CLIMATE CHANGE
18/2026

Final report

Pathways to an EU in 2050 with net-zero GHG-emissions

by:

Vicki Duscha, Khaled Al-Dabas, Gerda Deac, Johannes Eckstein, Fabio Frank, Bastian Weißenburger, Felix Neuner
Fraunhofer ISI, Karlsruhe

Lukas Emele, Hannes Böttcher, Klaus Hennenberg, Tilman Hesse, Sylvie Ludig, Margarethe Scheffler, Kirsten Wiegmann
Öko-Institut, Berlin

Eftim Popovski
IREES GmbH, Karlsruhe

publisher:
German Environment Agency

Umwelt Bundesamt

CLIMATE CHANGE 18/2026

KLIFOPLAN of the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety

Project No. (FKZ) 3721 41 5020
FB001965/ENG

Final report

Pathways to an EU in 2050 with net-zero GHG-emissions

by

Vicki Duscha, Khaled Al-Dabas, Gerda Deac, Johannes Eckstein, Fabio Frank, Bastian Weißenburger, Felix Neuner
Fraunhofer ISI, Karlsruhe

Lukas Emele, Hannes Böttcher, Klaus Hennenberg, Tilman Hesse, Sylvie Ludig, Margarethe Scheffler, Kirsten Wiegmann
Öko-Institut, Berlin

Eftim Popovski
IREES GmbH, Karlsruhe

On behalf of the German Environment Agency

Imprint

Publisher
Umweltbundesamt
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:
Fraunhofer Institute for Systems and Innovation Research (ISI)
Breslauer Strasse 48
76135 Karlsruhe
Deutschland

Öko-Institut e.V.
Borkumstrasse 2
13189 Berlin
Deutschland

IREES - Institut für Ressourceneffizienz und Energiestrategien GmbH
Durlacher Allee 77
76131 Karlsruhe
Deutschland

Report completed in:
October 2025

Edited by:
Section V1.2 Climate and Energy Strategies and Scenarios
René Lanz

DOI:
https://doi.org/10.60810/openumwelt-8104

ISSN 1862-4359

Dessau-Roßlau, March 2026

Abstract: Pathways to an EU in 2050 with net zero GHG-emissions

This is the final report of the project Pathways to an EU in 2050 with net-zero GHG-emissions. The report gives an overview and discusses results of the three scenarios EU Pathways Base (EUBase), EU Pathways Target (EUTarget) and EU Pathways Supreme (EUSupreme) developed within the project. First, the EUBase scenario and its results are presented. As a classic current-policies scenario, it does not focus on the achievement of climate protection targets in 2050 but rather examines the effectiveness of current policies and policies under negotiation (as of 2022). In some cases, policies that had not yet been adopted but for which a draft existed at EU level are also included in the modeling. Member state-specific policies are also examined. The two target scenarios, EUTarget and EUSupreme, on the other hand, show different possible paths towards an EU with net-zero greenhouse gas emissions in 2050. EUTarget focuses on technical options for reducing emissions. The EUSupreme scenario depicts an alternative path with significantly higher sustainability requirements and behavioural changes. The modeling is supplemented by analyses of the scenarios' conformity with the EU taxonomy.

Kurzbeschreibung: Pathways to an EU in 2050 with net-zero GHG-emissions

Dieser Bericht fasst die Ergebnisse des Projektes „Pfade zu einer EU mit netto-Null Treibhausgas-Emissionen in 2050“ zusammen. Der Bericht gibt einen Überblick über die angewandte Methodik, Szenariodefinitionen für drei Szenarien (EUBase, EUTarget, EUSupreme) und stellt die Ergebnisse der Szenarien gegenüber. Dabei wird zunächst das EUBase-Szenario und seine Ergebnisse dargestellt. Als klassisches „mit-aktuellen-Maßnahmen“-Szenario stellt das Szenario nicht auf die Erfüllung von Klimaschutzzielen in 2050 ab, sondern untersucht die Wirksamkeit der aktuellen und in Diskussion befindlicher Politiken (Stand 2022). In Teilen fließen auch Politiken, die bis dahin nicht verabschiedet, für die aber auf EU-Ebene ein Entwurf vorlag, in die Modellierung mit ein. Ebenso werden auch Mitgliedsstaaten-spezifische Politiken untersucht. Die zwei Zielszenarien EUTarget und EUSupreme dagegen zeigen verschiedene mögliche Wege hin zu einer EU mit netto-Null Treibhausgasemissionen in 2050. Dabei werden im EUTarget technische Möglichkeiten der Emissionsminderung in besonderem Maße untersucht. Das EUSupreme-Szenario dagegen bildet einen alternativen Pfad mit deutlich höheren Nachhaltigkeitsanforderungen und Verhaltensänderungen ab. Die Modellierung wird ergänzt durch Untersuchungen der Szenarien auf Konformität mit der EU-Taxonomie.

Table of content

List of figures

List of tables

List of abbreviations

Abbreviation	Explanation
BECCS	Bio-energy Carbon Capture and Storage
BEV	Battery Electric Vehicle
BOF	Basic Oxygen Furnace
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditures
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removals
CE	Circular Economy
CHP	Combined Heat and Power
CRF	Common Reporting Format
CSC	Conventional Steam Cracker
DAC	Direct Air Capture
DACCS	Direct Air Capture and Storage
DH	District Heating
EEA	European Environment Agency
EED	Energy Efficiency Directive
EPBD	Energy Performance in Buildings Directive
ESC	Electrical Steam Cracker
ESR	Effort Sharing Regulation
ETS	Emissions Trading System
EU	European Union
FCEV	Fuel Cell Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GVA	Gross Value Added
GVR	Gross Value Return
HTPH	High-Temperature Process Heating
HVCs	High Value Chemicals
HWP	Harvested Wood Products
IED	Industrial Emissions Directive

Abbreviation	Explanation
LNG	Liquefied Natural Gas
LULUCF	Land Use, Land Use Change and Forestry
MAC	Marginal abatement costs
MEPS	Minimum Energy Performance Standards
Mt	Metric ton
MTA	Methanol-to-aromatics
MTO	Methanol-to-olefins
MWh	Megawatt hour
NECP	National Energy and Climate Plan
NIR	National Inventory Reporting
OPEX	Operational Expenditures
OSM	OpenStreetMap
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
RES	Renewable Energy Sources
SAF	Sustainable Aviation Fuel
SRC	Short rotation coppices
TCO	Total Cost of Ownership
TED	Total Energy Demand
TRL	Technology Readiness Level
TWh	Terawatt hour
TYNDP	Ten Year Network Development Plan
UNFCCC	United Nations Framework Convention on Climate Change
UUA	Utilized agricultural area

Summary

This is the final report of the project "Pathways to an EU in 2050 with net-zero GHG-emissions". The report gives an overview and discusses results of the three scenarios EU Pathways Base (EUBase), EU Pathways Target (EUTarget) and EU Pathways Supreme (EUSupreme) developed within the project.

Objective and design of the study

In line with the Paris Agreement, the EU has set itself the target of reaching net-zero Greenhouse Gas (GHG) emissions by 2050. The idea of the project "Pathways to an EU in 2050 with net-zero GHG-emissions" was to illustrate different possible pathways of the EU and its Member States to a climate-neutral economy. This report presents the modeling framework, scenario definitions and assumptions and discusses the results of the three scenarios developed within the project: EUBase, EUTarget and EUSupreme. In addition to the modeling of those three scenarios a work package with the focus on the EU Taxonomy assessed how well aligned those scenarios are with the EU Taxonomy. It further touched upon the question what additions to the models applied here would be needed to allow for a modeling of the EU Taxonomy and its effects on GHG emissions.

The analysis focuses on the impacts of policies, strategies and measures on GHG emissions, energy demand and other sector-specific relevant physical values. Not included in the analysis are scenario impacts on costs and resulting monetary investment needs, scenario implications on energy prices or macro-economic indicators, in particular GDP developments and employment figures. Such values (monetary values and employment) are mainly out of the scope of the models applied, where results are available, they are not part of the analysis.

This summary concentrates on overall scenario results. Sector specific results and more detail is provided in the full report.

Modeling suite and assumptions

A suite of detailed sectoral models is applied to perform this study. We apply detailed techno-economic simulation models for the sectors transport (ALADIN) and industry (FORECAST Industry) including technology costs and energy carrier and CO_2 prices. The results for buildings build on the output from three underlying models: LCBE for space heating, cooling and water heating in residential and non-residential buildings, FORECAST Appliances for appliances as well as household space cooling and FORECAST Tertiary for appliances and processes in the tertiary sector. While the models for appliances and the tertiary sector are techno-economic models, the LCBE model is an accounting model, not taking into account costs, energy carrier or CO_2 prices. The energy supply side is modelled with the cost-optimization model Enertile. On top, the model NetHEAT provides detailed information on the district heating networks.

The energy side of the economy is complemented by models for agriculture (LiSE), land-use, land-use change and forestry (LULUCF, modelled by FABio-Land) and the waste sector (Waste_mod) to cover the non-energy related emissions. We also consider emissions from F-gases by estimations based on other modeling studies. For the target scenarios (EUTarget and EUSupreme), further considerations regarding industrial carbon dioxide removals (CDR) are added (including considerations on energy demand and CO_2 sources) to complete the emission balance. Not included are fugitive emissions and leakages from the extraction and transport of fossil or synthetic fuels as well as from CO_2 transport and storage. For an overall aggregation, all sectoral model results are collected and stored in a harmonized format in a database.

To generate consistent scenarios, the models are run in an iterative way. Starting point is the calculation of energy demand and related GHG emissions for the demand-side sectors (industry,

transport, buildings). In parallel, the non-energy sectors (agriculture, LULUCF and waste) are calculated to determine GHG emissions and the domestic supply of biogenic non-fossil fuels. The results are fed into the Enertile model to determine GHG emissions for electricity, heat and provision of non-biogenic non-fossil fuels and feedstocks. To complete the GHG balance, demand for CDR in 2050 is determined and these requirements fed back into the Enertile model to account for the related energy demand. Finally, the NetHeat model is used to provide detailed information on district heating networks.

The interaction of models and the balances of supply and demand make additional iterations necessary to harmonize results and assumptions such as CO_2 prices and energy carrier prices.

Scenario narratives

Three scenarios, a reference scenario (EUBase) and two target scenarios (EUTarget and EUSupreme) were developed and modelled. All three scenarios follow distinct narratives, designed to gain a deeper understanding of how to reach GHG-neutrality within the EU.

The **EUBase scenario** serves as the reference scenario for modeling work. It starts with political and socio-economic developments from 2022 and models the impact of economic development, population growth, energy prices, CO_2 prices and selected current policy packages on energy demand and supply, agriculture production, waste and the LULUCF sector along with related GHG emissions. Notably, it incorporates the effects of the Russian invasion into Ukraine on energy prices, as reflected in the energy price assumptions.

The EU policies considered include components of the energy and climate policy packages currently under discussion or recently agreed on in the European Fit-for-55 package and the EU REPower Package implemented in response to the European energy crisis. That includes CO_2 prices for industry and supply sector (EU ETS 1), but also for transport and buildings (EU ETS 2) as overarching policies. In addition, several sector-specific considerations are being applied. Here it is decided at a sector level which of the not yet implemented policies are being included in the scenario. Limited activities are implemented for a major part of the non-energy sectors. This reflects the current gap in legislative activities in these sectors. In particular, the LULUCF target for 2030 of providing a net sink of 310 Mt CO_2 is not implemented in the scenario, but different effects on the LULUCF sector stemming from interactions with other sectors, in particular the agriculture sector and the use of biomass as energy carrier are reflected here.

The scenario is designed to be technology-neutral, allowing for various options for decarbonizing the energy system, including carbon capture and storage (CCS), carbon capture and utilization (CCU) and nuclear power, reflecting different national approaches. In contrast to the following target scenarios, the EUBase scenario does not require meeting either the 2030 or 2050 GHG targets in the EU.

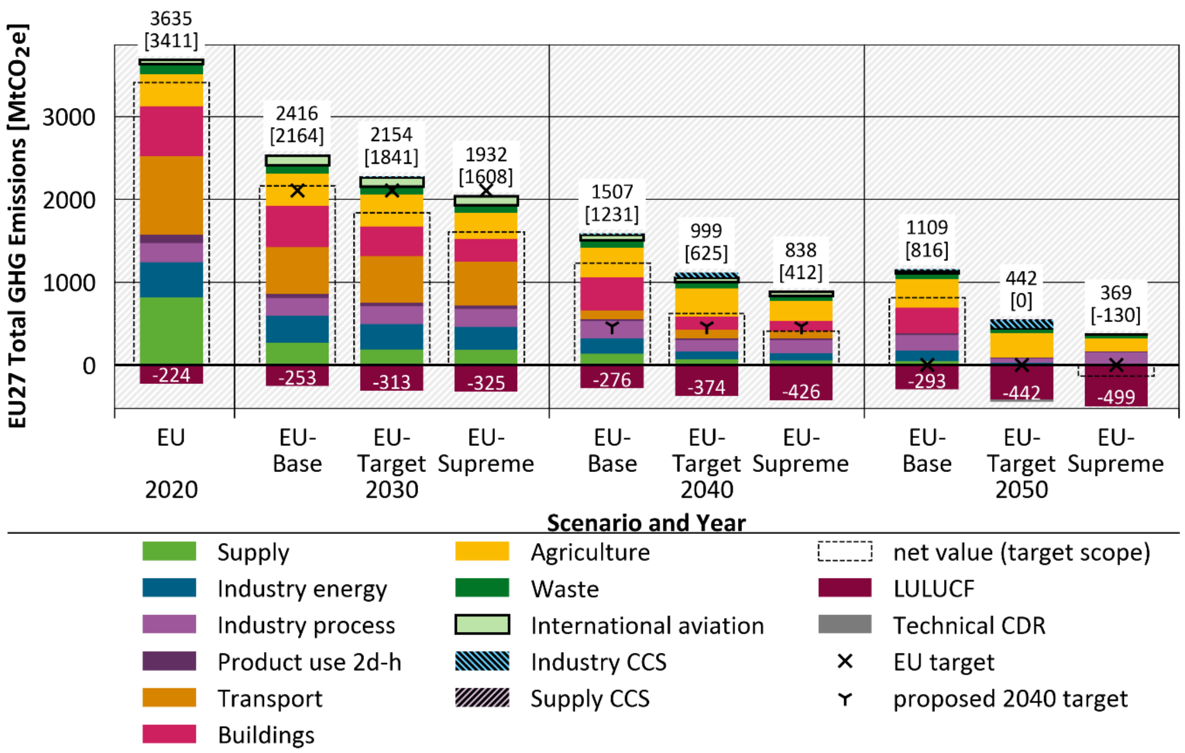
The **EUTarget scenario** adopts a classical technology-oriented approach. It builds upon the assumptions of the EUBase scenario, remaining technology-open and allowing for various mitigation strategies tailored to Member States based on their NECPs. In this scenario, the CO_2 price serves as a critical mechanism for reaching the 2050 climate target with separate prices for ETS 1 and ETS 2 sectors. The two prices and their development over time is determined within the modeling framework rather than being predefined as it is in the EUBase scenario. Meeting the 2050 target is the main determinant. However, determined prices are streamlined between sector models. The stronger CO_2 prices as well as assumptions on a stronger uptake of mitigation technologies to allow for meeting the 2050 target are main drivers in this scenario. The focus on technical mitigation measures is also applied in the agriculture sector, introducing a variety of additional mitigation measures compared to the EUBase scenario. Technical mitigation measures can be implemented through targeted support programmes and incentives schemes, particularly for smaller farms. Larger farms can be required to adopt such measures through binding obligations set out in regulatory laws, such as the Industrial Emissions Directive (IED).

In contrast, the **EUSupreme scenario** envisions the implementation of a comprehensive EU-wide mitigation strategy that emphasizes strong sustainability criteria, enhanced circularity, and non-technical behavioural changes. This scenario significantly limits the use of nuclear power and reduces biomass utilization in the energy system. It further visualizes a mitigation pathway without CCS. Instead, the scenario introduces stringent sufficiency and circular economy assumptions in the industry sector allowing for lower primary production levels and thus adding an additional mitigation lever. Additionally, it aims to lower energy demand more strongly than the EUTarget scenario and puts increased effort on fossil fuel phase-out such as coal phase-out by 2040 in the industry sector and a strict ban on the use of fossil fuels in 2050. For the agriculture sector, strong sufficiency assumptions allow to significantly reduce animal stocks and related emissions instead of applying technical mitigation measures. In combination with a stronger increase in organic farming and other robust assumptions on land use, the scenario allows for a pronounced increase of the natural carbon sink. Similar to the EUTarget scencario, reaching the 2050 GHG emission reduction target is a precondition.

Key results

The GHG balance across all sectors for the European Union under the different scenarios, compared to 2020 (see Figure 1) is a central project output. Emissions from international aviation and maritime transport are fully included, as well as emission storage in the LULUCF sector and CCS in later years.

Figure 1: GHG emission development in three pathways scenarios between 2020 and 2050 for the EU27

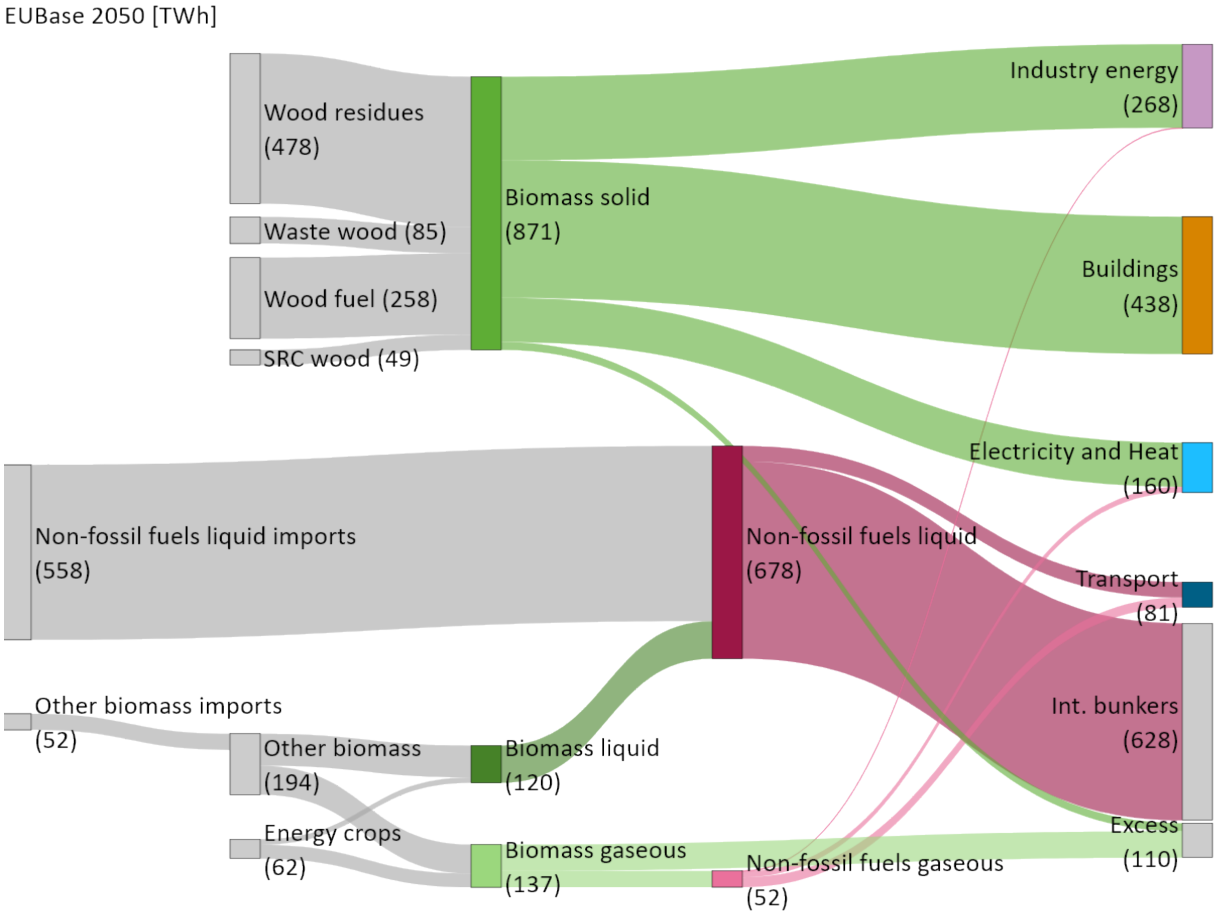


Source: own calculations Fraunhofer ISI, Oeko Institut

Net emissions (in brackets) are projected to be 2,164 Mt CO_2e in 2030, 1,231 Mt CO_2e in 2040 and 816 Mt CO_2e in 2050 in the EUBase scenario. That equals a reduction in net emissions of 54% below 1990 levels in 2030, barely missing the EU's reduction target of 55% reduction by 2030. In 2040 emissions are 74% below 1990 levels and in 2050 they reach a reduction level of 83% below 1990 levels. These results indicate that the currently implemented policies, as modelled in this scenario, are not at all in line with the EU's climate targets, in particular in later years. Significant emissions remain in industry, buildings and agriculture. Remaining emission levels in supply and transport are low, but even those two sectors do not reach zero emissions by 2050. Here, in particular international aviation continues to use fossil fuels, while road transport reaches almost complete decarbonization via the use of electric vehicles. CDR – completely nature-based - in the EUBase scenario increases from -224 Mt in 2020 to -293 Mt in 2050. Gross GHG emissions are slightly below generated GHG emissions in 2050 due to small amounts of CCS in cement industry (-17 Mt in 2050).

