excavator would only be higher if it were to operate for more than 50 hours per year. This is significantly lower than the typical average operating hours of mini excavators. For machine types that require a correspondingly large battery despite lower annual usage, the LCA for electric devices could be less favorable.

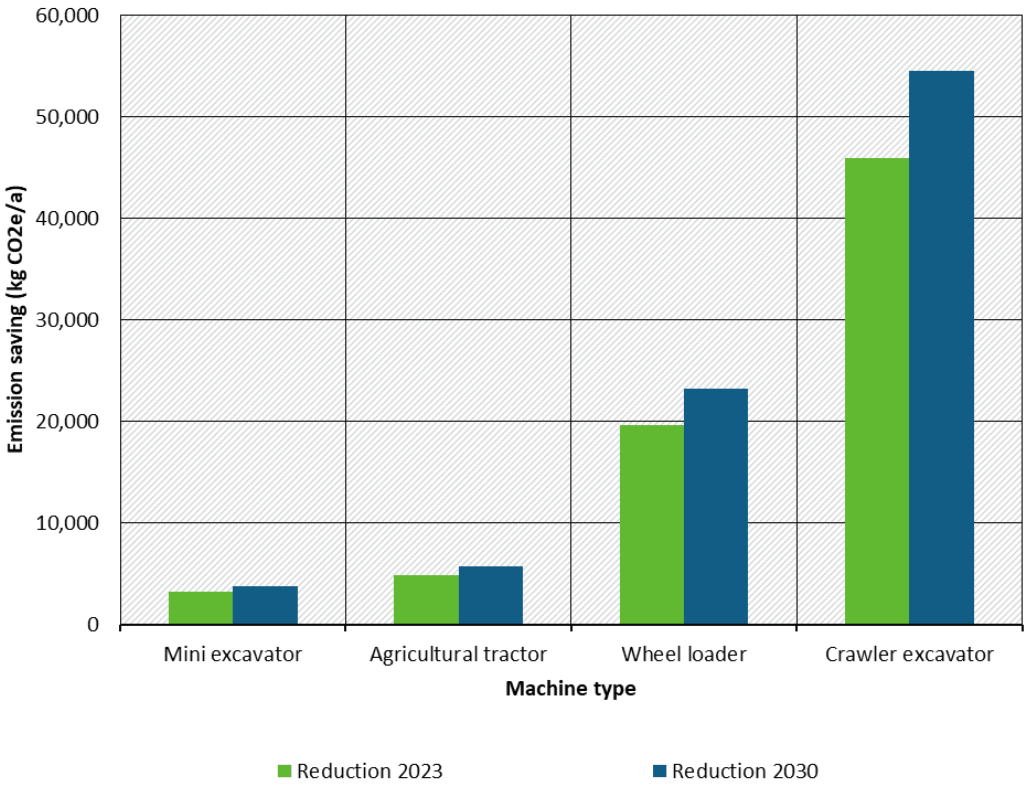
Figure 68: Specific LCA GHG emission of a mini excavator depending on annual use



Source: Own illustration by ifeu

The total reduction (Figure 69) also depends on the use intensity. Therefore, the electrification of less intensely used tractors, for instance, leads to a significantly lower annual GHG reduction than the electrification of heavily used wheel loaders, although the reduction per operating hour is similar. In 2030, higher GHG savings are expected than in 2023, as the electricity mix will improve significantly. Although an increase in the share of biofuels is also assumed for diesel equipment, this increase is significantly lower than the increase in renewable energies in electricity production.