Non-fossil fuels play an important role already in the EUBase scenario despite EU climate targets being missed. Hydrogen demand comes particularly from electricity and heat generation, but also from industry and industry feedstocks and low demand from transport and buildings. The demand, amounting to 376 TWh in 2050, can be met with domestic production. Imports are not required. In addition to hydrogen solid biomass and liquid and gaseous non-fossil fuels (which can contain carbon) have relevant shares in meeting final energy and feedstock demand (see Figure 2). Large amounts of solid biomass are used in buildings, industry and electricity and heat provision in 2050 in EUBase. Small amounts of gaseous and liquid biomass are also being used in transport, electricity and heat and industry. High demand for liquid non-fossil fuels arises from the transport sector, namely international bunkers.

Figure 2: Non-fossil fuels balance (excl. hydrogen) in the EU27 in EUBase in 2050



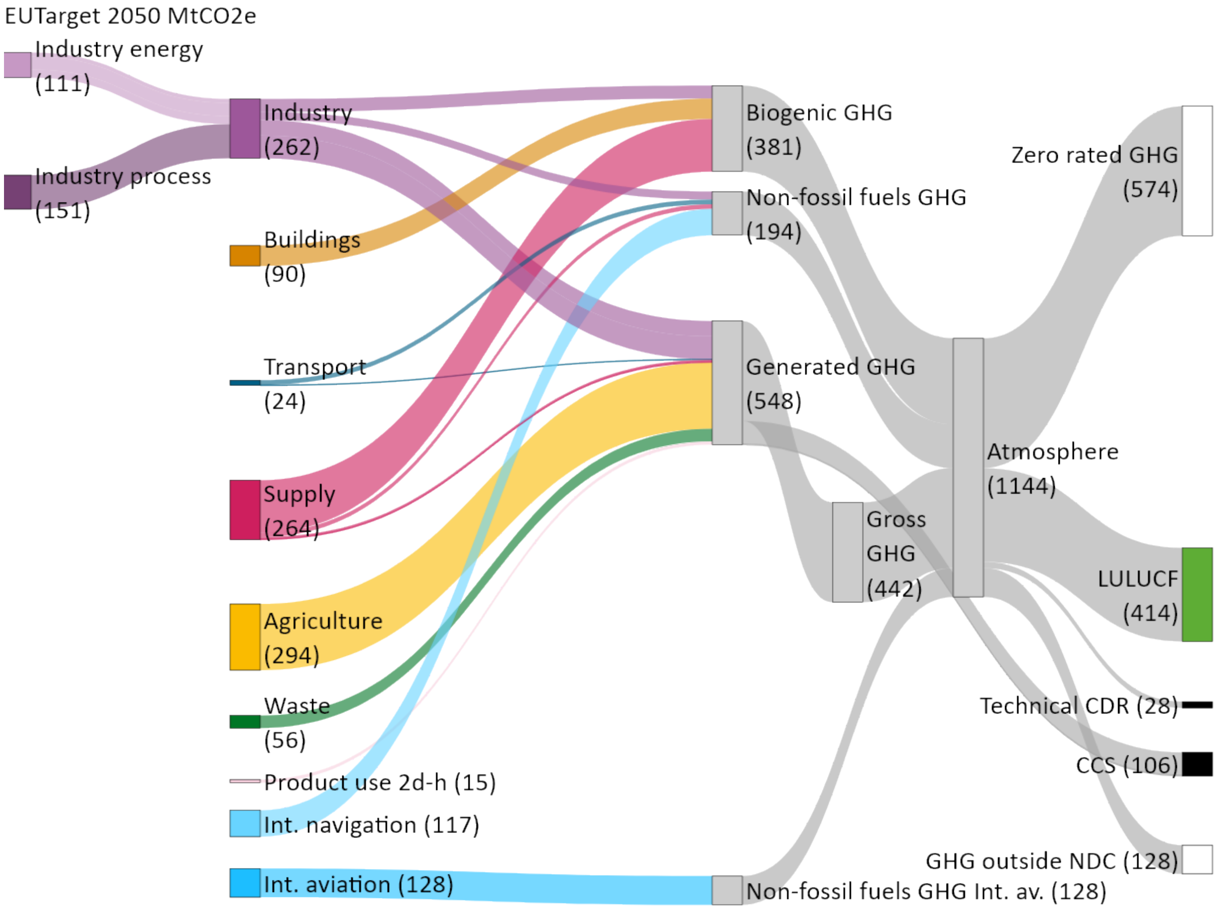
Source: Own calculations Fraunhofer ISI, Oeko Institut

In the **EUTarget scenario**, net-GHG emissions decrease significantly more compared to the EUBase scenario, in particular in later years. Net-emission levels reach 1,841 Mt CO_2e in 2030, 625 Mt CO_2e in 2040 and 0 Mt CO_2e in 2050. Compared to the EUBase scenario, that are additional emission reductions in the order of 323 Mt CO_2e in 2030, 606 Mt CO_2e in 2040 and 816 Mt CO_2e in 2050.

Different effects are triggering those results. Additional reductions in generated GHGs in the EUTarget scenario are found in particular in the buildings sector, but also in the supply sector in intermediate years. Gross emissions in industry can be reduced by the strong uptake of CCS, which reaches mitigation of 106 Mt CO_2 in 2050 (mainly from industry, small parts also from waste incineration in the supply sector). To balance remaining gross emissions, both nature-based and technical CDR is needed in this scenario. The LULUCF sink increases compared to the EUBase scenario and reaches storage amounts to -414 Mt in 2050. In addition, technical CDR (such as BECCS or DACCS, not further specified in the scenario) in the order of 28 Mt CO_2 is required to fill the emission reduction gap and reach a net-zero GHG balance.

Despite a net-zero GHG balance, a significant amount of carbon and CO_2 emissions remain part of the energy system in the EUTarget scenario (see Figure 3). That includes biogenic CO_2 as well as zero-rated CO_2 emissions from imported non-fossil fuels for international bunkers, transport and industry feedstocks.

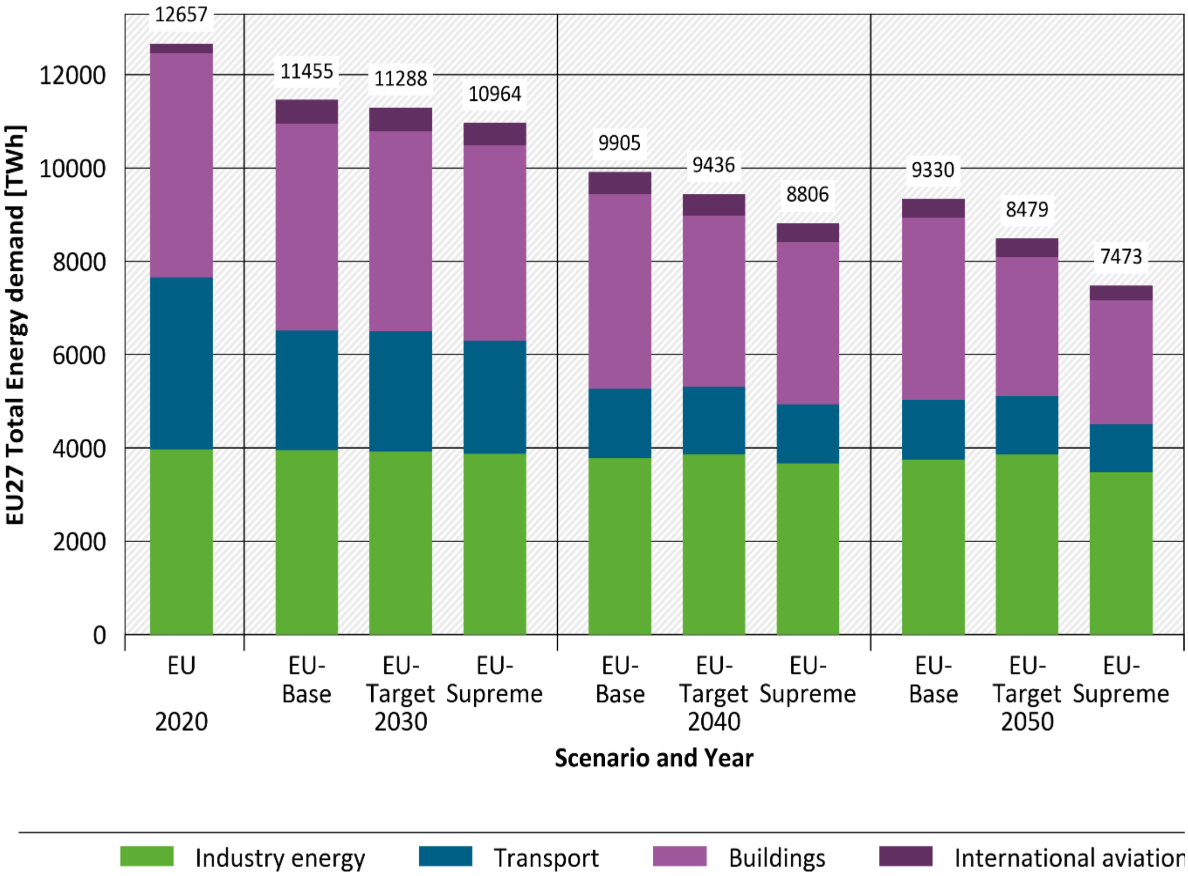
Figure 3: Emissions flow in EU27 in EUTarget in 2050



Source: own calculations Fraunhofer ISI, Oeko Institut

Final energy demand (see Figure 4) in the EUTarget scenario can be reduced compared to the EUBase scenario, by 851 TWh in 2050. This result is mainly driven by a reduced energy demand from buildings, driven by increasing renovation rates and standards. This reduction covers for a slight increase in energy demand in the industry sector due to the strong use of CCS. The development of final energy demand also shows that major differences only visualize in later years, while in 2030 differences are marginal and all three scenarios miss the EU's energy efficiency target of 8,626 TWh for final energy demand in 2030.

Figure 4: Final energy demand in EU27 between 2020 and 2050 in all pathway scenarios



Source: own calculations Fraunhofer ISI, Oeko Institut

Large differences can again be found in the renewable energy share in final energy demand. In the EUBase scenario the share already increased significantly from 19.2% in 2020 to 64% in 2050. In the EUTarget scenario it reaches 90.6% with only small amounts of fossil fuels. The share of electricity in the system at the same time increases significantly from 19% in 2020 to 46% in 2050. It reflects the strong role of electricity for decarbonization of sectors such as transport, buildings and industry.

Demand for hydrogen increases more significantly compared to EUBase reaching 557 TWh in 2050. The EU's electricity system is no longer able to provide the complete amount of hydrogen domestically, but imports account for 13% of total hydrogen demand in 2050. Carbon-containing liquid non-fossil fuels develop a more dominant role in the supply of non-fossil fuels excluding hydrogen. In addition to international bunkers major amounts are going into industry feedstocks.

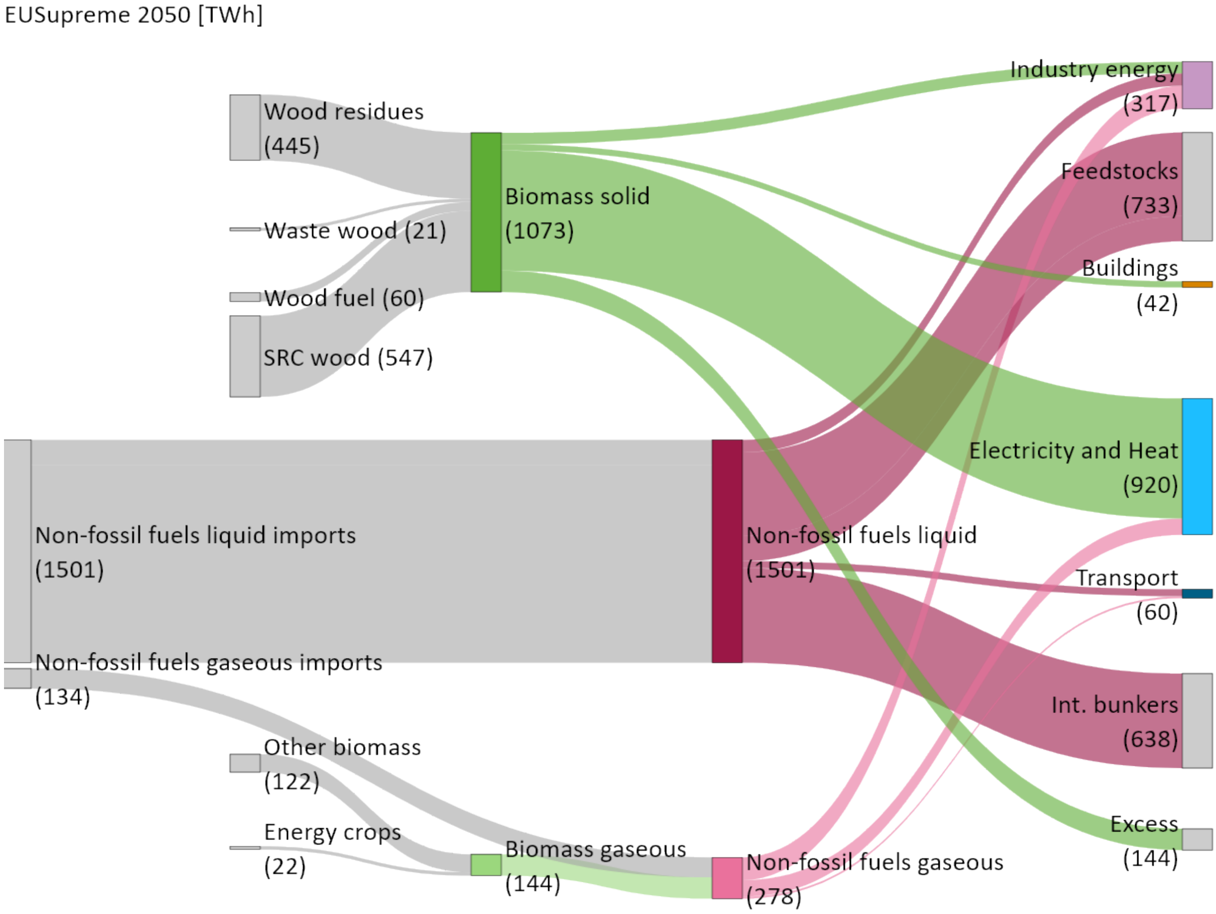
In addition to those imports of carbon-containing non-fossil fuels, there is also a direct demand for CO_2 from industry for methanol-to-olefins (MTO)/ methanol-to-aromatics (MTA) routes as well as for technical CDR. The amount of CO_2 required increases from 4 Mt CO_2 in 2030 to 149 Mt in 2050 as half of the production installations are replaced by MTO/MTA installations.

The most prominent decline in GHG emissions is found in the **EUSupreme scenario**. Net-GHG emissions decrease to 1,608 Mt CO_2e in 2030, 412 Mt CO_2e in 2040 and -130 Mt CO_2e in 2050. In 2040, that is an additional reduction of net emissions of 34% compared to EUTarget. In 2050, the scenario not only does not require the use of technical CDR to reach net-zero emissions as was the case in EUTarget. In contrast, gross emissions have further decreased significantly and the LULUCF sink could be further increased compared to EUTarget (by -86 Mt CO_2). In sum, that allows for a clear negative net-emission value in 2050.

Different sector effects contribute to this result. Non-energy sectors' emissions decrease significantly more in the EUSupreme scenario compared to EUTarget. The significant reduction in livestock numbers in agriculture allows not only to reduce emissions in that sector but has positive effects on the availability of land for the LULUCF sector and on emissions from waste due to the related reduction in animal protein intake. The waste sector further profits from the strong assumptions on circular economy, reducing the amount of waste. That, in turn, has also strongly positive effects on the industry sector as it allows for a reduction in production figures and a strengthening of recycled materials. For transparency it needs to be stated, that to reach a result with non-fossil fuels by 2050 in industry and transport bans on fossil fuels needed to be implemented.

Sufficiency assumptions for the transport and building along the circular economy assumptions result in a strong decrease in final energy demand. Compared to EUTarget an additional 1,000 TWh final energy can be saved (see Figure 4). That reduces pressure on the domestic electricity sector. While renewable energy shares in electricity in 2040 are similar to the EUTarget scenario, they reach higher levels, up from 86.2% in EUTarget to 92.2% in EUSupreme. The lower demand for electricity also allows to reduce demand and imports of non-fossil fuels and hydrogen. Also reduced is the demand for non-fossil biogenic fuels resulting in a slight excess of solid biomass in 2050 of 144 TWh (see Figure 5). The renewable energy share in final energy demand increases from 90.6% in the EUTarget scenario in 2050 to 94.9% in EUSupreme. Demand for domestic carbon resulting from chemical industry and technical CDR decrease compared to the EUTarget scenario, in line with a reduced demand for chemical feedstocks. It amounts to 101 Mt CO_2 in 2050, about 20 Mt CO_2 lower than in EUTarget.

Figure 5: Non-fossil fuels balance excluding hydrogen in EU27 in EUSupreme in 2050



Source: own calculations Fraunhofer ISI, Oeko Institut

EU Taxonomy

The EU Taxonomy regulation establishes a reporting obligation for large and capital market-oriented companies on the share of economic activities which are deemed sustainable (European Commission 2020b). The share of economic activity is defined as the share in investment or turnover, depending on the type of company. To do so, a catalogue of activities and technical screening criteria has been defined in subsequent delegated acts. Each activity must provide a significant contribution to one of six environmental objectives while not harming any of the other five (climate change mitigation, climate change adaptation, water resources, circular economy, pollution prevention and biodiversity).

As part of this report, we investigate how the effect of the taxonomy could be modelled. In a second step, we assess whether the results of the scenarios are aligned with the EU Taxonomy and more specifically the technical screening criteria it sets out.

Any implementation of the EU Taxonomy in models requires scenarios of the effectiveness of the EU Taxonomy. These scenarios would at least add an additional variable to the policy mix currently defining the scenarios of climate change mitigation. The link between cost of capital and effectiveness of the EU Taxonomy lacks empirical data, which increases the overall uncertainty of such an approach. Nevertheless, by investigating sensitivities of the cost of capital, the potential boundaries of the effectiveness of the EU Taxonomy could be evaluated.

The second objective of this report with regards to the EU Taxonomy is to evaluate the alignment of the scenarios developed in the Pathways project with the EU Taxonomy. Due to the data availability and model variables of the different sectoral models, such an analysis comes with major uncertainties and quantitative results can only be generated in limited cases. The overall qualitative assessment, however, gives an indication of the compliance of the three Pathway scenarios with the indicators. The two target scenarios, EUTarget and EUSupreme, reach taxonomy alignment earlier and to a higher degree compared to EUBase. Between the two target scenarios, EUSupreme reaches an equal or higher EU Taxonomy alignment compared to EUTarget. This can be explained by a limited number of activities, particularly in the agricultural sector and an earlier transformation of primary steel making. There are limited or no differences in the transformation, transport and buildings sectors.

The analysis comes with considerable uncertainties which are linked to the mismatch between the criteria covered by the EU Taxonomy and the modeling approach. This is mirrored in the results the models provide and variables they work with to simulate the transformation related to climate change mitigation.

Despite its limitations, the results of this analysis provide a good indication of the compatibility of the different scenarios with the technical screening criteria of the EU Taxonomy. Even if EU Taxonomy alignment cannot be fully assessed due to the technical limitations, the results present a valuable summary overview of the assumptions and model results, showing how the target of climate neutrality can be reached.

Summary and outlook

The summary and outlook section attempt an interpretation of those results in light of current policies and national as well as EU-wide mitigation strategies.

1. The analysis clearly shows that **current policies are neither in line with the EU's 2030 targets, nor do they allow for reaching net-zero emissions by 2050**. Despite the implementation of ambitious mitigation measures in the transport and energy sector where electrification, use of synthetic fuels and the further increased use of renewable energies result in strong emission reductions, neither the 2030 target for ETS nor for ESR is reached. Too slow progress in industry and buildings along with limited actions in the agriculture sector are key factors for too high remaining emission levels.
2. In contrast to the above outlined reference scenario (EUBase), the two target scenarios illustrate distinct pathways for reaching GHG-neutrality by 2050. Despite both scenarios reaching this pre-defined target, the analysis shows significant differences in the resulting 2050 energy carriers and GHG balances.
   In the **EUTarget scenario**, technological mitigation options allow to reach almost zero GHG emissions in the supply sector, the transport sector and the buildings sector. In the supply sector, a significant increase in renewable electricity capacities is required to meet the overall energy demand and de-fossilize the sector itself. Remaining fossil CO_2 generated from waste incineration can partly be reduced by the use of CCS. The transport sector shows a clear split: electrification of road transport allows to strongly reduce the use of carbon-containing fuels. In contrast, international transport remains heavily dependent on carbon-containing fuels, which need to be of non-fossil origin by 2050 to reach the GHG target. This results in imports of non-fossil carbon containing fuels, that partly replace today's fossil fuel imports. Domestic production of non-fossil carbon-containing fuels is not being built-up due to high energy prices in the EU compared to other parts of the world. In the buildings sector, a strong uptake of heat pumps along with high renovation rates and ambitious energy efficiency standards for both renovations and new buildings allow to phase out fossil fuels by 2050. CO_2 generated in the industry sector can partly be reduced by the application of CCS technologies, allowing the industry sector to reach even lower emission levels compared to the EUSupreme scenario despite higher production figures. In the agricultural sector, the limited effectiveness of technological measures becomes apparent**,** resulting in remaining

emission levels of close to **300 Mt CO_2e** by 2050. Although the LULUCF sink shows a strong increase compared to the EUBase scenario from close to 300 Mt CO_2 to more than 400 Mt CO_2 in 2050, it is not sufficient to reach GHG-neutrality. **Around 30 Mt technical CDR** (such as BECCS or DACCS, not further specified for the scenario) would be needed in 2050. Behavioral measures and stronger sustainability measures allow for a substantial reduction in GHG emissions in the **EUSupreme scenario**. Lower demand for electricity as well as non-fossil fuels disburdens the renewable energy system as well as carbon imports. Despite CCS not being available in industry, the slightly lower production figures due to increased circular economy and recycling assumptions allow for a slight decrease in GHG emissions compared to generated emissions in the EUTarget scenario. Nevertheless, the lack of CCS in industry – a key aspect of the narrative for this scenario - leads to significant gross emission levels from **industry of more 150 Mt CO_2e**. Large differences can be found for the **agriculture sector**. The introduction of strong sufficiency assumptions in diets allows for GHG **emissions in this sector to be almost cut in half in 2050 compared to the EUTarget scenario** (almost 140 Mt CO_2e less). In combination with a further strengthening of the LULUCF sink, which increases to almost 500 Mt CO_2 in 2050, the scenario allows to overfulfill the net-zero GHG emissions target by 2050. **Net emissions in 2050 are consequently around -115 Mt CO_2e**.

3. Both target scenarios require strong transformations building on **technology development, technology implementation, infrastructure build up and behavioral changes**. Moreover, interlinkages between the sectors of the economy become stronger: use of electricity for heat pumps, road transport and industry are key pieces for decarbonization of those sectors. Pressure on the electricity sector is increasingly high, to provide increasing amounts of electricity from renewable energy sources or – at least – non-fossil sources. Availability of land becomes a relevant factor for electricity generation, agricultural production and development of GHG emission sinks in the LULUCF sector. Circular economy can reduce industry emissions by reducing production, at the same time helping in reducing emissions from waste. Similarly, reduced consumption of protein consumption helps to effectively reduce emissions from the agricultural sector, but also from waste and wastewater. Extensification, possible due to the reduced demand for animal products, allows to reduce nitrogen input into soil, helping to further reduce emissions from land.
4. While the EUBase scenario is strongly based on existing policies and measures or targets defined in MS's NECPs, the target scenarios are mainly built on meeting the 2050 target for GHGs. As the analysis shows, current policies, as implemented in the EUBase scenario, are not in line with meeting the 2030 or 2050 targets. **Strong supporting policies are needed in all sectors** to realize the transformation towards net-zero GHG emissions. Those measures need to address different challenges in the different sectors.
   One relevant aspect here is that the EU ETS1, 2 and the ESR are not implemented in our modeling as binding quantity-based tools, but via a CO_2 price. This partly reflects the assumption that too high CO_2 prices would not be politically acceptable and would result in political activities that lower the CO_2 prices. Social justice and competitiveness of EU industry are two aspects that are key to policy makers and make such developments likely. The gaps to the binding caps of ETS 1, ETS 2 and ESR can be interpreted as missing additional measures and policy efforts to keep the CO_2 prices at the assumed trajectories.
5. A key factor for the illustrated transformation towards GHG-neutrality – independent of the chosen pathway – is the availability of financial resources. The **EU taxonomy is one central element of the EU energy and climate policy** which shall help to provide the much-needed private money for the transformation. Hence, gaining an understanding of the role of the EU taxonomy for financial flows and its effects on the decarbonization of the economy is essential. The analyses in this project show that the **modeling suite applied for the**

scenario analysis is not suited to adequately reflect this policy element. A proper integration into techno-economic models could be a step forward to assessing the speed possible for decarbonization of the economy. However, currently financial flows are not part of most models applied in this context and deriving suitable assumptions to estimate the effects can be tricky.

Zusammenfassung

Dies ist der Abschlussbericht des Projekts "Pathways to an EU in 2050 with net-zero GHG-emissions" (auf Deutsch: „Wege zu einer EU mit Netto-Null-Treibhausgasemissionen im Jahr 2050"). Der Bericht gibt einen Überblick und diskutiert die Ergebnisse der drei im Rahmen des Projekts entwickelten Szenarien EU Pathways Base (EUBase), EU Pathways Target (EUTarget) und EU Pathways Supreme (EUSupreme).

Zielsetzung und Aufbau der Studie

Im Einklang mit dem Pariser Abkommen hat sich die EU das Ziel gesetzt, bis 2050 Netto-Null-Treibhausgasemissionen zu erreichen. Die Idee des Projekts „Wege zu einer EU im Jahr 2050 mit Netto-Null-Treibhausgasemissionen" bestand darin, verschiedene mögliche Pfade für die EU und ihrer Mitgliedstaaten zu einer klimaneutralen Wirtschaft aufzuzeigen. Dieser Bericht stellt den Modellierungsrahmen, die Szenariodefinitionen und Annahmen vor und diskutiert die Ergebnisse der drei im Rahmen des Projekts entwickelten Szenarien: EUBase, EUTarget und EUSupreme. Zusätzlich zur Modellierung dieser drei Szenarien wurde in einem Arbeitspaket mit Schwerpunkt auf der EU-Taxonomie bewertet, wie gut diese Szenarien mit den Kriterien der EU-Taxonomie übereinstimmen. Außerdem wurde die Frage behandelt, welche Ergänzungen zu den hier angewandten Modellen erforderlich wären, um eine Modellierung der EU-Taxonomie und ihrer Auswirkungen auf die Treibhausgasemissionen zu ermöglichen.

Die Analyse konzentriert sich auf die Auswirkungen von Politiken, Strategien und Maßnahmen auf Treibhausgasemissionen, Energiebedarf und andere sektorspezifische relevante physikalische Werte. Nicht in die Analyse einbezogen sind die Auswirkungen der Szenarien auf die Kosten und den daraus resultierenden finanziellen Investitionsbedarf, die Auswirkungen der Szenarien auf die Energiepreise oder makroökonomische Indikatoren, insbesondere die Entwicklung des BIP und die Beschäftigungszahlen. Solche Werte (monetäre Werte und Beschäftigung) liegen größtenteils außerhalb des Anwendungsbereichs der verwendeten Modelle. Soweit Ergebnisse vorliegen, sind sie nicht Teil der Analyse.

Diese Zusammenfassung stellt die Gesamtergebnisse der Szenarien dar. Sektorspezifische Ergebnisse und weitere Details sind im vollständigen Bericht enthalten.

Modellierungssuite und Annahmen

Für diese Studie wird eine Reihe detaillierter sektoraler Modelle verwendet. Wir wenden detaillierte techno-ökonomische Simulationsmodelle für die Sektoren Verkehr (ALADIN) und Industrie (FORECAST Industry) an, einschließlich Technologiekosten und Preisen für Energieträger und CO_2. Die Ergebnisse für Gebäude basieren auf den Ergebnissen von drei zugrunde liegenden Modellen: LCBE für Raumheizung, Kühlung und Warmwasserbereitung in Wohn- und Nichtwohngebäuden, FORECAST Appliances für Haushaltsgeräte sowie Raumkühlung in Haushalten und FORECAST Tertiary für Geräte und Prozesse im tertiären Sektor. Während die Modelle für Haushaltsgeräte und den tertiären Sektor techno-ökonomische Modelle sind, handelt es sich beim LCBE-Modell um ein Accounting-Modell, das Kosten, Energieträger oder CO_2-Preise nicht berücksichtigt. Die Energieversorgungsseite wird mit dem Kostenoptimierungsmodell Enertile modelliert. Darüber hinaus liefert das Modell NetHEAT detaillierte Informationen zu den Fernwärmenetzen.

Der Energiebereich der Wirtschaft wird durch Modelle für die Landwirtschaft (LiSE), Landnutzung, Landnutzungsänderung und Forstwirtschaft (LULUCF, modelliert durch FABio-Land) sowie den Abfallsektor (Waste_mod) ergänzt, um die nicht energiebezogenen Emissionen abzudecken. Wir berücksichtigen auch Emissionen von F-Gasen anhand von Schätzungen, die auf anderen Modellstudien basieren. Für die Zielszenarien werden weitere Überlegungen zur industriellen Kohlendioxidentfernung (einschließlich Überlegungen zum Energiebedarf und zu CO_2-Quellen) hinzugefügt, um die Emissionsbilanz zu vervollständigen. Nicht berücksichtigt sind flüchtige Emissionen und Leckagen aus der Gewinnung und dem Transport fossiler oder synthetischer Brennstoffe sowie aus dem Transport und der Speicherung von CO_2. Für eine Gesamtaggregation werden alle sektoralen Modellergebnisse in einem harmonisierten Format in einer Datenbank gesammelt und gespeichert.

Um konsistente Szenarien zu generieren, werden die Modelle iterativ durchgeführt. Ausgangspunkt ist die Berechnung des Energiebedarfs und der damit verbundenen Treibhausgasemissionen für die nachfrageseitigen Sektoren (Industrie, Verkehr, Gebäude). Parallel dazu werden die nicht-energetischen Sektoren (Landwirtschaft, LULUCF und Abfall) berechnet, um die Treibhausgasemissionen und die inländische Versorgung mit biogenen nicht-fossilen Brennstoffen zu ermitteln. Die Ergebnisse werden in das Enertile-Modell eingespeist, um die Treibhausgasemissionen für Strom, Wärme und die Bereitstellung nicht-biogener nicht-fossiler Brennstoffe und Rohstoffe zu ermitteln. Um die Treibhausgasbilanz zu vervollständigen, wird der Bedarf an CDR im Jahr 2050 ermittelt und dieser Bedarf wieder in das Enertile-Modell eingespeist, um den damit verbundenen Energiebedarf zu berücksichtigen. Schließlich wird das NetHeat-Modell verwendet, um detaillierte Informationen über Fernwärmenetze zu liefern.

Das Zusammenspiel der Modelle und die Gleichgewichte von Angebot und Nachfrage machen zusätzliche Iterationen erforderlich, um die Ergebnisse und Annahmen wie CO_2-Preise und Energieträgerpreise in Einklang zu bringen.

Szenariobeschreibungen

Es wurden drei Szenarien entwickelt und modelliert: ein Referenzszenario (EUBase) und zwei Zielszenarien (EUTarget und EUSupreme). Alle drei Szenarien folgen unterschiedlichen Narrativen, die alle darauf abzielen, ein tieferes Verständnis dafür zu gewinnen, wie innerhalb der EU-Klimaneutralität erreicht werden kann.

Das **EUBase-Szenario** dient als Referenzszenario für die Modellierungsarbeit. Es geht von den politischen und sozioökonomischen Entwicklungen ab 2022 aus und modelliert die Auswirkungen der wirtschaftlichen Entwicklung, des Bevölkerungswachstums, der Energiepreise, der CO_2-Preise und ausgewählter aktueller Maßnahmenpakete auf die Energienachfrage und -versorgung, die landwirtschaftliche Produktion, den Abfallsektor und den LULUCF-Sektor sowie die damit verbundenen Treibhausgasemissionen. Insbesondere berücksichtigt es die Auswirkungen der russischen Invasion in der Ukraine auf die Energiepreise, wie sie sich in den Energiepreisannahmen widerspiegeln.

Die berücksichtigten EU-Maßnahmen umfassen Komponenten der Energie- und Klimapakete, die derzeit diskutiert werden oder kürzlich im Rahmen des europäischen „Fit-for-55“-Pakets und des EU-REPower-Pakets als Reaktion auf die europäische Energiekrise vereinbart wurden. Dazu gehören CO_2-Preise für die Industrie und den Versorgungssektor (EU ETS 1), aber auch für den Verkehr und Gebäude (EU ETS 2) als übergreifende Maßnahmen. Darüber hinaus werden mehrere sektorspezifische Überlegungen berücksichtigt. Hier wird auf Sektorebene entschieden, welche der noch nicht umgesetzten Maßnahmen in das Szenario aufgenommen werden. Für den Großteil der Nicht-Energiesektoren werden nur begrenzte Maßnahmen umgesetzt. Dies spiegelt die derzeitige Lücke in den Gesetzgebungsaktivitäten in diesen Sektoren wider. Insbesondere das LULUCF-Ziel für 2030, eine Netto-Senke von 310 Mt CO_2 zu schaffen, wird in dem Szenario nicht umgesetzt, aber verschiedene Auswirkungen auf den LULUCF-Sektor, die sich aus Wechselwirkungen mit anderen Sektoren, insbesondere dem Agrarsektor und der Nutzung von Biomasse als Energieträger, ergeben, werden hier berücksichtigt.

Das Szenario ist technologieneutral gestaltet und lässt verschiedene Optionen für die Dekarbonisierung des Energiesystems zu, darunter CCS, CCU und Kernkraft, die unterschiedliche nationale Ansätze widerspiegeln. Im Gegensatz zu den folgenden Zielszenarien erfordert das EUBase Szenario weder die Erfüllung der Treibhausgasziele für 2030 noch für 2050 in der EU.

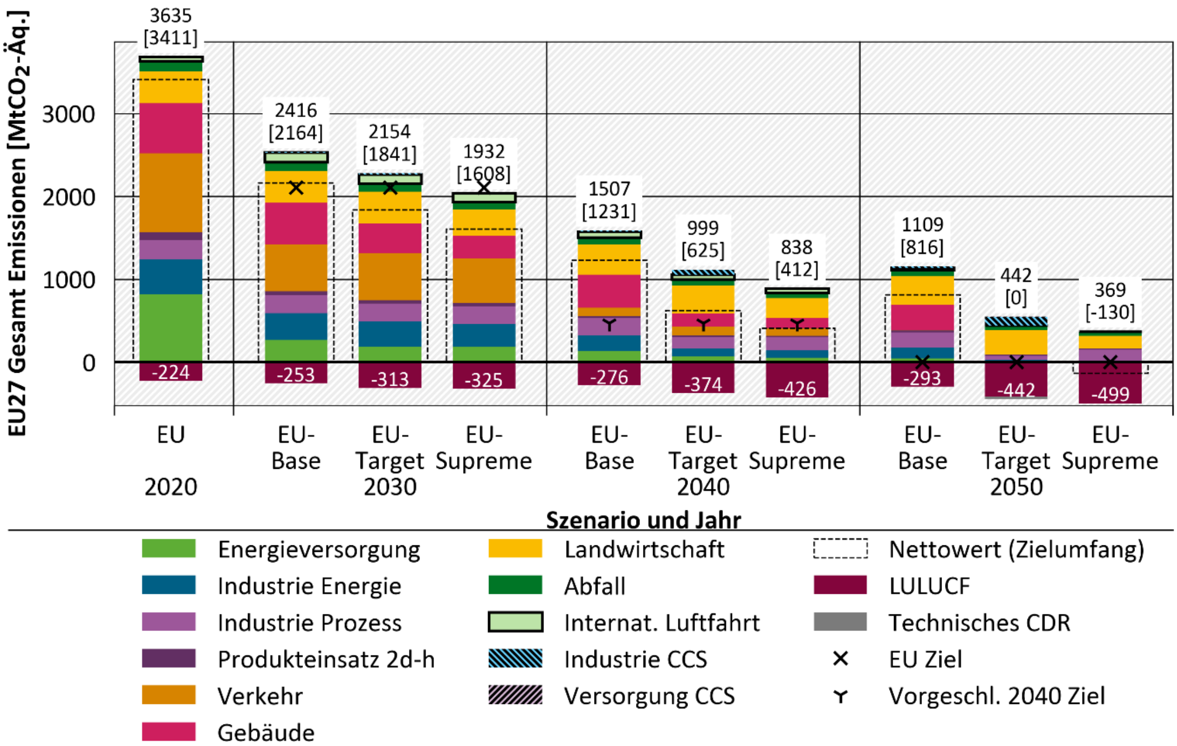
Das **EUTarget-Szenario** verfolgt einen klassischen technologieorientierten Ansatz. Es baut auf den Annahmen des EUBase-Szenarios auf, bleibt technologieoffen und ermöglicht verschiedene, auf die NECPs der Mitgliedstaaten zugeschnittene Minderungsstrategien. In diesem Szenario dient der CO_2-Preis als entscheidender Mechanismus zur Erreichung des Klimaziels für 2050, wobei für die Sektoren ETS 1 und ETS 2 unterschiedliche Preise gelten. Die beiden Preise und ihre Entwicklung im Laufe der Zeit werden innerhalb des Modellierungsrahmens festgelegt und sind nicht wie im EUBase-Szenario vordefiniert. Die Erreichung des Ziels für 2050 ist der wichtigste Faktor. Die festgelegten Preise werden jedoch zwischen den Sektormodellen harmonisiert. Die höheren CO_2-Preise sowie die Annahmen über eine stärkere Verbreitung von Klimaschutztechnologien, um das Ziel für 2050 zu erreichen, sind die wichtigsten Triebkräfte in diesem Szenario. Der Fokus auf technische Klimaschutzmaßnahmen wird auch im Agrarsektor angewendet, wo im Vergleich zum EUBase-Szenario eine Reihe zusätzlicher Klimaschutzmaßnahmen eingeführt werden. Technische Klimaschutzmaßnahmen können durch gezielte Förderprogramme und Anreizsysteme umgesetzt werden, insbesondere für kleinere landwirtschaftliche Betriebe. Größere Betriebe können durch verbindliche Verpflichtungen, die in Rechtsvorschriften wie der Industrieemissionsrichtlinie (IED) festgelegt sind, zur Umsetzung solcher Maßnahmen verpflichtet werden.