Figure 69: Annual LCA GHG emissions savings of selected electric vs. diesel machines, 2023 and 2030



Source: Own illustration by ifeu

6.2.3 Conclusions

The selected examples show clearly that electrification leads to a significant reduction of GHG emissions from NRMM compared to diesel machinery. The analysed categories have both a significant potential for electrification and a relevant share of total emissions. However, this is an average assessment. In particular, the local electricity mix influences the results. A higher share of fossil electricity generation will naturally lead to lower savings, and conversely a higher share of renewable energies will lead to higher savings. While the average share of renewable energies in the electricity mix in the EU27 was around 25 % in 2023, it was significantly higher in some Nordic countries (Sweden 66 %), for example, but lower in some Eastern European countries (Poland 17 %) and in Germany (22 %) (European Environment Agency 2026).

Usage profiles also have an important influence. E.g., recreational craft for private use, generators for emergency power supply or combine harvesters face the challenge that the energy requirement for a single use (e.g., for a trip or an operation) is comparatively high, but this only occurs on a few days per year. This reduces the ratio of emissions from the use phase to battery production, and the advantage over combustion engines is smaller or no longer exists. However, with increasing reductions in emissions from power generation and battery manufacturing[26], electric machines could also gain an advantage here in the future.

[26] For simplicity, this study assumed constant emissions from battery production for 2023 and 2030. In reality, the carbon footprint of batteries is expected to decrease already by 2030.

LCA results from other studies

During the expert workshop, the manufacturer Liebherr presented LCAs for various types of construction machinery and energy sources, including diesel and electricity (with the German electricity mix) as well as hydrogen, HVO and other renewable energies. It was found that, even in this case, BEVs with an average German electricity mix had lower emissions than combustion engines in wheel loaders and concrete mixer trucks. However, this was not the case for mobile cranes, because the manufacturing emissions for the battery were relatively high compared to the emissions of diesel vehicles.

Ricardo's study on boats shows, for example, that electric devices can in some cases have higher LCA emissions than gasoline or diesel-powered boats. This is due to a very low annual usage (in some cases less than 50 hours per year) combined with high power and battery size. Emission savings from the use phase can then not compensate the additional emissions from battery production. In many cases, drop-in fuels were assessed as an alternative with lower CO_2 emissions. Only in applications with comparatively high usage, e.g., commercial PWCs (with 156 h/a), were BEVs the best ecological alternative. (Zenié et al. 2023)

7 Feedback from stakeholders

The aim of the stakeholder involvement during this study was to provide contextual and practical insights that complement the analytical work of the study and help ensure that the assessment and findings align with real-world conditions, sector-specific knowledge, and the diversity of perspectives relevant to the subject matter. This chapter summarizes the perspectives of external stakeholders that were collected over the course of the project.

The analysis integrates contributions from numerous online exchanges conducted with individual stakeholder groups and the expert workshop that took place in Brussels (see A.4). These include e.g. machine and engine manufacturers, associations, machine operators, authorities, NGOs and research institutes. These exchanges addressed specific questions related to individual sectors and groups of machinery as well as feedback about the study.

The synthesis presented here is based primarily on the presentations and written feedback provided by external experts and was supplemented with notes prepared by the project team. Prior to publication, the text below was not discussed or formally validated with the stakeholders involved and therefore reflects the assessment of the project team. Since the results are not derived from a scientifically representative survey, they may therefore disproportionately reflect the industry perspective, as stakeholders from this group were involved to a greater extent than those from other groups.