Im Gegensatz dazu sieht das **EUSupreme-Szenario** die Umsetzung einer umfassenden EU-weiten Klimaschutzstrategie vor, die strenge Nachhaltigkeitskriterien, eine verbesserte Kreislaufwirtschaft und nicht-technische Verhaltensänderungen in den Vordergrund stellt. Dieses Szenario schränkt die Nutzung von Kernenergie erheblich ein und reduziert die Nutzung von Biomasse im Energiesystem. Es sieht außerdem einen Klimaschutzpfad ohne CCS vor. Stattdessen führt das Szenario strenge Annahmen hinsichtlich Suffizienz und Kreislaufwirtschaft im Industriesektor ein, die niedrigere Primärproduktionsniveaus ermöglichen und somit einen zusätzlichen Hebel für den Klimaschutz schaffen. Darüber hinaus zielt es darauf ab, den Energiebedarf stärker als das EUTarget-Szenario zu senken, und legt einen verstärkten Fokus auf den Ausstieg aus fossilen Brennstoffen, wie beispielsweise den Ausstieg aus der Kohle bis 2040 im Industriesektor und ein striktes Verbot der Nutzung fossiler Brennstoffe im Jahr 2050. Für den Agrarsektor ermöglichen strenge Annahmen hinsichtlich der Suffizienz eine erhebliche Reduzierung der Tierbestände und der damit verbundenen Emissionen, anstatt technische Klimaschutzmaßnahmen anzuwenden. In Kombination mit einem stärkeren Anstieg des ökologischen Landbaus und anderen robusten Annahmen zur Landnutzung ermöglicht das Szenario eine deutliche Zunahme der natürlichen Kohlenstoffsenke.

Wichtigste Ergebnisse

Die Treibhausgasbilanz aller Sektoren der Europäischen Union unter verschiedenen Szenarien im Vergleich zu 2020 (siehe Abbildung 1) ist ein zentrales Ergebnis des Projekts. Die Emissionen aus dem internationalen Luft- und Seeverkehr sind vollständig berücksichtigt, ebenso wie die Emissionsspeicherung im LULUCF-Sektor und CCS in späteren Jahren.

Abbildung 1: Entwicklung der Treibhausgasemissionen in den drei Projektszenarien für die EU27 zwischen 2020 und 2050



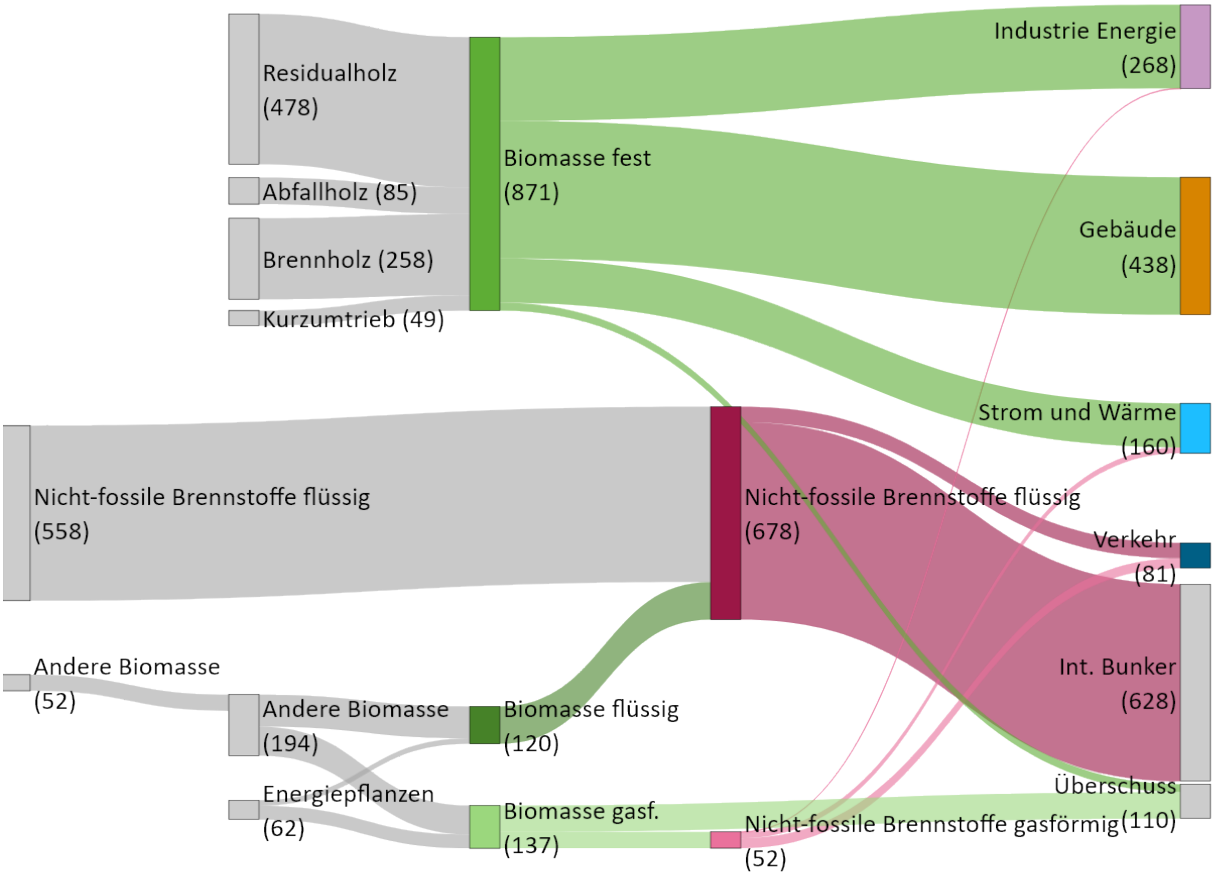
Quelle: eigene Berechnungen Fraunhofer ISI, Öko-Institut

Die Nettoemissionen (in Klammern) werden im EUBase-Szenario für 2030 auf 2.164 Mt CO_2-Äq., für 2040 auf 1.231 Mt CO_2-Äq.und für 2050 auf 816 Mt CO_2-Äq. prognostiziert. Dies entspricht einer Verringerung der Nettoemissionen um 54 % gegenüber dem Stand von 1990 im Jahr 2030, womit das Reduktionsziel der EU von 55 % bis 2030 knapp verfehlt wird. Im Jahr 2040 liegen die Emissionen um 74 % unter dem Niveau von 1990, im Jahr 250 erreichen sie ein Reduktionsniveau von 83 % unter dem Niveau von 1990. Diese Ergebnisse zeigen, dass die derzeit umgesetzten und diskutierten Maßnahmen, wie sie in diesem Szenario modelliert sind, insbesondere in den späteren Jahren überhaupt nicht mit den Klimazielen der EU in Einklang stehen. In der Industrie, im Gebäudebereich und in der Landwirtschaft bleiben erhebliche Emissionen bestehen. Die verbleibenden Emissionswerte in den Bereichen Versorgung und Verkehr sind gering, aber selbst diese beiden Sektoren erreichen bis 2050 keine Null-Emissionen. Hier nutzt insbesondere der internationale Luftverkehr weiterhin fossile Brennstoffe, während der Straßenverkehr durch den Einsatz von Elektrofahrzeugen eine fast vollständige Dekarbonisierung erreicht. CDR – vollständig naturbasiert – steigt im EUBase-Szenario von -224 Mt im Jahr 2020 auf -293 Mt im Jahr 2050. Die Brutto-Treibhausgasemissionen liegen aufgrund geringer Mengen an CCS in der Zementindustrie (-17 Mt im Jahr 2050) leicht unter den erzeugten Treibhausgasemissionen im Jahr 2050.

Nicht-fossile Brennstoffe spielen bereits im EUBase-Szenario eine wichtige Rolle, obwohl die EU-Klimaziele verfehlt werden. Die Nachfrage nach Wasserstoff entsteht insbesondere durch die Strom- und Wärmeerzeugung, aber auch durch die Industrie und industrielle Rohstoffe sowie durch die geringe Nachfrage aus dem Verkehrs- und Gebäudesektor. Die Nachfrage, die sich im Jahr 2050 auf 376 TWh beläuft, kann durch die heimische Produktion gedeckt werden. Importe sind nicht erforderlich. Neben Wasserstoff haben feste Biomasse sowie flüssige und gasförmige nicht-fossile Brennstoffe, (die Kohlenstoff enthalten können), einen relevanten Anteil an der Deckung des Endenergie- und Rohstoffbedarfs (siehe Abbildung 2). Im EUBase-Szenario werden im Jahr 2050 große Mengen fester Biomasse in Gebäuden, in der Industrie sowie bei der Strom- und Wärmeerzeugung eingesetzt. Geringe Mengen gasförmiger und flüssiger Biomasse werden auch im Verkehr, bei der Strom- und Wärmeerzeugung sowie in der Industrie verwendet. Eine hohe Nachfrage nach flüssigen nicht-fossilen Brennstoffen entsteht im Verkehrssektor, insbesondere bei internationalen Bunkerkraftstoffen.

Abbildung 2: Nicht-fossile Energieträger im EUBase-Szenario in 2050

EUBase 2050 [TWh]



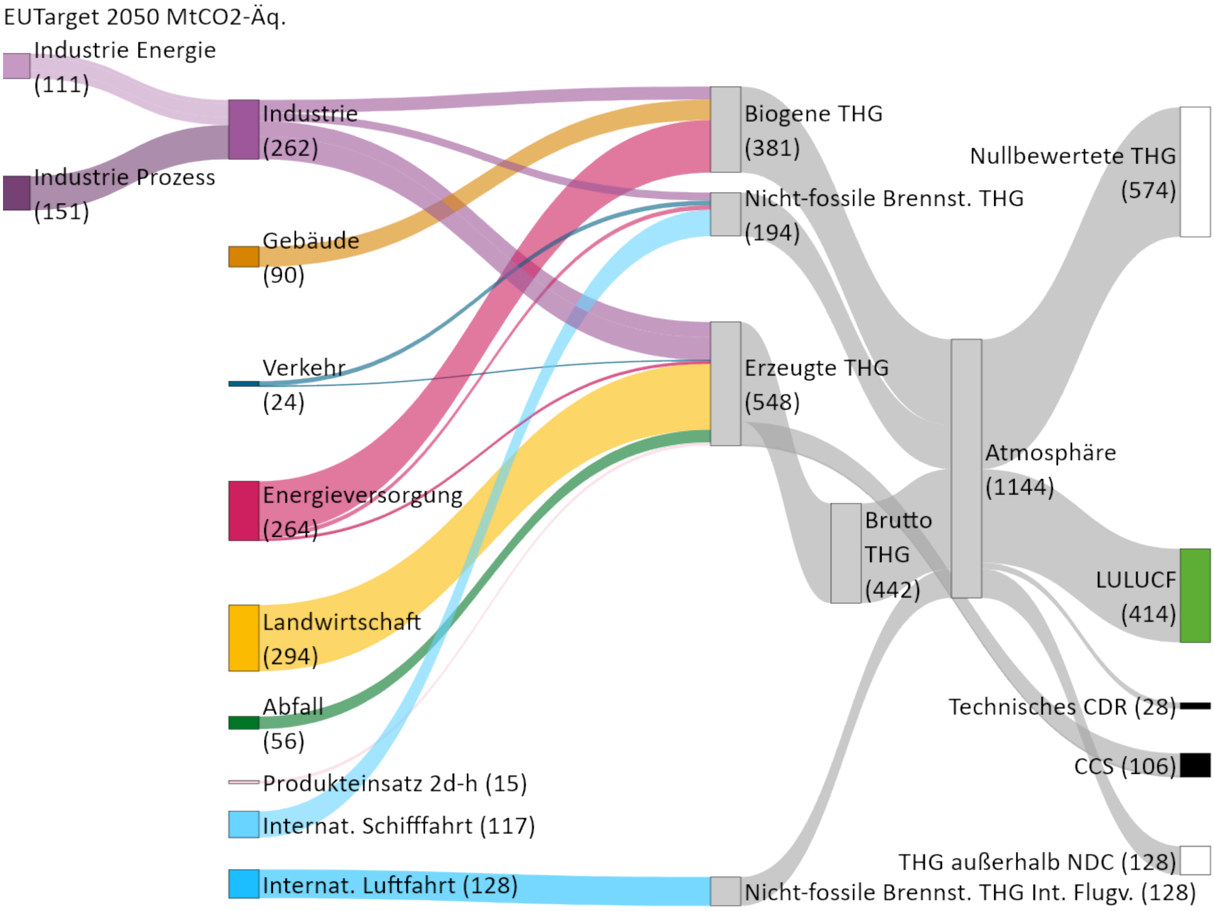
Quelle: eigene Berechnungen Fraunhofer ISI, Öko-Institut

Im EUTarget-Szenario sinken die Netto-Treibhausgasemissionen im Vergleich zum EUBase-Szenario deutlich stärker, insbesondere in den späteren Jahren. Die Nettoemissionen erreichen 1.841 Mt CO_2-Äq. im Jahr 2030, 625 Mt CO_2-Äq. im Jahr 2040 und 0 Mt CO_2-Äq. im Jahr 2050. Das sind zusätzliche Emissionsminderungen in Höhe von 323 Mt CO_2-Äq. im Jahr 2030, 606 Mt CO_2-Äq. im Jahr 2040 und 816 Mt CO_2-Äq. im Jahr 2050.

Diese Ergebnisse werden durch verschiedene Effekte ausgelöst. Zusätzliche Reduktionen der erzeugten Treibhausgase im EUTarget-Szenario sind insbesondere im Gebäudesektor, aber auch im Versorgungssektor in den Zwischenjahren zu verzeichnen. Die Bruttoemissionen in der Industrie können durch den starken Einsatz von CCS reduziert werden, wodurch bis 2050 eine Minderung von 106 Mt CO_2 erreicht wird (hauptsächlich aus der Industrie, zu einem kleinen Teil auch aus der Abfallverbrennung im Versorgungssektor). Um die verbleibenden Bruttoemissionen auszugleichen, sind in diesem Szenario sowohl naturbasierte als auch technische CDR erforderlich. Die LULUCF-Senke nimmt im Vergleich zum EUBase-Szenario zu und erreicht im Jahr 2050 eine Speicherkapazität von -414 Mt. Darüber hinaus sind technische CDR in einer Größenordnung von 28 Mt CO_2 erforderlich, um die Emissionslücke zu schließen und eine Netto-Null-Treibhausgasbilanz zu erreichen.

Trotz einer Netto-Null-Treibhausgasbilanz verbleibt im EUTarget-Szenario eine erhebliche Menge an Kohlenstoff- und CO_2-Emissionen im Energiesystem (siehe Abbildung 3). Dazu gehören biogenes CO_2 sowie CO_2-Emissionen, die in der Bilanz mit Emissionsfaktor Null belegt werden, aus importierten nicht-fossilen Brennstoffen für internationale Bunker, Transport und industrielle Rohstoffe.

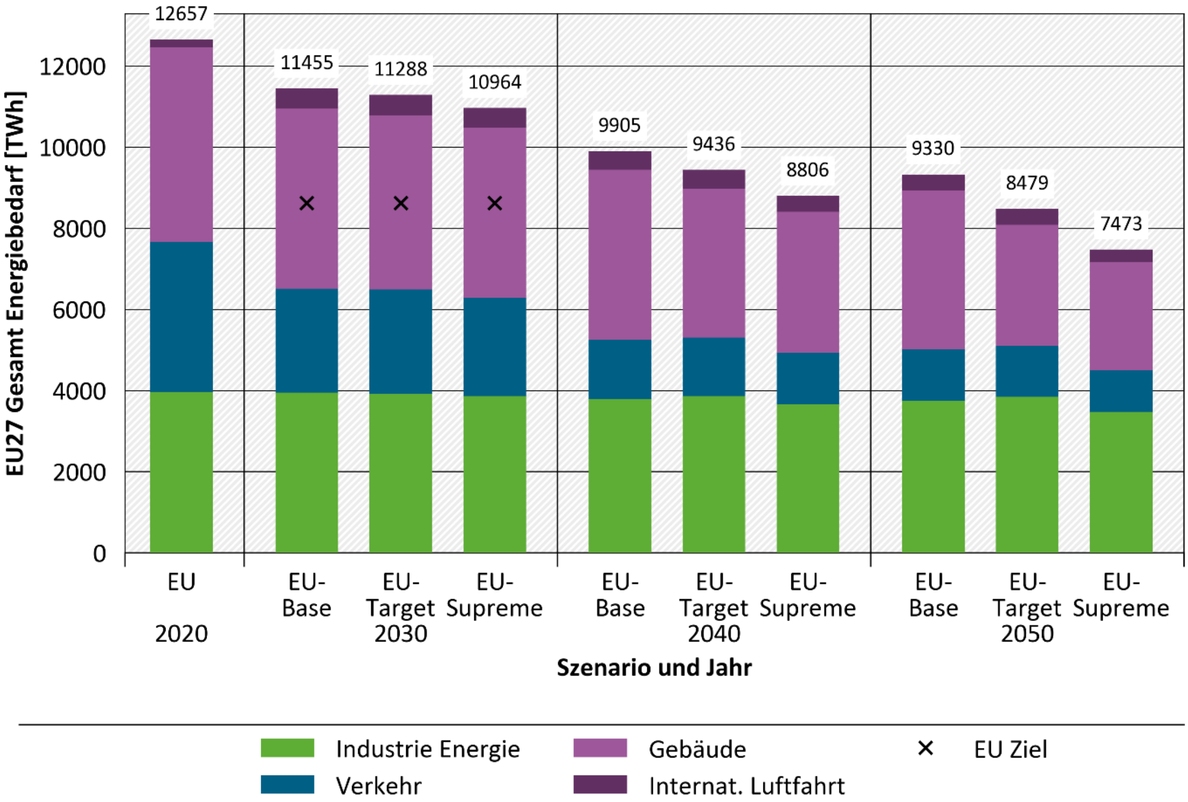
Abbildung 3: Treibhausgasflüsse in EUTarget in 2050 in der EU27



Quelle: eigene Berechnungen Fraunhofer ISI, Öko-Institut

Der Endenergiebedarf (siehe Abbildung 4) im EUTarget-Szenario kann im Vergleich zum EUBase-Szenario bis 2050 um 851 TWh gesenkt werden. Dieses Ergebnis ist hauptsächlich auf einen geringeren Energiebedarf von Gebäuden zurückzuführen, der durch steigende Renovierungsraten und Standards bedingt ist. Diese Reduzierung gleicht einen leichten Anstieg des Energiebedarfs im Industriesektor aufgrund des starken Einsatzes von CCS aus. Die Entwicklung des Endenergiebedarfs zeigt auch, dass sich größere Unterschiede erst in späteren Jahren abzeichnen, während die Unterschiede im Jahr 2030 marginal sind und alle drei Szenarien das Energieeffizienzziel der EU von 8.626 TWh für den Endenergiebedarf im Jahr 2030 verfehlen.