- **Innovation pathways and industry commitment:** Industry is strongly committed to decarbonisation and is investing across a broad innovation portfolio, including electrification, hybrid systems, alternative and renewable fuels, hydrogen concepts, efficiency improvements, and digital technologies. Manufacturers have successfully applied electrified machines in multiple applications for several years and continue to expand these deployments, demonstrating practical and scalable solutions. This portfolio approach reflects the diversity of applications and is seen as the most effective way to achieve meaningful emission reductions while maintaining performance and customer value. Within the framework of the eNRMM project and with regard to NRMM, it was primarily construction machinery manufacturers who were already developing and offering electric solutions, while these are still less developed in the agricultural sector.
- **Diversity of use cases – no one-fits-all solution:** Across NRMM, recreational craft and powered two-wheelers, applications differ fundamentally in duty cycles, power demand, operating environments and customer requirements. It was emphasized that the appropriate technical solution is primarily determined by the specific use case rather than by the machine category. This implies that each use case requires an adapted solution, reinforcing that a one-size-fits-all or fleet-based approach is often not suitable and multiple technologies will need to coexist over the long term. One example is a small farm tractor, which is technically easy to electrify. This is a good option for livestock farms due to the existing connections for electrical appliances, often in combination with PV systems on barn roofs. However, farms that focus on grain production often do not have these prerequisites, but often do have own refueling stations.
- **Electrification opportunities and clear limitations:** Electrification can be an effective decarbonisation pathway for certain applications with predictable usage patterns, sufficient infrastructure, and moderate power requirements. Many manufacturers have successfully deployed electric machines in selected applications, demonstrating that electrification can work in practice where conditions allow. However, in many use cases, electrification faces structural limitations such as energy storage density, space and weight constraints, long

operating hours, limited charging access, and low annual utilisation. In these cases, hybrid solutions or alternative fuels often represent more practical pathways than full electric concepts. A rigid electrification focus risks excluding more effective solutions and slowing overall emission reductions.

- **Technology neutrality and openness are essential:** Within the industry, the prevailing opinion is that decarbonisation policies must remain technology neutral. A technology-neutral approach is essential to reflect real-world conditions and sector diversity. A strong focus on electrification alone is insufficient and risks overlooking viable and necessary alternatives. It was emphasized that combustion engines powered by biogenic, renewable or other low-carbon fuels will continue to play a crucial role, especially given the long service life of existing fleets. Maintaining technological openness is therefore essential to ensure realistic and effective emission reductions. Any regulatory changes should therefore be preceded by comprehensive impact assessments.

- **Infrastructure and energy availability as critical enablers:** The success of decarbonisation efforts depends heavily on the availability and suitability of energy infrastructure. Grid capacity, charging access, mobile refuelling solutions and the production, distribution and storage of alternative energy carriers are decisive factors. Demand-side measures are therefore crucial, such as public funding for alternative fuel and charging infrastructure. Infrastructure planning must reflect real operational conditions and user behaviour. Without adequate and accessible infrastructure, even technically viable solutions will not achieve market uptake or climate impact.

- **Lifecycle perspective over tailpipe-only focus:** A full Life Cycle Assessment (LCA) approach is widely recognised as the most comprehensive and effective framework for decarbonisation. LCA captures emissions from manufacturing, energy production, use phase, and end-of-life, and avoids burden shifting from use to production. This is especially relevant for sectors with long product lifetimes and low-usage intensity, such as recreational craft. LCA-based regulation aligns well with existing EU frameworks such as the Green Claims Directive, and the Ecodesign Regulation. The industry is strongly aligned around LCA and is actively developing transparent, science-based, and ISO-aligned methodologies at European and global level to ensure harmonisation and credibility. In addition, the issue of long-term availability of resources (e.g., rare earths) was mentioned as an important topic for market ramp-up.

- **Economic viability and Total Cost of Ownership (TCO):** Market uptake of low-emission technologies depends not only on technical feasibility but also on economic viability. Customers base purchasing decisions on total cost of ownership, operational reliability, productivity and ease of use and service. While electrified solutions are approaching cost parity in some segments, in many segments, particularly heavy-duty and low-volume applications, electrified solutions remain significantly more expensive and offer limited economic benefit to customers. Sustainable and renewable fuels, including e-fuels, offer a viable route by leveraging existing fleets and infrastructure. Incentives, supportive financing schemes and fleet renewal programmes are therefore important to accelerate adoption and to enable economically viable decarbonisation.

- **Global markets and economies of scale:** Due to comparatively low production volumes, NRMM products and powertrains are typically developed for global markets to achieve sufficient economies of scale. Many manufacturers are SMEs or low-volume producers, sometimes producing only single-digit units per model. The EU market alone is generally too small to justify unique technical solutions across all machine categories. Fragmented or region-specific regulation risks increasing costs, slowing innovation and weakening industrial resilience.

- **Importance of stable, predictable, and proportionate regulation:** Effective decarbonisation requires regulatory frameworks that are stable, long-term and proportionate to the size and structure of the sector. Zero-emission fleet mandates are not appropriate for sectors, where no fleet-level compliance mechanisms exist and where EU-wide registration systems are fragmented or absent altogether. While national initiatives can help stimulate early adoption, EU-wide and international alignment is essential to create scale and planning certainty. Overly prescriptive regulation risks creating new dependencies, reducing competitiveness and undermining the European manufacturing base.

Key enablers for successful decarbonization: Effective decarbonisation requires technology neutrality, lifecycle-based assessment, infrastructure readiness, availability of sustainable energy carriers, and economically viable solutions for users. Equally important are a competitive business environment, fair global competition and policies that support fleet renewal and the decarbonisation of existing machines. Together, these elements form the foundation for a realistic and sustainable transition.

8 Policy recommendations

NRMM contribute a significant share towards CO_2 emissions but remain the last non-regulated mobile source. Our analysis finds that NRMMs account for a non-negligible share of EU greenhouse gas emissions—around 3 % of total EU GHG emissions and approximately 90–110 Mt CO_2e annually—yet these CO_2 emission remain largely outside the scope of EU regulation, in contrast to road transport, aviation, and maritime sectors. Agriculture and construction alone represent the majority of NRMM emissions, and without targeted regulatory intervention these emissions are projected to persist well beyond 2030, creating challenges for Europe's net-zero target for 2050. The absence of any CO_2-focused regulatory framework for NRMM therefore represents a clear policy gap that risks locking in fossil-fuel-based technologies in a sector with long equipment lifetimes and slow turnover.

A high degree of electrification will be possible by 2030 in multiple sectors. Our technical assessment shows that a high degree of electrification is already feasible by 2030 for many NRMM segments, particularly in lower power classes of hand-held equipment, forklifts, small construction machinery, and the two-wheeler sector. These categories combine relatively low daily energy demand, predictable duty cycles, and comparatively good access to charging infrastructure, resulting in high or very high electrification potential. While larger and more energy-intensive machinery will remain challenging to electrify, substantial CO_2 reductions could be achieved this decade by prioritising those segments where electrification is technically viable without requiring major behavioural or operational changes. However, our own analysis and feedback from stakeholders show that there is considerable variation within the categories and that not every use case is equally suitable for electrification. Future policies face the challenge of leveraging existing potential while taking limitations into account.

Stage V could be amended to further incentivise electrification. A review of the Stage V regulation presents a near-term opportunity to strengthen incentives for electrification without creating an entirely new regulatory framework. Although Stage V currently focuses on air pollutant emissions rather than CO_2, tightening existing pollutant limits for selected engine categories with high electrification potential could effectively accelerate the uptake of battery-electric machinery—for example through lowering the pollutant limits or by introducing an in-service conformity. Such an approach would be particularly suitable for smaller engines and segments where we find near-complete electrification potential by 2030, while avoiding undue burden on harder-to-electrify applications. Leveraging Stage V in this way would build on a familiar regulatory structure while delivering climate benefits. Flexibility schemes would also have to be developed, as data uncertainties mean that even in segments which this analysis has found there to be 100 % electrification potential, there will be certain cases where electrification is not possible. For example, an incentive for the production of large zero-emission machines could be created by providing limited exemptions to manufacturers to comply with a post-Stage V standard if they may prove that they have placed a number of large zero-emission machines on the market instead of diesel fueled machines.