Abbildung 4: Endenergiebdarf in den drei Szenarien zwischen 2020 und 2050 in der EU27



Quelle: eigene Berechnungen Fraunhofer ISI, Öko-Institut

Auch beim Anteil erneuerbarer Energien am Endenergiebedarf sind erneut große Unterschiede festzustellen. Im EUBase-Szenario stieg der Anteil bereits deutlich von 19,2 % im Jahr 2020 auf 64 % im Jahr 2050. Im EUTarget-Szenario erreicht er 90,6 % bei nur geringen Mengen fossiler Brennstoffe. Der Anteil der Elektrizität am Gesamtsystem steigt gleichzeitig deutlich von 19 % im Jahr 2020 auf 46 % im Jahr 2050. Dies spiegelt die wichtige Rolle der Elektrizität für die Dekarbonisierung von Sektoren wie Verkehr, Gebäude und Industrie wider.

Die Nachfrage nach Wasserstoff steigt im Vergleich zu EUBase deutlicher an und erreicht 557 TWh im Jahr 2050. Das Stromsystem der EU ist nicht mehr in der Lage, den gesamten Wasserstoffbedarf im Inland zu decken, aber Importe machen 2050 13 % des gesamten Wasserstoffbedarfs aus. Kohlenstoffhaltige flüssige nicht-fossile Brennstoffe spielen eine dominantere Rolle bei der Versorgung mit nicht-fossilen Brennstoffen ohne Wasserstoff. Neben internationalen Bunkerkraftstoffen fließen große Mengen in industrielle Rohstoffe.

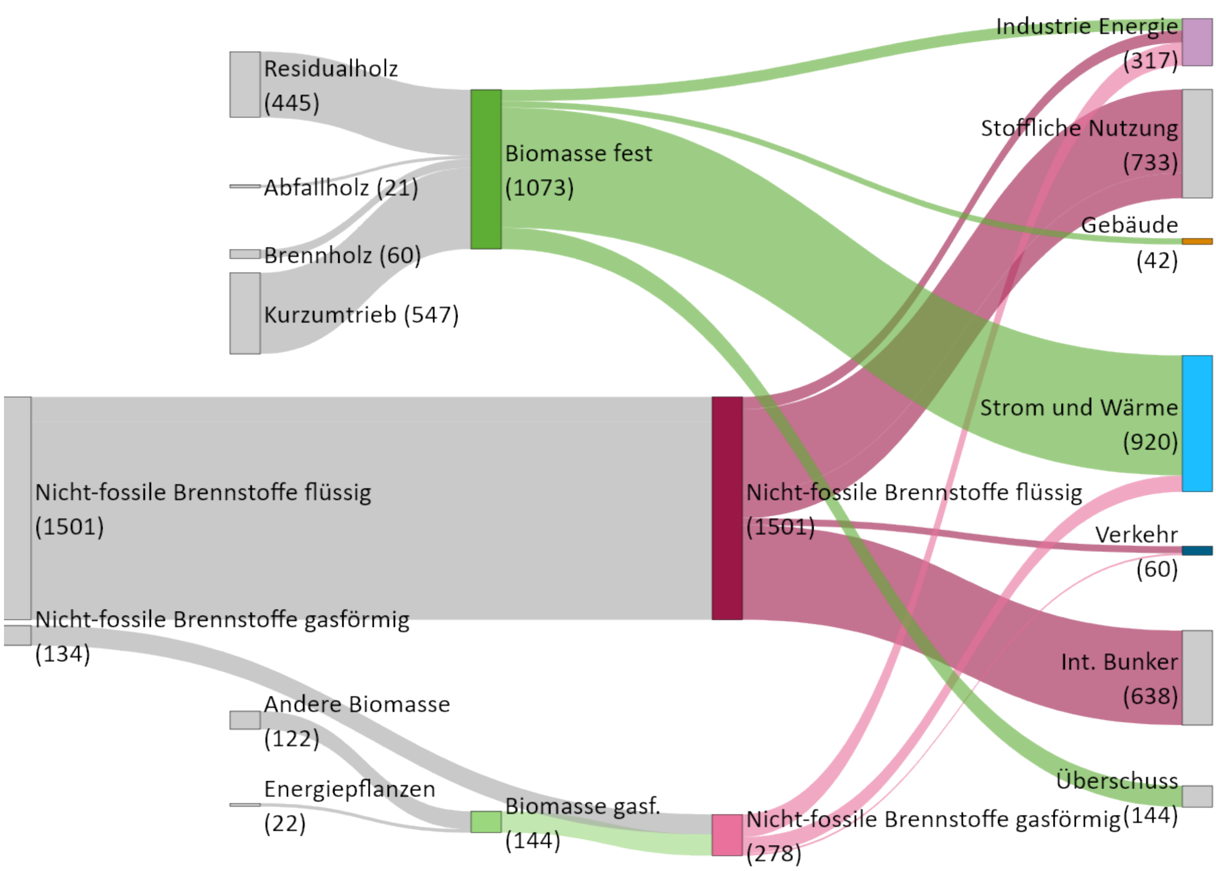
Zusätzlich zu diesen Importen von kohlenstoffhaltigen nicht-fossilen Brennstoffen besteht auch eine direkte Nachfrage nach CO_2 aus der Industrie für MTO/MTA-Routen. Die benötigte CO_2-Menge steigt von 187 Mt CO_2 im Jahr 2030 auf 388 Mt im Jahr 2050, da die Hälfte der Produktionsanlagen durch MTO/MTA-Anlagen ersetzt wird.

Der deutlichste Rückgang der Treibhausgasemissionen ist im EUSupreme-Szenario zu verzeichnen. Die Netto-Treibhausgasemissionen sinken auf 1.608 Mt CO_2-Äq. im Jahr 2030, 412 Mt CO_2-Äq. im Jahr 2040 und -130 Mt CO_2-Äq. im Jahr 2050. Im Jahr 2040 entspricht dies einer zusätzlichen Reduzierung der Nettoemissionen um 34 % gegenüber EUTarget. Im Jahr 2050 erfordert das Szenario nicht nur keinen Einsatz technischer CDR-Maßnahmen, um Netto-Null-Emissionen zu erreichen, wie es bei EUTarget der Fall war. Im Gegensatz dazu sind die Bruttoemissionen weiter deutlich zurückgegangen, und die LULUCF-Senke könnte im Vergleich zu EUTarget weiter erhöht werden (um -86 Mt CO_2). Insgesamt ermöglicht dies einen klar negativen Nettoemissionswert im Jahr 2050.

Verschiedene Sektoreffekte tragen zu diesem Ergebnis bei. Die Emissionen der Nicht-Energiesektoren sinken im EUSupreme-Szenario deutlich stärker als im EUTarget-Szenario. Der erhebliche Rückgang der Viehbestände in der Landwirtschaft ermöglicht nicht nur eine Verringerung der Emissionen in diesem Sektor, sondern wirkt sich auch positiv auf die Verfügbarkeit von Flächen für den LULUCF-Sektor und auf die Emissionen aus Abfällen aus, da der Verbrauch an tierischen Proteinen zurückgeht. Der Abfallsektor profitiert zusätzlich von den starken Annahmen zur Kreislaufwirtschaft, wodurch die Abfallmenge reduziert wird. Dies hat wiederum auch sehr positive Auswirkungen auf den Industriesektor, da es eine Verringerung der Produktionszahlen und eine Stärkung der recycelten Materialien ermöglicht. Aus Gründen der Transparenz muss darauf hingewiesen werden, dass zur Erreichung eines Ergebnisses mit nicht-fossilen Brennstoffen bis 2050 in Industrie und Verkehr Verbote für fossile Brennstoffe umgesetzt werden mussten.

Annahmen zur Suffizienz für den Verkehr und den Gebäudesektor in Verbindung mit den Annahmen zur Kreislaufwirtschaft führen zu einem starken Rückgang des Endenergiebedarfs. Im Vergleich zu EUTarget können zusätzlich 1.000 TWh Endenergie eingespart werden. Das verringert den Druck auf den heimischen Stromsektor und erlaubt einen weiteren Anstieg des Erneuerbaren-Anteils an der Stromerzeugung in 2050 – von 86.2% auf 92.2% (bei noch nahezu gleichen Anteilen in 2040). Es ermöglicht zudem eine Reduzierung der Importe von nicht-fossilen Brennstoffen und Wasserstoff. Ebenfalls reduziert wird die Nachfrage nach nicht-fossilen biogenen Brennstoffen, was zu einem leichten Überschuss an fester Biomasse im Jahr 2050 von 144 TWh führt (siehe Abbildung 5). Der Anteil der Erneuerbaren Energie an der Gesamtenergienachfrage steigt von 90.6 auf 94.9% in 2050 im EUSupreme verglichen mit dem EUTarget-Szenario. Die Nachfrage nach Kohlenstoff aus MTO und MTA-Anlagen liegt – passend zur Entwicklung der Gesamtnachfrage nach chemischer Primärproduktion. Er liegt bei 101 Mt CO_2 in 2050, 20 Mt unter dem Bedarf im EUTarget-Szenario.

Abbildung 5: Nicht-fossile Energieträger im EUSupreme-Szenario in 2050



Quelle: eigene Berechnungen Fraunhofer ISI, Öko-Institut

EU-Taxonomie

Die EU-Taxonomie-Verordnung verpflichtet große und kapitalmarktorientierte Unternehmen zur Berichterstattung über den Anteil ihrer wirtschaftlichen Tätigkeiten, die als nachhaltig gelten (European Commission 2020b). Der Anteil der wirtschaftlichen Tätigkeit wird je nach Art des Unternehmens als Anteil an den Investitionen oder am Umsatz definiert. Zu diesem Zweck wurde in delegierten Rechtsakten, die der EU-Taxonomie nachfolgten, ein Katalog von wirtschaftlichen Aktivitäten und technischen Prüfkriterien festgelegt. Jede dort definierte Tätigkeit muss einen wesentlichen Beitrag zu einem der sechs Umweltziele leisten, ohne die anderen fünf zu beeinträchtigen um als nachhaltig zu gelten (die sechs Umweltziele sind dabei Klimaschutz, Anpassung an den Klimawandel, Schutz der Wasserressourcen, Kreislaufwirtschaft, Vermeidung von Umweltverschmutzung und Biodiversität).

In diesem Bericht wird untersucht, wie die Auswirkungen der Taxonomie modelliert werden könnten. In einem zweiten Schritt wird bewertet wir, ob die Ergebnisse der Szenarien mit der EU-Taxonomie in Einklang stehen, insbesondere mit den darin festgelegten technischen Screening-Kriterien.

Zur direkten Modellierung der EU-Taxonomie müssten Szenarien zu ihrer Wirksamkeit der EU-Taxonomie entwickelt werden, wenn die EU-Taxonomie direkt modelliert wird. Dies wäre eine zusätzliche Variable im Policy-Mix, der die Klimaschutz-Szenarien definiert. Für den Zusammenhang zwischen Kapitalkosten und Wirksamkeit der EU-Taxonomie fehlen empirische Daten, was die allgemeine Unsicherheit eines solchen Ansatzes erhöht. Dennoch könnten durch eine Sensitivitätsanalyse der Kapitalkosten die potenziellen Grenzen der Wirksamkeit der EU-Taxonomie bewertet werden.

Das zweite Ziel dieses Berichts mit Blick auf die EU-Taxonomie ist die Bewertung der Konformität der Szenarien mit der EU-Taxonomie. Aufgrund der Datenverfügbarkeit und der Modellvariablen der verschiedenen sektoralen Modelle ist eine solche Analyse mit großen Unsicherheiten behaftet und quantitative Ergebnisse können nur in begrenztem Umfang erzielt werden. Die qualitative Gesamtbewertung liefert jedoch einen Hinweis auf die Übereinstimmung der drei Szenarien mit den Kriterien der Taxonomie. Die beiden Zielszenarien „EUTarget“ und „EUSupreme “ erreichen die Übereinstimmung mit der EU-Taxonomie früher und in höherem Maße als „EUBase“. Zwischen den beiden Zielszenarien erreicht EUSupreme eine gleiche oder höhere EU-Taxonomie-Konformität als EUTarget. Dies lässt sich auf eine begrenzte Anzahl von Aktivitäten, insbesondere im Agrarsektor, zurückführen und durch eine frühere Umstellung der Primärstahlherstellung erklären. In den Sektoren Umwandlung, Verkehr und Gebäude gibt es nur begrenzte oder keine Unterschiede.

Die Analyse ist mit erheblichen Unsicherheiten verbunden, die auf die Diskrepanz zwischen den Kriterien der EU-Taxonomie und dem Modellierungsansatz zurückzuführen sind. Der Modellierungsansatz definiert die Ergebnisse der Modelle und die Variablen, mit denen die Modelle die Transformation simulieren und somit die Daten, die zur Untersuchung der Konformität bereitstehen.

Trotz ihrer Einschränkungen vermitteln die Ergebnisse dieser Analyse einen guten Eindruck von der Vereinbarkeit der verschiedenen Szenarien mit den technischen Prüfkriterien der EU-Taxonomie. Auch wenn die Übereinstimmung mit der EU-Taxonomie aufgrund der technischen Einschränkungen nicht vollständig bewertet werden kann, bieten die Ergebnisse einen wertvollen Überblick über die Annahmen und Modellergebnisse, die zeigen, wie das Ziel der Klimaneutralität erreicht werden kann.

Zusammenfassung und Ausblick

Der Abschnitt „Zusammenfassung und Ausblick“ versucht eine Interpretation dieser Ergebnisse vor dem Hintergrund der aktuellen Politik und der nationalen sowie EU-weiten Klimaschutzstrategien.

1. Die Analyse zeigt deutlich, dass die aktuellen politischen Maßnahmen weder mit den Zielen der EU für 2030 im Einklang stehen noch eine Netto-Null-Emissionsbilanz bis 2050 ermöglichen. Trotz der Umsetzung ehrgeiziger Klimaschutzmaßnahmen im Verkehrs- und Energiesektor, wo Elektrifizierung, der Einsatz synthetischer Kraftstoffe und die weitere verstärkte Nutzung erneuerbarer Energien zu starken Emissionsreduktionen führen, werden weder das Ziel für 2030 für das Emissionshandelssystem (Emission Trading System - ETS) noch für die Lastenteilungsverordnung (Effort Sharing Regulation - ESR) erreicht. Zu langsame Fortschritte in der Industrie und im Gebäudebereich sowie begrenzte Maßnahmen im Agrarsektor sind die Hauptgründe für die zu hohen verbleibenden Emissionswerte.
2. Im Gegensatz zu dem oben skizzierten Referenzszenario (EUBase) zeigen die beiden Zielszenarien unterschiedliche Wege zur Erreichung der Treibhausgasneutralität bis 2050 auf. Obwohl beide Szenarien dieses vordefinierte Ziel erreichen, zeigt die Analyse erhebliche Unterschiede bei den resultierenden Energieträgern und Treibhausgasbilanzen für 2050. Im EUTarget-Szenario ermöglichen technologische Minderungsoptionen, im Versorgungssektor, im Verkehrssektor und im Gebäudesektor nahezu null Treibhausgasemissionen zu erreichen. Im Versorgungssektor ist eine erhebliche Steigerung der Kapazitäten für erneuerbare Energien erforderlich, um den Gesamtenergiebedarf zu decken und den Sektor selbst zu de-fossilisieren. Die verbleibenden fossilen CO_2-Emissionen aus der Abfallverbrennung können durch den Einsatz von CCS teilweise reduziert werden. Der Verkehrssektor weist eine klare Zweiteilung auf: Durch die Elektrifizierung des

Straßenverkehrs kann der Verbrauch kohlenstoffhaltiger Kraftstoffe stark reduziert werden. Im Gegensatz dazu ist der internationale Verkehr nach wie vor stark von kohlenstoffhaltigen Kraftstoffen abhängig, die bis 2050 aus nicht fossilen Quellen stammen müssen, um das Treibhausgasziel zu erreichen. Dies führt zu Importen von nicht fossilen kohlenstoffhaltigen Kraftstoffen, die die heutigen Importe fossiler Kraftstoffe teilweise ersetzen. Die heimische Produktion von nicht fossilen kohlenstoffhaltigen Kraftstoffen wird aufgrund der im Vergleich zu anderen Teilen der Welt hohen Energiepreise in der EU nicht ausgebaut. Im Gebäudesektor ermöglichen der starke Einsatz von Wärmepumpen in Verbindung mit hohen Renovierungsraten und ehrgeizigen Energieeffizienzstandards sowohl für Renovierungen als auch für Neubauten den Ausstieg aus fossilen Brennstoffen bis 2050. Die im Industriesektor erzeugten CO_2-Emissionen können durch den Einsatz von CCS-Technologien teilweise reduziert werden, sodass der Industriesektor trotz höherer Produktionszahlen noch niedrigere Emissionswerte als im EUSupreme-Szenario erreichen kann. Im Agrarsektor zeigt sich die begrenzte Wirksamkeit technologischer Maßnahmen, was zu verbleibenden Emissionswerten von fast 300 Mt CO_2 Äq. bis 2050 führt. Obwohl die LULUCF-Senke im Vergleich zum EUBase-Szenario einen starken Anstieg von knapp 300 Mt CO_2 auf über 400 Mt CO_2 im Jahr 2050 verzeichnet, reicht dies nicht aus, um die Treibhausgasneutralität zu erreichen. Im Jahr 2050 wären etwa 28 Mt technische CDR erforderlich.
Verhaltensmaßnahmen und strengere Nachhaltigkeitsmaßnahmen ermöglichen eine erhebliche Reduzierung der Treibhausgasemissionen im EUSupreme-Szenario. Eine geringere Nachfrage nach Strom und nicht-fossilen Brennstoffen entlastet das System der erneuerbaren Energien sowie die Kohlenstoffimporte. Obwohl CCS in der Industrie nicht verfügbar ist, ermöglichen die aufgrund der verstärkten Kreislaufwirtschaft und Recyclingannahmen leicht niedrigeren Produktionszahlen einen leichten Rückgang der Treibhausgasemissionen im Vergleich zu den im EUTarget-Szenario erzeugten Emissionen. Dennoch führt der Ausschluss von CCS in der Industrie – ein zentraler Aspekt dieses Szenarios – zu erheblichen Bruttoemissionen aus der Industrie von mehr als 150 Mt CO_2 Äq.. Große Unterschiede sind im Agrarsektor zu verzeichnen. Durch die Einführung strenger Annahmen zur ausreichenden Ernährung können die Treibhausgasemissionen in diesem Sektor bis 2050 im Vergleich zum EUTarget-Szenario fast halbiert werden (fast 140 Mt CO_2e weniger). In Kombination mit einer weiteren Stärkung der LULUCF-Senke, die bis 2050 auf fast 500 Mt CO_2 ansteigt, ermöglicht das Szenario eine Übererfüllung des Netto-Null-Treibhausgasemissionsziels bis 2050. Die Nettoemissionen im Jahr 2050 liegen somit bei etwa -115 Mt CO_2e.

3. Beide Zielszenarien erfordern tiefgreifende Veränderungen, die auf technologischer Entwicklung, Technologieimplementierung, Infrastrukturaufbau und Verhaltensänderungen basieren. Gleichzeitig werden die Verflechtungen zwischen den Wirtschaftssektoren stärker: Die Nutzung von Strom für Wärmepumpen, den Straßenverkehr und die Industrie sind Schlüsselelemente für die Dekarbonisierung dieser Sektoren. Der Druck auf den Stromsektor wächst, immer mehr Strom aus erneuerbaren Energiequellen oder zumindest aus nicht fossilen Quellen bereitzustellen. Die Verfügbarkeit von Land wird zu einem relevanten Faktor für die Stromerzeugung, die landwirtschaftliche Produktion und die Entwicklung von Treibhausgas-Senken im LULUCF-Sektor. Die Kreislaufwirtschaft kann die Emissionen der Industrie durch eine Verringerung der Produktion reduzieren und gleichzeitig dazu beitragen, die Emissionen aus Abfällen zu senken. Ebenso trägt ein geringerer Proteinkonsum dazu bei, die Emissionen aus dem Agrarsektor, aber auch aus Abfall und Abwasser wirksam zu reduzieren. Die Extensivierung, die durch die geringere Nachfrage nach tierischen Produkten möglich wird, ermöglicht eine Verringerung des Stickstoffeintrags in den Boden und trägt so zu einer weiteren Reduzierung der Emissionen aus dem Landbereich bei.