A wider-spread regulation could be introduced to address CO_2 emissions from large categories. Harnessing CO_2 reduction potentials from NRMM more comprehensively will ultimately require a broader regulatory framework that goes beyond engine-level pollutant standards – for example, through the setting of zero-emission mandates for manufacturers. Such a framework would be more effective at addressing CO_2 emissions from NRMM, however significant challenges remain in its establishment. There is a lack of harmonised registration and sales data for NRMM across Member States, which complicates monitoring, compliance, and enforcement. Existing CO_2 standards in Europe rely on manufacturer declarations and registration data from national authorities. While establishing a zero-emission mandate would prove the most effective means of increasing the supply of zero-emission larger machines into the European market, setting such targets is not possible without tracking the sales volume. A pre-requisite for a ZEV mandate would require a harmonized registration procedure.

Demand-side measures can complement supply-side regulation. Oslo has used public procurement to accelerate zero-emission construction equipment, London has introduced a low-emission zone for construction machinery, the Netherlands combines voluntary targets with substantial public funding, and New York City is testing electric construction machinery through pilot programmes. Similar EU measures could include extending clean public procurement rules to NRMM, supporting charging infrastructure, using fuel taxation or CO_2 pricing, and creating incentives through renewable fuel or electricity crediting schemes.

The European Commission should start engaging more in this area. Despite the clear emissions relevance and growing technical feasibility of electrification, NRMM decarbonisation has so far received limited strategic attention at EU level. Responsibility for NRMM climate impacts formally lies with DG CLIMA (Unit B3), yet the sector has not been actively integrated into EU climate policy development or decarbonisation roadmaps. Given the scale of emissions, the availability of regulatory precedents in other jurisdictions, and the increasing maturity of zero-emission technologies, the European Commission should initiate a more proactive policy process, including analytical work, stakeholder engagement, and the development of a long-term regulatory vision for NRMM aligned with the EU’s 2030 and 2050 climate objectives. As short-term measure, the European Union could think about incentives to push electrification effectively forward. A first important step should be the development of an independent information platform on available machines including users’ specific demands and mission profiles. Such a platform should highlight opportunities for electrification and thus make users generally aware of that possibility.

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A Annex

A.1 Additional data used in the emission inventory

A.1.1 Prodcom categories

Table 94: Mapping of PRODCOM Categories in eNRMM

PRODCOM code	PRODCOM label	eNRMM subsector
28131185	Concrete pumps	Concrete pumps
28132400	Air compressors mounted on a wheeled chassis for towing	Compressor
28221435	Transporter cranes, gantry cranes and bridge cranes	Mobil crane
28922130	Crawler dozers (excluding wheeled)	Bulldozer
28922150	Wheeled dozers (excluding track-laying)	Bulldozer
28922210	Motor graders, levelers and scrapers	Grader
28922400	Ride-on compaction equipment and the like	Roller
28922550	Wheeled or crawler front-end shovel loaders (excl. specially designed for underground use)	Wheeled loader
28922600	Self-propelled mechanical shovels, excavators and shovel loaders, with a 360 degree revolving superstructure, except front-end shovel loaders	Excavator
28922730	Self-propelled mechanical shovels, excavators and shovel loaders (excl. self-propelled mechanical shovels with a 360° revolving superstructure and front-end shovel loaders)	Backhoe loader
28922900	Dumpers for off-highway use	Dumper
28923050	Tamping or compacting machinery (excluding self-propelled)	Compacting equipment
28924050	Concrete or mortar mixers	Concrete mixer
28302100	New agricultural and forestry tractors, wheeled, of an engine power <= 37 kW	Agricultural tractors
28302200	…> 37 kW but <= 59 kW,	Agricultural tractors
28302330	… > 59 kW but <= 75 kW,	Agricultural tractors
28302350	… > 75 kW but <= 90 kW,	Agricultural tractors
28302370	…> 90 kW	Agricultural tractors
28304030	Combine harvester-threshers	Combine Harvesters
28305420	Potato-diggers and potato harvesters	Combine Harvesters
28305960	Forage harvesters, self-propelled	Combine Harvesters
28305450	Beet-topping machines and beet harvesters	Combine Harvesters