4. Während das EUBase-Szenario stark auf bestehenden Politiken und Maßnahmen oder Zielen basiert, die in den NECPs der Mitgliedstaaten definiert sind, basieren die Zielszenarien hauptsächlich auf der Erreichung des 2050-Ziels für Treibhausgase. Wie die Analyse zeigt, sind die aktuellen Politiken, wie sie im EUBase-Szenario umgesetzt werden, nicht mit der Erreichung der Ziele für 2030 oder 2050 vereinbar. In allen Sektoren sind starke unterstützende Maßnahmen erforderlich, um den Übergang zu Netto-Null-Treibhausgasemissionen zu verwirklichen. Diese Maßnahmen müssen den unterschiedlichen Herausforderungen in den verschiedenen Sektoren Rechnung tragen. Ein relevanter Aspekt hierbei ist, dass das EU-Emissionshandelssystem (EU ETS) 1 und 2 sowie die Lastenteilungsverordnung (ESR) in der Modellierung nicht als verbindliche mengenbasierte Instrumente umgesetzt sind, sondern über einen CO_2-Preis. Dies spiegelt teilweise die Annahme wider, dass zu hohe CO_2-Preise politisch nicht akzeptabel wären und zu politischen Maßnahmen führen würden, die die CO_2-Preise senken. Soziale Gerechtigkeit und Wettbewerbsfähigkeit der EU-Industrie sind zwei Aspekte, die für politische Entscheidungsträger von zentraler Bedeutung sind und solche Entwicklungen wahrscheinlich machen. Die Lücken zu den verbindlichen Obergrenzen von ETS 1, ETS 2 und ESR können als fehlende zusätzliche Maßnahmen und politische Anstrengungen interpretiert werden, um die CO_2-Preise auf den angenommenen Pfaden zu halten.
5. Ein entscheidender Faktor für die dargestellte Transformation hin zur Treibhausgasneutralität – unabhängig vom gewählten Weg – ist die Verfügbarkeit finanzieller Ressourcen. Die EU-Taxonomie ist ein zentrales Element der Energie- und Klimapolitik der EU, das dazu beitragen soll, die dringend benötigten privaten Mittel für die Transformation bereitzustellen. Daher ist es von entscheidender Bedeutung, die Rolle der Taxonomie für Finanzströme und ihre Auswirkungen auf die Dekarbonisierung der Wirtschaft zu verstehen. Die Analysen in diesem Projekt zeigen, dass die für die Szenarioanalyse verwendete Modellreihe nicht geeignet ist, um dieses politische Element angemessen widerzuspiegeln. Eine angemessene Integration in techno-ökonomische Modelle könnte ein Schritt vorwärts sein, um die mögliche Geschwindigkeit der Dekarbonisierung der Wirtschaft zu bewerten. Derzeit sind Finanzströme jedoch nicht Teil der meisten in diesem Zusammenhang verwendeten Modelle, und die Ableitung geeigneter Annahmen zur Abschätzung der Auswirkungen kann schwierig sein.

1 Introduction

The project aims at illustrating different possible pathways for a transformation of the EU and its Member States to a climate-neutral continent. For that, a reference scenario (EUBase) and two target scenarios (EUTarget, and EUSupreme) were developed and modelled. The EUBase scenario is used to show the ambition of existing and negotiated policy packages such as the EU Fit-for-55 Package, the REPower EU Package or the policies suggested in the National Energy and Climate Plans (NECPs) on Member State level. It serves as the reference scenario for the two target scenarios, where additional policies are implemented to ensure that EU climate targets for 2030 and climate neutrality by 2050 are met.

Both target scenarios assume, that by 2050 the EU Member States manage to lower their gross greenhouse gas emissions (GHG) to a minimum under the defined technological conditions and assumptions on industry production and agricultural productivity. At the same time, carbon removals from natural sinks as well as technological options, such as bioenergy combined with carbon capture and storage (BECCS) or direct air carbon capture and storage (DACCS), allow to offset the remaining GHG emissions so that in total the EU achieves GHG-neutrality.

The two target scenarios illustrate different pathways of reaching GHG-neutrality. In particular, the EUTarget scenario focuses on individual Member State policies by modeling Member State specific targets and measures, e.g. described in the National Energy and Climate Plans (NECPs) for the energy sector or support schemes for decarbonization of industry. It puts a stronger focus on technical solutions and is more technology-open. It allows for carbon capture and storage (CCS) as a way to mitigate emissions in industry and the supply sector (emissions from burning of waste only). It also allows for technical carbon dioxide removals (CDR) in addition to natural CDR from the LULUCF sector to reach the pre-defined emission targets. Energy efficiency and deployment of renewable energy technologies are key measures to reach emission reductions.

The EUSupreme scenario presents a pathway, which puts strong emphasis on non-technical mitigation options and includes highly ambitious assumptions regarding sustainability. This is realized by including strong assumptions on behavioural changes such as dietary changes, lower industry production levels and a reduction in transport volume both on road and in the air along with high levels of circularity within the economy. At the same time, the technology portfolio available is limited, in particular nuclear power (no commissioning of new nuclear power stations) and no use of carbon capture and storage, not even for technical CDR. It limits the use of CDR options to nature-based solutions within the LULUCF sector and excludes all other options. Stronger sustainability criteria for biomass compared to the other scenarios are applied, limiting further its utilization in the energy system.

All scenarios use the same assumptions on demographic development (impacting among others demand for heating and transport) as well as growth in gross domestic product (GDP) (and gross value added). Other drivers, including energy prices, are adapted in the different scenarios to derive consistent narratives. A longer set of differing assumptions are described in the annex to this report.

To summarize, we study three different scenarios:

- *EUBase*: This scenario, serving as the reference scenario for the project, analyses the ambition of existing and negotiated policy packages on the EU and Member State level with regards to the 2030 and 2050 climate targets (as of 2022). Reaching the EU emission reduction targets for 2030 and 2050 is not preconditioned.

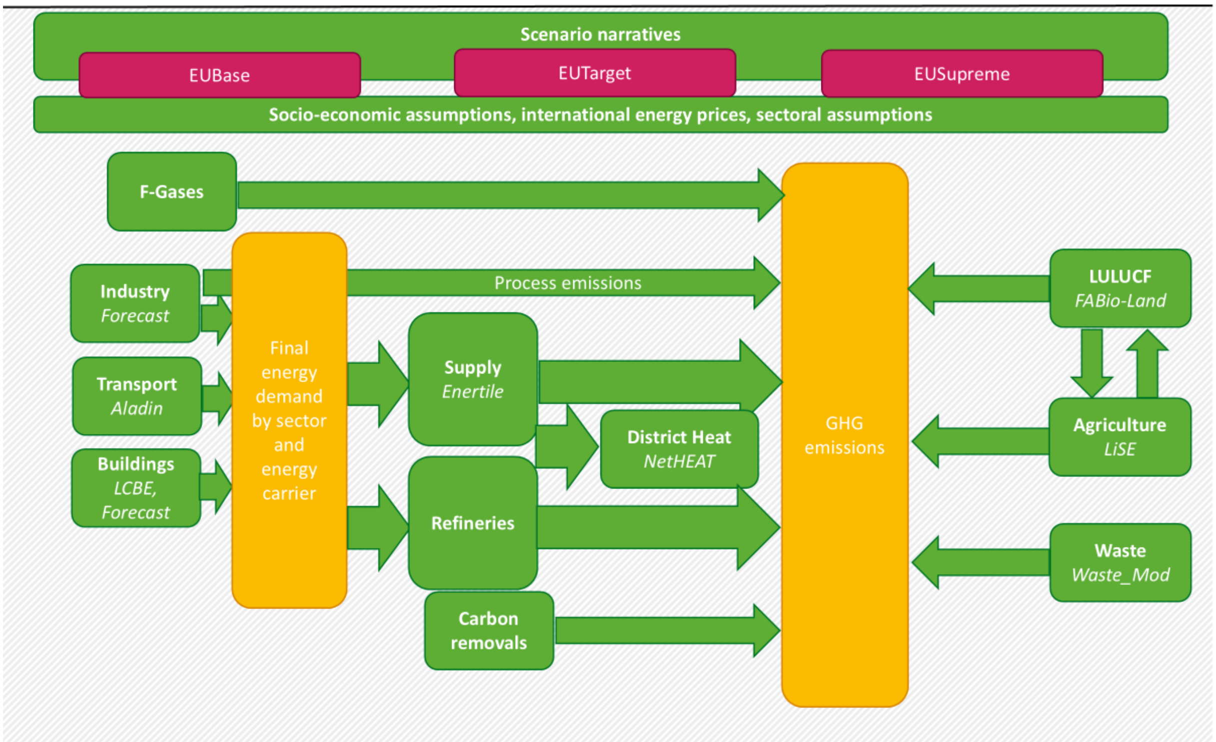
- *EUTarget*: This target scenario illustrates a pathway to GHG-neutrality by putting a strong focus on technical solutions and on national mitigation strategies. It builds on EUBase but makes assumptions on additional measures to reach the EU emission reduction targets for 2030 and 2050. These assumptions reflect expert knowledge on possible technological pathways and policy developments.
- *EUSupreme:* This second target scenario is based on the common application of strong sustainability criteria in the context of mitigation technologies and a strong focus on non-technical and behavioural mitigation options. Like the EUTarget scenario the scenario builds on EUBase but makes stronger assumptions on sustainability and circularity and implements behavioural change illustrating a highly sustainable pathway to reach GHG-neutrality in the EU.

This report first describes the modeling approach taken in this project. It introduces the sector-specific bottom-up models being used and explains the interaction between models. Subsequently, results for the three scenarios EUBase, EUTarget and EUSupreme are presented. The scenario presentation starts with the scenario narrative, before providing results on the overall system and then going into the sector-details thereafter.

2 Modeling approach

2.1 Overall modeling approach

Figure 6: Overview of sectoral models applied in this study



Source: own illustration, Fraunhofer ISI

The analysis focuses on the impacts of policies, strategies and measures on GHG emissions, energy demand and other sector-specific relevant physical values. Not included in the analysis are scenario-impacts on costs and resulting monetary investment needs, scenario implications on energy prices or macro-economic indicators, in particular GDP developments and employment figures. Such values (monetary values and employment) are mainly out of the scope of the models applied, where results are available, they are not part of the analysis.

A suite of detailed sectoral models is applied to perform this study. We apply detailed techno-economic simulation models for the sectors transport (ALADIN) and industry (FORECAST Industry) including technology costs and energy carrier and CO_2 prices. The results for buildings build on the output from three underlying models: LCBE for space heating, cooling and water heating in residential and non-residential buildings, FORECAST Appliances for appliances as well as household space cooling and FORECAST Tertiary for appliances and processes in the tertiary sector. While the models for appliances and the tertiary sector are techno-economic models, the LCBE model is an accounting model, not taking into account costs, energy carrier or CO_2 prices. The energy supply side is modelled with the cost-optimization model Enertile. On top, the model NetHEAT provides detailed information on the district heating networks.

The energy side of the economy is complemented by models for agriculture (LiSE), land-use, land-use change and forestry (LULUCF, modelled by FABio-Land) and the waste sector (Waste_mod) to cover the non-energy related emissions. We also consider emissions from F-gases by estimations based on other modeling studies. For the target scenarios, further considerations regarding industrial carbon dioxide removals are added (including considerations on energy demand and CO_2 sources) to complete the emission balance. Not included are fugitive emissions and leakages from the extraction and transport of fossil or synthetic fuels as well as from CO_2 transport and storage. For an overall aggregation, all sectoral model results are collected and stored in a harmonized format in a database. The approach behind each model is explained in more detail in section 2.3.

Each model is run to generate results for the EU 27 for the years 2030, 2040 and 2050 for each of the three scenarios (EUBase, EUTarget, EUSupreme). Most models also generate values for the historic year 2020 and these are complemented with historic data where this is not the case.1 Most models for energy sectors build on disaggregated data for all 27 Member States that are aggregated. Where this is not the case, results at least build on groups of Member States. These groups are model-specific and aggregate countries with similar characteristics and conditions. Non-energy sectors are modelled at the EU level only. This allows to generate an almost complete overview of the energy demand and supply as well as the GHG emissions in the EU 27 including sector and country characteristics.

All models use common as well as sector-specific input data. Common input data include - where relevant - GDP, population, international energy prices and CO_2 prices. The most important sector specific-input data are described further in the model descriptions. Values for the common input data are provided in section 2.4.

To generate consistent scenarios, the models are run in an iterative way. Starting point is the calculation of energy demand and related GHG emissions for the demand-side sectors (industry, transport, buildings). In parallel, the non-energy sectors (agriculture, LULUCF and waste) are calculated to determine GHG emissions and the domestic supply of biogenic non-fossil fuels. The results are fed into the Enertile model to determine GHG emissions for electricity, heat and provision of non-biogenic non-fossil fuels and feedstocks. To complete the GHG balance, demand for technical CDR in 2050 is determined and these requirements fed back into the Enertile model to account for the related energy demand. Finally, the NetHeat model is used to provide detailed information on district heating networks.

The interaction of models and the balances of supply and demand make additional iterations necessary to harmonize results and assumptions such as CO_2 prices and energy carrier prices.

2.2 Scope of models and official emissions reporting

The modeling includes all 27 EU Member States, partly clustered as in case of the LCE buildings model or as EU 27 aggregate as in case of non-energy sectors. Results are reported on the EU level.

Official emissions reporting of the EU and its Member States follows the Common Reporting Format (CRF) for National Inventory Reporting (NIR) and usually differs from the coverage of different sector models. Table 1 provides an overview of the NIR emission categories and which emissions are covered under which model for clarification. Figure 7 below shows NIR emissions for the year 2020 vs. GHG emissions covered within the models.

A gap of roughly 90 Mt (2% of total net GHG emissions) exists between NIR data for 2020 and emissions covered by the models (with NIR data being higher) when excluding fugitive emissions which are not covered by our model suite. A closer look at the sector level shows that for most sectors differences are between 0 and 5%. More significant differences can only be found for agriculture (8%), where 2020 data for calibration of the model are taken from a later submission (NIR 2023) and for product use (11%), where our approach builds mainly on a

[1] Availability of historic data, characteristics of specific years that may not be representative for later years as well as the time needed for calibration of models can lead to models not starting with most recent base years.

different study[2]. Including fugitive emissions, which are not covered by our model suite, increases the gap to 160 Mt CO_2e or 4% of 2020 NIR data.

Note: the inventory reporting as our modeling approach is based on a reporting of direct emissions ("scope 1 emissions"), to prevent double counting. It does not necessarily reflect a polluter-pays principle, e.g. in case of electricity use when emissions are reported under the supply sector, but the electricity is used in different end uses.

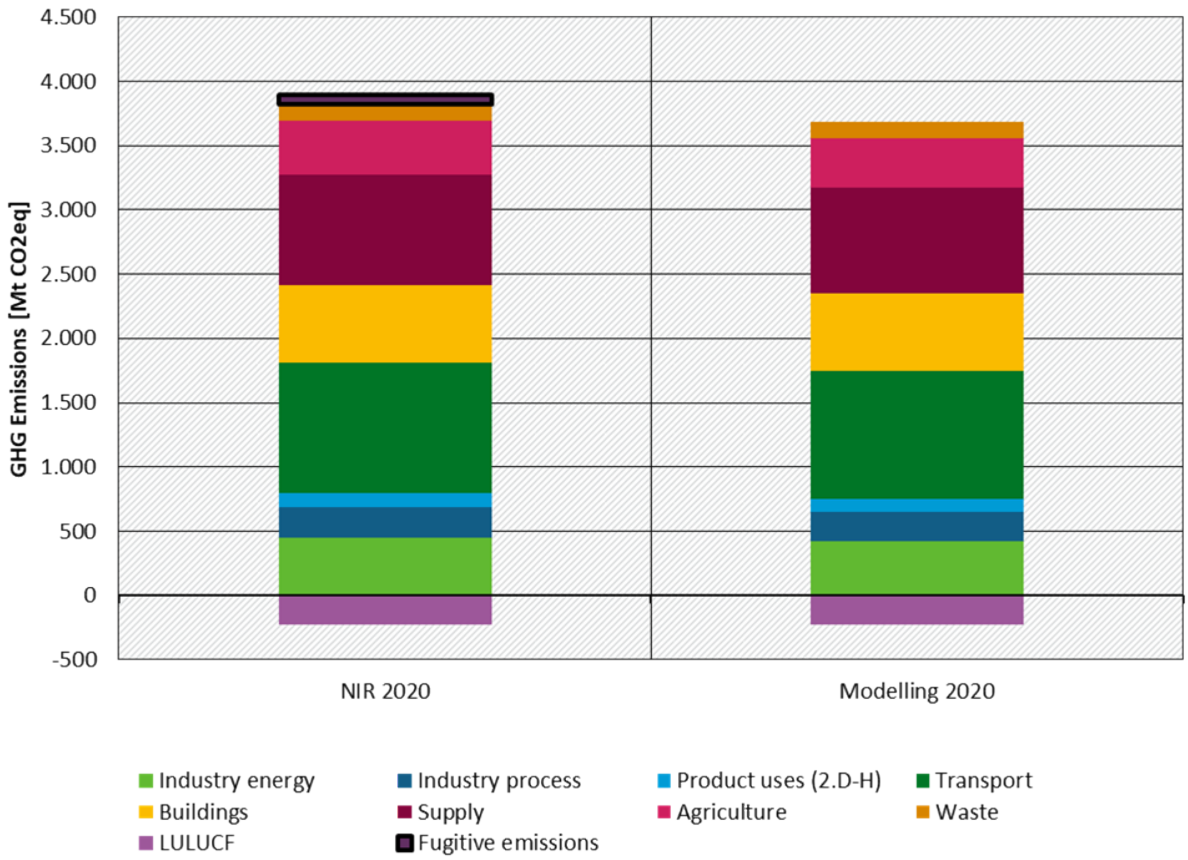
Table 1: Official EU emissions reporting (2020 data from 2022 submission) and scope of models

NIR category	Model	Comments
1.A.1.a Public electricity and heat production	Enertile	
1.A.1.b Petroleum refining	---	Estimated based on use of oil
1.A.1.c Manufacture of solid fuels and other energy industries	---	Estimated based on use of coal
1.A.2. Manufacturing industries and construction	FORECAST Industry	
1.A.3 Transport	ALADIN	
1.A.4.a. Commercial/institutional	LCBE + FORECAST Appliances + FORECAST Tertiary	
1.A.4.b. Residential	LCBE + FORECAST Appliances	
1.A.4.c Agriculture/forestry/fishing	FORECAST Tertiary	
1.A.5. Other	FORECAST Tertiary	
1.B. Fugitive emissions from fuels	---	Not covered within the project
1.C. CO_2 Transport and storage	FORECAST Industry / own calculations outside the modeling framework	
International Bunkers	ALADIN	
2.A. Mineral industry	FORECAST Industry	
2.B. Chemical industry	FORECAST Industry	
2.C. Metal industry	FORECAST Industry	
2.D. Non-energy products from fuels and solvent use	F-Gas calculations (excl non F-gases)	Own estimates for CO_2, CH_4, N_2Os
2.E Electronics industry	F-Gas calculations (excl. non-F-gases)	Own estimates for CO_2, CH_4, N_2Os
2.F Product uses as substitutes for ODS	F-Gas calculations (excl. non-F-gases)	Own estimates for CO_2, CH_4, N_2Os

[2] Gschrey, Barbara, Behringer, David, Kleinschmidt, Jlia et al. 2022, for further information see section 3.2.1.4

NIR category	Model	Comments
2.G. Other product manufacture and use	F-Gas calculations (excl. non-F-gases)	Own estimates for CO_2, CH_4, N_2Os
2.H Other	F-Gas calculations (excl. non-F-gases)	Own estimates for CO_2, CH_4, N_2Os
3. Total agriculture	LiSE	
4. Total LULUCF	FABio-Land	
5. Total Waste	Waste_Mod	

Figure 7: EU27 GHG Emissions Inventory vs. Emissions modeling



Source: own illustration based on data from NIR submission 2022 and model data

2.3 Details on sectoral models

The following sections give a general introduction to each of the models applied in this project. Tables summarizing the technical assumptions underlying the different scenarios in each sector are given in Annex B.2.

2.3.1 Industry - FORECAST Industry

The model FORECAST Industry is used to calculate scenarios for the industry sector's transition. FORECAST Industry is a comprehensive and robust strategic decision support tool, primarily designed to develop detailed long-term scenarios for energy demand, GHG emissions, and decarbonization strategies for the industry sector. The model's ability to explicitly account for the technology diffusion and turnover in stock is pivotal in its capability to provide valuable insights into potential transition pathways and their corresponding timelines. By explicitly considering these factors, FORECAST Industry can offer valuable information regarding how various technologies are adopted and replaced over time, thereby facilitating an understanding of possible trajectories towards the desired target.

One of FORECAST Industry's significant strengths is its strategic combination of both bottom-up and top-down methodologies that results in a well-rounded perspective on industrial transition. The bottom-up approach in the FORECAST Industry model ensures a high level of technological detail. It delves deep into the industrial sector, its specific processes and technologies, and comprehensively assesses a wide range of mitigation options. Simultaneously, the top-down approach in FORECAST Industry closes knowledge gaps and calibrates the model to align with energy balances and larger economic and policy dynamics.

FORECAST Industry considers the following mitigation options: energy efficiency (incremental and radical change), fuel switching (to renewable and low-carbon energy carriers), carbon capture and storage, circular economy and recycling, material efficiency and substitution down the value chain. The model is designed to cover the entire industrial sector according to the Eurostat energy balances, which encompass eight separate industries defined by the NACE 2 classification. These include both energy-intensive (iron and steel, chemicals, non-metallic minerals and others) and less energy-intensive sub-sectors. This structure enables detailed simulations of individual sub-sectors and applications, providing valuable insights into each domain. The model's scope is defined by the energy balances (Eurostat) with a focus on final energy, but it also accounts for useful energy. Useful energy is derived by applying technology-specific efficiencies to final energy demand and, in some cases, includes additional energy gains from ambient heat sources, for example, in industrial heat pumps

The bottom-up simulation of energy demand on process level allows a detailed breakdown of GHG emissions by source. These emissions are categorized into two primary groups based on their sources: energy-related emissions and process-related emissions. Energy-related emissions consist of two subcategories. The direct energy-related occur directly on-site as a result of the combustion of energy sources and indirect GHG emissions from the use of electricity. Process-related emissions, on the other hand, are released as a direct result of specific industrial processes. These emissions are predominantly associated with industries like basic chemical manufacturing and cement production.

FORECAST Industry utilizes a wide range of input data. These are drawn from a wide range of relevant databases and resources and are carefully organised and updated annually in the platform's extensive model database. The comprehensive data include economic and physical indicators, such as sectoral Gross Value Added (GVA), energy prices, and production statistics that shape energy demand and emission trajectories. The model also includes data related to existing policy measures, such as the EU Emissions Trading System (EU ETS) and forthcoming ones that directly influence energy demand and emission trajectories. Furthermore, structural details and technical specifications provide a granular view of the industrial sector, encompassing information about facilities, their age, technologies in use, and detailed technical parameters of current and prospective technologies. These also include short-term factors such as business cycles and temperature (heating and cooling degree days) that can affect energy demand within a one-year horizon. By combining detailed economic and physical drivers, structural and technical specifications with broader policy, regulation and behaviour patterns, generate robust and realistic scenarios that aid policymakers and industrial stakeholders in making strategic decisions for a sustainable industrial future.

The model is calibrated using the most recent EUROSTAT statistics for parameters such as energy balances, employment, value added, and energy prices. In cases where EUROSTAT data are unavailable, particularly energy carrier prices, supplementary data are taken from the International Energy Agency (IEA) and other reputable sources to fill the gaps. This data-based approach can accommodate a broad spectrum of different scenarios of prospective developments.

Industrial statistics and future production quantities at process and country level (e.g. electric steel production in Italy) comprise a major input. These are collected and updated annually using a variety of data sources including PRODCOM, UN commodity production database, US geological survey, UNFCCC, and industry organisations (World Steel Association, CEPI, Cembureau, Eurochlor, etc.).

Technology data (costs, efficiencies, age distribution etc.) are generally not available from public data sources but need to be gathered from the literature or estimated in consultation with industry representatives. The technology database is continuously improved by individual research projects. For a more detailed model description we refer to (Fleiter et al. 2018) and (Rehfeldt et al. 2020).

2.3.2 Transport – ALADIN

The modeling of the transport sector differs by subsector. The road transportation is modelled using a version of the ALADIN market diffusion model (Plötz et al. 2014) adapted for Europe. For the non-road transport modes – rail transport, aviation, and navigation – future energy demand and emission scenarios are developed using a top-down approach based on exogenous assumptions regarding transport activity and technology diffusion, drawing on policy targets and literature. For each country and transport subsector, GHG emissions and final energy demands are calibrated to 2019 NIR data. The different modeling approaches for passenger cars (incl. two-wheelers), commercial vehicles (encompassing light-duty trucks <3.5 t as well as medium-duty and heavy-duty vehicles) and the non-road transport modes (rail, aviation, navigation) are presented below.

2.3.2.1 Road transport

ALADIN (Alternative automobile diffusion and infrastructure) is a market diffusion model for passenger cars and commercial vehicles, which calculates market shares of alternative fuel vehicles, simulates the development of vehicle stocks, and derives final energy demands and CO_2 emissions for road transport.

In its original version for Germany (Plötz et al. 2014), the model is built on an agent-based simulation of alternative drive purchase decisions in road transport, using real-world driving data from several thousand individua vehicles. It calculates the total cost of ownership (TCO) for different drivetrains (e.g., gasoline, diesel, battery electric vehicles, plug-in hybrid electric vehicles, fuel cell electric vehicles, etc.) and determines the utility-maximizing powertrain option for each individual vehicle, while accounting for various restrictions such as infrastructure limitations and availability of new drivetrain technologies. This approach yields annual market share estimates for each drivetrain technology. With the market shares and the driving behaviour data, the final energy demand differentiated by energy carrier (e.g., hydrogen, electricity, diesel fuel) from road transport can be calculated. Further information on modeling, reference projects and publications can be found at www.aladin-model.eu.

For the modeling of the European road transport sector, ALADIN was adapted and two different modeling approaches for cars and commercial vehicles were developed:

- In the passenger car subsector, the original agent-based model was substituted by a logistic model named ALADIN-EU in order to account for national differences between EU27 countries. For passenger cars, electric vehicles are already common and are diffusing into the market, albeit at different speeds in the different countries. Assuming that only the battery electric drivetrain will prevail in the passenger car market in the long term, a logistic function is used to estimate country-specific growth rates for electric vehicle market shares. ALADIN-EU considers national differences in customer energy prices, current electric vehicle diffusion, and the development of charging infrastructure on a national level (see details in subsection 2.3.2.1.1).
- For commercial vehicles, the discussion about alternative powertrain options is still open and the market development is not that clear yet. Therefore, the original agent-based simulation model for the German market is used, which selects the best out of different drivetrain options for individual driving profiles to calculate market shares and to derive energy demands, and its results for Germany are extrapolated to other countries (see details in subsection 2.3.2.1.2).

2.3.2.1.1 Passenger cars

As electric powertrains in form of plug-in electric vehicles (PEVs, encompassing battery electric vehicles, BEVs, and plug-in hybrid electric vehicles, PHEVs) are already common in cars, the future market diffusion can be estimated based on empirical data. The market diffusion, which depends on national framework conditions, is represented by a logistic growth function for each country. The logistic growth function is selected for its compatibility with empirical data and its alignment with the projected market saturation, consistently set at 100% for all countries, reflecting the quite certain substitution of conventional drive technologies by PEVs. The EU ban for new internal combustion engine cars from 2035 and the clear positioning in automobile industry towards PEV allow this model approach. Fuel cell electric vehicles (FCEVs) are not expected to significantly penetrate the passenger car market in the future due to the high costs associated with fuel cells and hydrogen as well as the current predominance of BEVs.

The logistic growth function is built on a regression analysis on the Norwegian market development from 2009 to 2021. Norway is the forerunner country in electric mobility with an 83% market share of PEVs in mid-2021 (ACEA European Automobile Manufacturers Association 2021). Starting point of the growth model is today's market situation in each considered country, which is described by current stock sizes, annual passenger car registrations, and market shares of BEVs and PHEVs as published by ACEA (2022). To adapt the annual national growth rates to each country, consideration is given to national fuel to electricity price ratios, national monetary incentives, and the national availability of charging infrastructure. Monetary incentives include all cost savings associated with PEVs compared to conventional vehicles. The impact of these factors on market share is determined by regression coefficients calculated through a panel analysis from Münzel et al. (2019). The development of registration numbers is exogenously set based on literature (see scenario assumptions in section 3.2.2). Future car stocks by powertrain are calculated from registration numbers based on the assumption that all cars have a service life of 12 years, which corresponds to the average life expectancy of a passenger car in historic vehicle stock data from Germany (Plötz et al. 2013). Annual energy demands of the national car stocks are calculated assuming an average annual mileage per car, which remains constant in the future but differs between countries. Annual emissions are calculated from the fossil fuel demand. While not explicitly modelled as part of the stock, two-wheelers are covered by the passenger car model as the energy demand for each country is calibrated to NIR data for cars and motorcycles.

2.3.2.1.2 Commercial vehicles

As there is hardly any empirical data on market diffusion of alternative drives for heavy-duty vehicles, the agent-based simulation model, developed for the German market, is used. Here, ALADIN distinguishes between six drive alternatives for commercial vehicles: (1) diesel vehicles, (2) PHEV, (3) BEV, (4) FCEV and catenary vehicles that are either equipped (5) with an additional battery or (6) with an additional diesel engine. The simulation differentiates five vehicle size classes: (1) light commercial vehicles with a gross vehicle weight of less than 3.5 t, (2) trucks with a gross vehicle weight of 3.5 t to 7.5 t, (3) trucks with a gross vehicle weight of 7.5 t to 12 t, (4) trucks with a gross vehicle weight greater than 12 t, and (5) tractor-trailers.

The simulation is built on vehicle usage data from 6,098 conventional vehicles (Wermuth 2012, Truckscout24 2016) – each user is characterized by a real-world vehicle driving profile. For each year under consideration, the simulation follows three steps: In the first step, the driving profiles are individually simulated to check the technical feasibility of a BEV for this use case and to calculate the electric driving share of a PHEV for this use case, given the assumptions on specific energy consumption and battery capacity in the simulation year. This is followed by the calculation of individual TCO (which are the main driver of the purchase decision of commercial vehicles (Kluschke et al. 2019)). From all available and feasible powertrain options, the model selects the one with the lowest TCO for each individual user. In the third step, the individual vehicle purchase decisions are aggregated to derive market shares of drivetrains in the new registrations of the year under consideration and flow into a vehicle stock model. Assumptions on the development of the total number of registrations in Germany are generally taken from the ASTRA-M model. Further information on the procedure for commercial vehicles can be found in Wietschel et al. (2017) and Gnann et al. (2017).

The described agent-based simulation calculates the annual energy carrier demands and CO_2 emissions from fossil fuel consumption for commercial vehicles in Germany until 2050. For the other European countries, their annual energy demand and emissions are calculated by scaling the results for Germany according to the NIR data of the base year. For this calibration process, the model uses the sum of the two CRF categories "light duty trucks" and "heavy duty trucks and buses" for each country. Thus, the annual energy demands and emissions calculated by the model cover all commercial vehicles (including vans, rigid trucks, and tractor-trailers) as well as buses and coaches.

2.3.2.2 Non-road transport

Non-road transport is modelled based on assumptions for transport performance development, efficiency improvements, and fuel mix. Individual models are built for the following subsectors according to the CRF classification: railway, domestic aviation, international aviation, domestic navigation (covering inland waterways and domestic maritime transport), and international navigation. In each subsector model, the base year's energy demand of each country is calibrated to the national figures reported in the NIR to UNFCCC.

In aviation and navigation, the final energy demand of the following years is calculated based on assumed energy efficiency improvements and the assumed development of the transport performance. The total energy demand is then distributed on fossil and non-fossil fuels according to assumed quotas. CO_2 emissions are calculated from the resulting fossil fuel demand.

In the rail transport model, passenger and freight transport performances for each country are split into electric traction and diesel traction according to a Lorenz curve, which models the relation between electrification of railway routes and electric rail transport performance. Given the percentage of electrified kilometres (via track electrification or use of battery electric trains), it predicts the percentage of electric transport performance, modeling the diminishing marginal utility of electrification. The annual electricity demand is then projected based on the calculated electric performances in both freight and passenger rail transport and assumed efficiency improvements. The remaining freight and passenger transport performances are covered by diesel-powered rail transport. Therefore, the model calculates the associated energy demand, allocating it to fossil fuel and biogenic fuel based on assumed quotas. CO_2 emissions are calculated from the resulting fossil fuel demand.

2.3.3 Buildings

As specified above, results for the buildings sector are provided by three distinct models, details for which are given in the following subsections.

2.3.3.1 Heating and cooling - LCBE

The energy demand for heating and cooling in residential and non-residential buildings is calculated by means of a stock exchange accounting model (Low-Carbon-Europe, LCBE). Various drivers such as the rate of newly built buildings, the demolition rate, the renovation rate as well as energy consumption levels of existing, new and renovated buildings are implemented in the model and change over time. The Status-quo data on energy carrier distributions in the EU-27 were taken from the EU COM “RES-H under the revised RED” study (Kranzl et al. 2022).

To take account of the broad differences in energy carrier distributions in the various EU 27 countries, we formed six country clusters (see Table 2). The clusters contain countries that share similar characteristics such as a high share of biomass usage or a broadly developed district heating infrastructure. The various characteristics were also used to set the 2050 energy carrier distributions taking into account the historical energy use in each cluster.

Table 2: Cluster definition buildings

Cluster	Countries	Typical characteristic
North	Denmark, Finland, Sweden	High shares of district heating systems and electrical heating, efficient buildings, moderate space heating demand
Northeast	Estonia, Latvia, Lithuania	High shares of district heating and biomass usage, low-efficiency buildings, high space heating demand
East	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia	Still some usage of coal, high shares of biomass and gas usage. Low-efficiency buildings
South	Croatia, Cyprus, Greece, Italy, Malta, Portugal, Spain	High shares of biomass and heating oil usage, low space heating energy demand
West	Belgium, France, Ireland, The Netherlands	High shares of gas and heating oil usage, moderate to high space heating demand, low district heating shares
Central	Austria, Germany, Luxemburg	High shares of gas and heating oil usage, moderate to high space heating demand, moderate district heating share

Source: Definitions Oeko-Institut

The impact of policy measures on heating and cooling demand can be assessed by changing the different drivers the model: the energy standards for new and existing buildings can be altered as can the rate of renovation or the rate at which new buildings are being built.

The data used in the model derive from several sources. Renovation rates were taken from PRIMES modeling for the Fit-for-55 MIX scenario up until 2030. Thereafter, we made own assumptions regarding the renovation rate. For other drivers like the demolition rate, the rate of newly built buildings etc. we also made assumptions (see Annex B). Data for the floor areas as well as final energy demand and energy carrier distributions in 2017 in each country were taken from the EU COM "RES-H under the revised RED" study (Kranzl et al. 2022).

2.3.3.2 Household appliances – FORECAST Appliances

For the representation of appliance adoption behaviour, the bottom-up simulation model FORECAST Appliances is used, which covers large electrical appliances, ICT, lighting, air-conditioning, as well as small electrical appliances. Given the bottom-up-design, socio-economic drivers (e.g. energy carrier prices), techno-economic characteristics (e.g. operation and standby-power, investments) and user behaviour (e.g. operation hours) can be explicitly modelled. The high level of disaggregation makes it possible to also consider technological trends such as the enforced technology phase-outs. Furthermore, the model allows considering saturation effects as well as policy regulation on a technology specific level.

FORECAST Appliances is composed by the following appliances (e.g. television), which are further distinguished by technologies (e.g. LCD, plasma) and efficiency classes (e.g. A, B, C):

- White appliances (refrigerators, freezers, washing machines, etc.),
- ICT-appliances (PC screens, laptops, televisions, etc.),
- Lighting (LED lighting, fluorescent lamps, etc.)
- Air-conditioners,
- Small electricity appliances (tablets, mobile phones, game consoles, etc.),
- Other electricity appliances: this category is an aggregate of all appliances that are not explicitly modelled containing a variety of further small appliances (e.g. coffee machines) as well as the electricity demand of potentially new appliances which will diffuse in the market until 2050.

The global socio-economic parameters setting the framework for electricity demand modeling are the end consumer prices and the number of households. For the projection of the appliance stock, sigmoid growth curves (Bass function) are applied, which are fitted to the empirical stock development on the basis of the method of least squares. Stock turnover is based on the lifetime of each appliance with a normal distributed failure probability. The market share of new technologies and efficiency classes diffusing into the market essentially depends on the appliance investment and other utility-related parameters. In the long run, cost digression of investments is anticipated, thus learning curves are applied to consider this aspect. To analyse the impact of policy measures on residential electricity demand, the model incorporates scenario-discrete settings for representing the major appliance-related policies in the EU, including Ecodesign and energy labelling. Annual electricity demand of all appliances is calculated by the product of specific consumption and the appliance stock.

Technology adoption and ensuing stock turnover in FORECAST Appliances is largely based on techno-economic drivers (unit price, power per unit, etc.) and assumed user behaviour (e.g. washing machine cycles per year). This data is primarily derived from the technology-specific preparatory studies that accompany the development of requirements under the EU Ecodesign Directive and the complementary Energy Labelling Regulation. These preparatory studies typically characterise a range of relatively inefficient to energy efficient product variants, along with their unit costs, typical operating conditions and resulting specific energy consumption. Unit prices are collected for the EU as a whole and turned into country-specific numbers using purchasing power parities.

2.3.3.3 Appliances and processes in the tertiary sector – FORECAST Tertiary

In this project, FORECAST Tertiary is used to calculate the energy consumption of the appliances and processes in the service sector. FORECAST Tertiary covers 16 sectors according to the NACE classification and 23 activities (i.e., energy end-uses). The activities are allocated to the sectors according to the (Rohde et al. 2022) survey in Germany. For other Member States in the base year, where there is no empirical data, the distribution of energy carriers and activities is based on German values. However, the total sum is scaled so that, when combined with space and water heating, it matches the tertiary sector's final energy demand. For each activity, FORECAST Tertiary considers multiple technologies. Different technologies of one activity can consume different energy carriers, for example cooking technologies based on electricity and gas. Finally, when applicable, seven efficiency classes are considered for one technology.

FORECAST Tertiary follows the bottom-up simulation approach in an agent-based framework. Each sector is represented by a large-enough population of agents, which correspond to the firms in the economy. For the base year, all the agents are initialized with the technologies that can satisfy the demand of activities. These technologies have specific lifetimes (e.g. 5 years for lighting and 17 years for freezers) and will be replaced when they reach the end of their lifecycle. The agents make technology adoption and replacement decisions, which can be influenced by (1) energy carrier prices and (2) policies. For example, the availability of different technologies may be regulated by enforced phasing-out policies or eco-design.

FORECAST Tertiary calculates the energy consumption by energy carrier at the activity level of each sector, which is the multiplication of

- Driver, i.e., employee number of the sector.
- Adoption coefficient of the activity, i.e., number of adoptions per employee.
- Penetration rate of the activity.
- Activity intensity, e.g., operation hours per year and working cycles per year.
- Energy intensity, e.g., kW and kWh per cycle.

The first four parts are estimated based on (1) framework data input, e.g., the employee number; (2) survey data, e.g., adoption coefficient, penetration rate, and activity intensity.