PRODCOM code	PRODCOM label	eNRMM subsector
28304030	Grape harvesters	Combine Harvesters
28221530	Self-propelled works trucks fitted with lifting or handling equipment, powered by an electric motor, with lifting or handling equipment, non-powered by an electric motor	Forklift
28221513	[…] powered by an electric motor, with a lifting height >= 1 m	Forklift
27113110	Generating sets with compression-ignition internal combustion piston engines of an output <= 75 kVA	Generators
27113130	[…] of an output > 75 kVA but <= 375 kVA	Generators
27113150	[…] of an output > 375 kVA but <= 750 kVA	Generators
27113170	[…] of an output > 750 kVA	Generators
27113233	Generating sets with spark-ignition internal combustion piston engines of an output <= 7.5 kVA	Generators (not considered)
27113235	[…] of an output > 7,5 kVA	Generators (not considered)
28304010	Electric mowers for lawns, parks, golf courses or sports grounds	lawn mower
28304030	Mowers for lawns, parks or sports grounds, powered non-electrically, with the cutting device rotating in a horizontal plane	lawn mower/ride-on mower
28304050	Motor mowers for lawns, parks or sports grounds, powered non-electrically, with the cutting device rotating in a vertical plane or with cutter bars	lawn mower/ride-on mower
28305130	Motor mowers (excluding for lawns, parks, golf courses or sports grounds)	lawn mower/ride-on mower
28241123	Electromechanical chainsaws	chainsaw
28241260	Chainsaws with a self-contained non-electric motor	chainsaw
28241180	Electromechanical hedge trimmers and lawn edge cutters	Trimmer
28923050	Tamping or compacting machinery (excluding self-propelled)	Compaction equipment

A.1.2 Annual Operation Hours and load factors

The annual operating hours were largely taken from the TREMOD-MM model. The assumptions and data sources are described in (Heidt et al. 2020). However, new data was collected for the following machine categories/segments.

- For railcars and electric locomotives, the operating hours were taken from EMISIA (Mellios et al. 2019).

- For diesel locomotives, the slightly lower operating hours from (Notter, Schmied 2015) were used, as otherwise the GHG emissions from rail transport would be significantly higher than those reported by EU member states to the UNFCCC.
- For cargo ships and push boats, separate assumptions were made, which were developed for the TREMOD model in consultation with the VDMA and other experts. The annual operating hours with 2,500 h/a lead to a good agreement with the UNFCCC data in terms of total GHG emissions.
- After consultation with ICOMIA and other experts, the operating hours for PWCs with 50 h/a were set lower than in other publications, e.g. 135 h by (Zenié et al. 2023), 85 h by (emisia et al. 2021). The experts otherwise considered the total emissions for PWCs to be too high and argued that a large proportion of PWCs, especially those used by private users, are more likely to be used like outboard boats, whereas higher values such as in Ricardo refer to commercial applications.
- The hours for generators with >130 kW were revised downwards compared to TREMOD-MM. In TREMOD-MM, it was assumed that, similar to other equipment, e.g., construction machinery, usage for higher kW classes would increase significantly. However, in discussions with Europgen, the high hours were deemed unrealistic. Therefore, based on older sources (Krasenbrinck, Dobranskyte-Niskota 2008) and own evaluations, it is assumed that generators are operated for a maximum of 500 h/a on average.

The average annual operation hours and load factors are given in Table 95.

Table 95: Average use (operating hours/year) and load factors

Subsector	Use (hr/yr)	LF
Agricultural tractors	100-300	0.3
Combine harvester	150	0.55
Wheel loader	350-1310	0.25
Telehandlers	360-950	0.3
Concrete mixers	280	0.5
Tower cranes	500	0-0.2
Mobile and truck-mounted cranes	490-860	0.4
Construction lifts	300	0-0.5
Concrete pumps	250	0.8
Mortar conveyors and plastering equipment	300	0.5
Dumpers	200-1220	0.4
Mini excavators	290-560	0.4
Crawler excavators	290-1280	0.4
Wheel excavators	280-1280	0.25
Backhoe loaders	650	0.35

Subsector	Use (hr/yr)	LF
Dozers	820–1220	0.4
Wheel loader	350–1390	0.25
Crawler loader	650	0.4
Compact dumper	260–390	0.25
Telehandlers	290–860	0.3
Motor graders	310–1560	0.35
Ram	300	0.2
Compaction equipment	130–140	0.2–0.35
Asphalt mixers	300	0.5
Asphalt boilers	300	0.5
Road pavers	200–930	0.3
Construction compressors	80–530	0.5
Rollers	380–670	0.35
Forestry tractors	600	0.3
Carrier tractors/ forwarders	1,000	0.5
Harvesters	1,000	0.5
Debarkers	1,000	0.5
Chainsaws professional	150	0.85
Lawn Mower private	13	0.5
Lawn Mower professional	100	0.5
Ride-on Mower / Lawn Tractor private	15	0.4
Ride-on Mower / Lawn Tractor (Sport and Hobby)	35	0.4
Ride-on Mower / Lawn Tractor (public lawns)	280	0.4
Ride-on Mower / Lawn Tractor (company)	128	0.4
Chainsaws private	6	0.5
Chainsaws professional	150	0.85
Trimmer private	6	0.5
Trimmer professional	200	0.5
Other equipment private	6	0.5
Other equipment professional	150	0.5
Motorboat outboard engine	35	0.21
Motorboat inboard engine	48	0.34

Subsector	Use (hr/yr)	LF
Day trip ships	1,000	0.5
River cruise ship	1,000	0.5
Cargo vessel	2,500	0.35
Push boat	2,500	0.35
PWCs	50	0.21
Other boats (incl. sailers)	35	0.21–0.34
Generators	100–500	0.5
Forklifts	650–1,200	0.3
Locomotives	1600–3,500	0.3
Railcars	1600–3,500	0.58

A.1.3 Engine energy efficiency

The energy demand of NRMMs is calculated using the engine power used (rated power x load factor) and the specific energy demand (g fuel or MJ energy per kWh engine power). The quotient of the engine power and the specific energy demand indicates the efficiency.

As part of the eNRMM project, the specific energy requirement values of the TREMOD-MM model were updated. For diesel engines, new values were derived based on the US EPA type approval data for CO_2 (g/kWh) per engine category, power class, and year of approval. These values better reflect the efficiency gains of diesel engines in recent years than the previous data and can also be differentiated by power class. The specific consumption values for electric, hydrogen combustion, and fuel cell drives were estimated from data for heavy duty vehicles from the HBEFA 5.1 and not differentiated by power class.

Table 96: Engine energy efficiency by power class for NRE (from Stage V on)

Fuel typp	< 19kW	19 ≤ 36kW	37 ≤ 55kW	56 ≤ 74kW	75 ≤ 129kW	130 ≤ 299kW	300 ≤ 559kW	≥ 560 kW
Diesel	28 %	32 %	35 %	38 %	37 %	37 %	38 %	37 %
Electric	85 %	85 %	85 %	85 %	85 %	85 %	85 %	85 %
H2-FC				54 %	54 %	54 %	54 %	54 %
H2-ICE				39 %	39 %	39 %	39 %	39 %

A.2 Market data NRMM batteries

Table 97: Market data on NRMM batteries

Battery technology	Cathode Material	Parameter	Unit	Value	Source
Li-ion	NMC	Energy density	[Wh/L]	203	(Webasto 2026a)
Li-ion	NMC	Energy density	[Wh/L]	232	(Webasto 2026b)
Li-ion	NMC	Energy density	[Wh/L]	266	(Webasto 2025)
Li-ion	LFP	Specific energy	[Wh/kg]	129	(omnibusrevue.de 2024)
Li-ion	LFP	Specific energy	[Wh/kg]	138	(Werwitzke 2023)
Li-ion	NMC	Specific energy	[Wh/kg]	118	(Webasto 2026a)
Li-ion	NMC	Specific energy	[Wh/kg]	135	(Webasto 2026b)
Li-ion	NMC	Specific energy	[Wh/kg]	145	(eurotransport 2021)
Li-ion	NMC	Specific energy	[Wh/kg]	158	(Volkswagen AG 2022)
Li-ion	NMC	Specific energy	[Wh/kg]	162	(ADAC 2022)
Li-ion	NMC	Specific energy	[Wh/kg]	170	(Webasto 2025)

A.3 Machine types by tiered group

Table 98: NRMM categories by tiered group

Tiered group	Machine type
Agri machines	Combine harvester
	Harvesters
	Debarkers
Agri vehicles	Agricultural tractors
	Wheel loader
	Telehandlers
	Forestry tractors
	Carrier tractors/ forwarders
Generators	Generators
Hand-held hobby	Chainsaws private
	Trimmer private
	Other equipment private
hand-held professional	Chainsaws professional

Tiered group	Machine type
	Trimmer professional
	Other equipment professional
Mobile construction	Mobile and truck-mounted cranes
	Dumpers
	Mini excavators
	Crawler excavators
	Wheel excavators
	Backhoe loaders
	Dozers
	Wheel loader
	Crawler loader
	Compact dumper
	Telehandlers
	Motor graders
	Ram
	Compaction equipment
	Road pavers
	Rollers
	Forklifts
Non-mobile construction	Concrete mixers
	Tower cranes
	Construction lifts
	Concrete pumps
	Mortar conveyors and plastering equipment
	Asphalt mixers
	Asphalt boilers
	Construction compressors
Passenger/cargo – lake	Day trip ships
Passenger/cargo – river	River cruise ship
	Cargo vessel
PWC	Push boat
	PWCs

Tiered group	Machine type
	Other boats (incl. sailers, yachts)
Ride mower	Ride-on Mower / Lawn Tractor private
	Ride-on Mower / Lawn Tractor (Sport and Hobby)
	Ride-on Mower / Lawn Tractor (public lawns)
	Ride-on Mower / Lawn Tractor (company)
Sport boat inboard engine	Sportboat inboard engine
Sport boat outboard engine	Sportboat outboard engine
Walk behind mower	Lawn Mower private
	Lawn Mower professional

A.4 Participants in the expert workshop

Table 99: Participants in the expert workshop, 30th September 2025, Brussels (excluding project team, UBA and BMUKN)

Institution/Company	Last name	First name
ACEM	Fenoglio	Francesco
AECC	Demuynck	Joachim
BELLONA EU	Domínguez	Irene
Caterpillar	Brewer	Mike
CCNR	Boyer	Benjamin
CNH	Hale	Nicholas
DG GROW	Uhlik	Krisztian
DG MOVE	Elemenler	Muhammed
EBI	Easthill	Philip
Euromot	Scherm	Peter
Finnish Environment Institute	Auvinen	Karoliina
ICOMIA	Hemp	Patrick
Liebherr	Theuerkauf	Stefan
MAN	Thum	Dirk
Ministry of Environment, Finland	Siikavirta	Hanne
Ministry of Infrastructure and Water Management, The Netherlands	Kollenveld	Robin

Institution/Company	Last name	First name
Representation of Sweden to the European Union	Ashton	David
Stihl	Kölmel	Armin
STRABAG BMTI	Figl	Thomas
Transport & Environment	Mollière	Max
VDMA	Münz	Markus
VDMA	Hipp	Johannes