The fifth part, energy intensity, is calibrate for the base year according to the technology-specific preparatory studies that accompany the development of requirements under the EU Eco-design Directive and the complementary Energy Labelling Regulation. Then, the energy intensity is modelled to be changing following the bottom-up simulation approach.

2.3.4 Supply – Enertile

General Description

Enertile is a linear optimization model that minimizes the costs of generating, transmitting, and storing of different energy sources for energy supply systems until 2050. Enertile simultaneously optimises the expansion of power generation capacity and the hourly utilization of all system components based on exogenous demands for electricity, heat, and hydrogen. Additionally, it accounts for demand-side flexibility.

Model Components

The model includes various system components, including

- Conventional Power Plants and Combined Heat and Power (CHP) Plants: The model considers existing capacities along with their expected operational lifetimes. There is no endogenous decommissioning; however, the utilization of these plants is reduced when variable costs increase. The addition of fossil power plants is only permitted as a transitional measure, with a shortened operational lifespan. The construction and decommissioning of nuclear power plants are aligned with national energy plans, which vary across the different scenarios.
- Renewable Energy Sources (RES): The model assesses the potential for wind and solar energy generation based on country-specific cost-potential curves, which reflect the unique hourly supply characteristics of each country. These cost-potential curves are derived from extensive historical weather data spanning multiple years; however, they do not account for future changes in weather patterns that are currently difficult to quantify. The expansion of flexible renewable energy sources, such as biomass, is also considered, incorporating both fixed and variable costs associated with their deployment.
- District Heating Technologies: The model considers various central heating systems, including biomass CHP plants, large heat pumps, solar thermal systems, geothermal heat, and heat storage solutions.
- Cross-Border Transmission Capacities: The model includes existing capacities and capacity expansion options to transmit electricity and hydrogen between countries.
- Batteries: The model allows for endogenous expansion of battery capacities or exogenous capacity expansion, depending on the scenario narrative.
- Electrolysers and Hydrogen Storage Technologies: The model assesses the potential for hydrogen production and hydrogen storage to balance supply and demand effectively.

Optimization Approach

The optimization problem aims to minimize the total costs associated with various technologies and system components. The decision variables include:

- Installed capacities for electricity generation technologies
- Capacities for district heating and hydrogen production
- Capacities for electricity and hydrogen storage
- Transmission capacities for electricity and hydrogen between countries

Additionally, the model incorporates costs related to fuel consumption and GHG emissions.

Input Data

The input data for the Enertile model is derived from multiple sources, including:

- Energy Demand Data: Sourced from other models within the modeling framework, ensuring consistency across sectors.
- Fuel and CO_2 Prices: Detailed in Annex A.

- Infrastructure Parameters: Defined by the Ten Year Network Development Plan (TYNDP) and additional assumptions regarding the electricity grid and hydrogen infrastructure.
- Constraints: These reflect national policies and scenario characteristics.

2.3.5 District heating – NetHEAT

The analyses related to the district heating infrastructure are calculated by the NetHEAT bottom-up spatial energy simulation model. The model maps renewable heat sources, heat demand, district heating supply infrastructure, and potentials for new investments. It calculates costs related to the expansion and operation of district heating infrastructure and derives the optimal district heating infrastructure associated with different input data and restrictions. By using a hectare-level resolution for all EU countries, it captures specific local situations regarding heat demands, street lengths, number of buildings, and specific investment costs related to the percentage of sealed area.

The input data used by the NetHEAT model is generated by various sources and methods. Table 3 describes the model input data and the sources used. The heat density map relies upon the results of the LCBE model. The country specific district heating demand is then disaggregated on a hectare level based on the methodology defined in (Müller et al. 2019). A filtered subset of the OpenStreetMap (OSM) data is used to determine the length of the streets used for the installation of the district heating pipeline. A correlation between the connected buildings and the street length used for laying the district heating pipe determines the length of the district heating network within an examined area. Additional to the street length, for each building a building connection pipeline is calculated. To do so, the number of buildings within an area is determined by several sources such as OSM, degree of urbanization and population density raster for the EU. The CORINE Land Cover and Imperviousness Density datasets[3] provided by the European Copernicus Land Monitoring Service are used to determine the availability of land area, its type, and potential cost of infrastructure investments.

Table 3: Overview of the input data and data sources used in the NetHEAT model

Model input	Data sources	Description
Heat density map	LCBE model results Hotmaps	LCBE model results for each country disaggregated on hectare level
Street length map	OpenStreetMap	Selected subset of roads used for the installation of the district heating pipeline
Number of buildings map	OpenStreetMap Degree of urbanization (Eurostat 2021) Population density (European Commission) Built up area (Copernicus Land Monitoring Service 2018)	Number of buildings used to calculate the length of the building connection pipeline
Percentage of sealed area map	CORINE Land Cover Impervious density	The percentage of sealed area is used to define the type of urban area (e.g., park area vs. inner city)

[3] See https://land.copernicus.eu/en/products/corine-land-cover

2.3.6 Agriculture – LiSE

The agricultural model LiSE (LiSE stands for Livestock, Soil and Energy emissions) is an Excel-based model that calculates greenhouse gas emissions and other environmentally relevant indicators of agricultural production from livestock farming and the use of agricultural soils, as well as energy-related emissions from agriculture and horticulture. The model is based on the inventory and structural data of the National Greenhouse Gas Inventories and produces emissions for the corresponding source groups in a bottom-up approach. In addition to greenhouse gas emissions, the model calculates other variables such as the development of land use and nitrogen balances as well as others. The model consists of three main modules: livestock farming, agricultural soils and energy use. In addition, it is possible to differentiate according to individual demand groups in animal husbandry (incl. feed), plant-based food and biomass production for material and energy use.

External variables, demand, and derivation of relevant activity variables

The model uses external assumptions on the development of animal stocks and the demand for agricultural products and biomass production for material and energy use as input data. These variables are based on literature, such as agricultural economic projections on market development, political guidelines, or expert assumptions on the development of consumer behaviour, as well as other models of the Oeko-Institut, such as the biomass demand of other sectors.

The model can also take into account other external requirements that are derived from political objectives and the implementation of legal requirements. These include, for example, different forms of agriculture and livestock farming and their yield and performance development, as well as expansion of biodiversity areas leading to increase land usage, areas for peatland protection or the land demand for settlement and infrastructure.

Spatial and temporal resolution

The model has a spatial resolution at the level of Member States in its basic version. Originally it was developed for Germany and extended and adapted for the EU-27.[4] But it can also work at the level of federal states or NUTS2 regions. For detailed analyses, the model can also operate at the district level.

The model uses input variables with a temporal resolution of five- to ten-year steps. This means that external influences such as legal requirements or assumptions on important consumption or performance developments are determined in larger steps. The model then interpolates the resulting activity variables and emission factors for the intermediate years. Therefore, the model can output the results on a year-by-year basis.

Use of agricultural area

The LiSE model determines the use of agricultural land by the different demands for animal feed, plant food and biomass production for material and energy use. The model distinguishes between the demand for arable feed land and grassland from animal husbandry. The model also differentiates all land uses according to conventional and organic farming. Moreover, the model can take into account specifications on unfertilised areas (ecological priority areas, structural elements, etc.), crop rotation, arable land occupancy and grassland use intensity.

[4] A model description for the German Model can be found here: https://www.oeko.de/fileadmin/oekodoc/Modellbeschreibung_LISE.pdf

Livestock farming

The livestock module includes all relevant livestock classes and their methane emissions, as well as direct and indirect nitrous oxide emissions. Initially, the key variable is the livestock population itself. Key activity variables of the model are: Livestock population sizes, milk yield, Nitrogen (N) and Volatile solids (VS) excretion rates, methane formation rates for farm manure, and manure fermentation.

Other important parameters characterize the housing (straw or slurry-based, tethered or free-range systems) and the manure storage. For the latter, it is specified what proportion is fermented anaerobically and to what extent the fermentation residue is stored gas-tight. The effect of covered storage can also be determined for non-fermented manure.

Performance parameters and nitrogen-optimized feeding can also be considered over the entire scenario period. For enteric digestion and emissions from stables and manure storage, the specific emission factors of the individual animal groups are updated. Herd management measures for cows and cattle could be mapped using the ratios of adult to juvenile animals.

Agricultural soils

The nitrogen fertilizer use is determined via the occupancy of the agricultural area with the various arable crops and grassland use. For this purpose, the fertilizer requirements of the individual crops are used to calculate total nitrogen demand. From the animal model, the farm manure produced is determined based on the nitrogen excretion of the individual animal species. The nitrogen flow via renewable raw materials biogas substrates is included via external specifications for bioenergy. Depending on the nitrogen demand and the crediting rules used for organic nitrogen fertilizers, the remaining demand is covered with synthetic nitrogen fertilizer. The emission factors for the application of farm manure can be changed on a technology-specific basis over the scenario period under consideration and thus incorporate changing legal requirements. At the level of nitrogen flows, the overall balance can be shown as a central environmental indicator in agriculture.

For the determination of direct and indirect nitrous oxide emissions from agricultural land use, fertilizer application (mineral, animal and plant manure), harvest residues, organic soil management, sewage sludge application and excrement from pasture farming are taken into account.

Nitrogen Input in agricultural soils

The development of N_2O emissions from fertilization is calculated based on the agricultural area and the land use of the individual Member States. The nitrogen demand is then calculated in the LiSE model, which assumes an optimal nitrogen input that covers the nitrogen demand of the plants. The model also assumes that fertilizer use is targeted, and that surplus farm manure is exported to arable regions. This is represented in the model by an increase in fertilizer efficiency. The main steps to calculate the final nitrogen input and the N_2O emissions from fertilization are summarized in the following table.

Table 4: Overview of calculation of nitrogen input to soils

Category	Description
Area	The development of agricultural area is based on LULUCF modeling. This includes information on development of cropland, grassland, agroforestry and rewetting of organic soils.
Agricultural land use	For agricultural land, the use is determined based on assumptions specific to each scenario. The development of areas for organic farming,

Category	Description
	fallow land for biodiversity, and agroforestry systems relies on external scenario assumptions.
Crop cultivation	Starting point is the current cropping mix. Change in crop cultivation is based on dynamics concerning the feed requirements, the bioenergy demand, and the demand for plant-based food.
Nitrogen demand	Total nitrogen demand is a result of cultivation area and yield expectation of single crops. In a second step, N-input from available organic fertilizer (manure, digestates) and the N-efficiency of the manure as well as mineral nitrogen soil stock (N-min) and the N-input of the residues and N-fixation of the previous crop is considered.
Final N-demand from mineral fertilizer	Based on the total nitrogen demand and information on N-available from other sources the total demand for synthetic N-fertilizer is calculated.

Source: Own presentation Oeko-Institut

Data, calibration and uncertainties

The model uses the latest available data from Member States inventories for UNFCCC. In addition, data from the current statistics (Eurostat etc.) are used as a basis. Likewise, the model results are compared with the current statistics, e.g. on the demand for animal feed quantities, land utilization, etc. In this way, errors can be identified and corrected. However, uncertainties due to small deviations from the statistics remain. The following table provides an overview of the data sources used as input data for the EU LISE Model. The data sources presented in Table 5 are available on Member States level.

Table 5: Overview of data sources for input data

Category	Data sources	Data description
Agricultural area	Eurostat database	Cropland, grassland, legumes and protein crops, fallow land, low yield permanent grassland
Organic farming data	Eurostat database	Area for cropland, grassland, permanent crops, Animal numbers
Agricultural use of organic soils	UNFCCC inventory data	Area and emission factors for N_2O emissions
Nitrogen input	UNFCCC inventory data	N-Input for synthetic fertilizer, organic fertilizer, crop residues, manure left on pastures
Manure Management	UNFCCC inventory data	Nitrogen excretion rate, share of animals on pasture and paddocks, share of anaerobic digestion, emission factors for CH_4 and N_2O
Animal stocks	UNFCCC inventory data	Animal number, emission factors, total emissions
Production of meat and milk	EU short term outlook balance sheet	Milk yield, carcass weight,

Source: Own overview, Oeko-Institut

2.3.7 LULUCF – FABio-Land

The Forest and Agriculture Biomass – Land use (FABio-Land) model projects GHG emissions from sources and carbon removals by sinks in the LULUCF sector. FABio-Land covers all land use categories included in GHG reporting under the UNFCCC, for example forest land, cropland, grassland, wetlands, peat extraction, settlements, and other land. Land use categories are further differentiated by mineral and organic soils, as well as sub-categories for land in transition between land use categories ("land converted to"). The model applies a transition period of 20 years (according to IPCC rules (IPCC 2006b)) before converted land (e.g. Cropland converted to forest land) is entered into the new land use category (e.g. forest land).

The model uses historical emission factors and land transition coefficients for each category derived from GHG inventories and National Inventory Reports (NIRs) of EU countries. This corresponds to a Tier 2 methodology, i.e. country-specific emission factors and activity data. However, the model considers the EU countries as one and does not differentiate individual Member States. Based on historic data extracted from the EU inventory, area changes and associated emissions and removals are extrapolated. Mitigation measures in the model are described as change factors for area transitions and/or as change factors for emission factors. For example, for simulating afforestation measures, the area entering the sub-category "Land converted to forest land" is increased. For simulating short rotation coppice plantations, the emission/removal factor for cropland is adapted for the respective share of area. A model interface exchanges data on area development of cropland, grassland and wetland with the agricultural model to ensure consistency between the sectors. Calculations in FABio-Land are done with a temporal resolution of one year and extend up to the year 2050.

2.3.8 Waste – Waste_Mod

In the waste sector, only non-energy greenhouse gas emissions from waste management are addressed (CRF category 5) in accordance with the systematics of the National Greenhouse Gas Inventories. These include methane emissions from landfilling, methane and nitrous oxide emissions from biological waste treatment and from mechanical-biological waste treatment plants. Methane and nitrous oxide emissions from wastewater treatment are also taken into account.

Some activities in the waste sector, such as the operation of waste incineration plants or recycling measures, usually lead to emissions or savings in other sectors. Emission reductions by increasing the share of recycling, for example, do not affect greenhouse gas emissions in the waste sector (CRF category 5), but in the energy and industry sectors, e.g. if less of this waste is incinerated due to increasing recycling shares. Thus, the core elements of emission reduction such as waste-avoiding production, distribution and use as well as the intensification of recycling and material recovery do not occur in this sector but are considered in the energy and industry sectors.

The non-energy related emissions of the waste sector amounted to 138 million t CO_2eq. in 2018, which is about 3% of the total emissions of the EU. Since residual emissions also remain in the waste sector due to biological processes, these must be included in the calculations.

For the modeling, the Waste_Mod model of Oeko-Institut is used, which is extended on the basis of the EU inventory data to 27 Member States, using individual activity data and emission factors. Furthermore, individual waste models are available for the big Member States, which have been developed in a previous project[5]. In the modular waste model, all emission categories of the UNFCCC reporting are taken into account.

Waste_Mod is a waste model with a modular structure that maps the emissions from CRF category 5 (non-energy-related emissions of the waste sector) on the basis of 3 modules. The three modules of the model represent the relevant source categories of waste and wastewater treatment. The first module calculates emissions from landfilling based on the multi-phase waste model developed by the IPCC (emissions from landfilling, source group 5.A). In addition, the mitigation effects of landfill ventilation measures can be included. In the second module, emissions from biological waste treatment are calculated. The data on emissions from biowaste treatment plants and mechanical-biological waste treatment plants are calculated in relation to the plant throughput. For this purpose, the most recent data on waste statistics from Eurostat available during processing are to be evaluated. The development of the plant throughput is dependent on implemented or planned measures for the separate collection and recovery of waste but is also influenced by climate protection measures for the reduction of food waste. In the third module, for the sub-source groups of municipal and industrial wastewater treatment (5.D) and others (5.E), the population-specific framework data are used and the emission factors from the most recent inventory report are updated according to the assumptions on the development of protein intake and the connection rate to the public sewer system.

2.3.9 Fuel balances, carbon demand and supply, GHG balances for ETS and ESR and other balancing

To produce a coherent scenario with the above described models, an additional step is being implemented when developing the scenarios. Based on an aggregation of scenario results from different models, the following fuel and resources balances are being developed:

- non-fossil fuels, defined as all non-fossil energy carriers for this project; the analysis includes a differentiation into fuels including carbon (e.g. e-Kerosine or eDiesel) and fuels not including carbon (such as hydrogen or ammonia) and a differentiation of fuels of biogenic origin, i.e. biofuel. Supply of biomass (solid, gaseous and liquid) is considered for calculation of the non-fossil fuel balances
- carbon demand and supply, including feedstock demand and taking into consideration carbon of biogenic origin and carbon of atmospheric origin. Demand for atmospheric carbon goes back as input into the supply-side modeling
- GHG results for EU ETS sectors and ESR sectors are being analyzed to discuss target fulfilment of EU-wide targets under the current climate policy architecture
- Recycling quota are being matched with assumptions in the waste sector and development of production figures in the industry sector
- demand for land area for PV is matched with assumptions on demand for agricultural land and supply of specific types of land area as assumed under the LULUCF modeling

Final results need to fulfil all main balances (i.e. provision of non-fossil fuels, can also be from imports, carbon demand and supply, recycling quota, availability of waste and industry production and land demand for agricultural land (including demand for agriculture, for energy production and for LULUCF sink).

[5] For further information see Duscha et al. 2019

2.3.10 Scenario limitations

A number of limitations exist within the scenario modeling. The most important aspects not or only partly covered are:

- Technical carbon dioxide removals are outside of the system boundaries for this project. Carbon storage options from LULUCF and industry CCS are included, but considerations on permanence of those storage options as well as whether industry CCS is coupled with biogenic emissions are left out. Also DACCS is not modelled. As a result, where technical CDR is required in addition to natural CDR to meet the defined targets, only the amount of technical CDR necessary in 2050 can be calculated. The analysis does not provide insights into the development of technical CDR over time nor on which type of industrial CDR would be used. The scenario also does not account for energy demand for technical CDR.
- Fugitive emissions from exploitation of fossil fuels, transport of fuels (fossil as well as synthetic) and carbon dioxide as well as leakages from geological storage of carbon dioxide are not taken into account
- Petroleum refineries and manufacture of solid fuels and other energy industries (i.e. inventory categories A.1.b and A.1.c) are not fully modelled within the project as they are not part of the model suite applied. To not miss out on these emissions in the overall GHG balance, a rough estimate on their development is included. This estimate is based on today's emissions from each of the two sectors relative to oil, respectively coal use. Future emissions are estimated based on the development of total demand for coal and oil respectively. In the two target scenarios EUTarget and EUSupreme we assume that the basis for chemical products, which is almost completely fossil today, changes to CCU-based products (with 30% being replaced by 2030, 70% being replaced by 2040 and 100% being replaced by 2050). Efficiency gains or other mitigation activities in that sector are not considered.

2.4 General modeling assumptions

General assumptions regarding population and GDP development were taken from PRIMES Reference scenario 2020.

International energy prices are used consistently in EUBase and EUTarget (adopted from Politikszenarien XI (UBA 2022)), but adjusted in EUSupreme to better reflect the scenario narrative (based on the Net Zero Emissions scenario of the World Energy Outlook 2022). The price of hydrogen is reduced in EUSupreme relative to EUBase. This reduction is based on the assumption that hydrogen will become less expensive due to a global uptake of hydrogen paired with high efficiency standards and strong sufficiency measures around the world.

The EU ETS1, 2 and ESR are not implemented here as quantity-based policies. In line with other modeling exercises, a CO_2 price is used to model the impact of those policies. In turn, EU ETS 1, 2 and ESR do not necessarily meet their interim targets.

The CO_2 price is not constant across the scenarios but given exogenously in case of EUBase (also adopted from Politikszenarien IX) and EUSupreme (adopted from a sister project (CARE)). In case of EUTarget, the CO_2 price serves as a variable in the models to reach the target and is therefore not given exogenously. It is determined via iterative model runs with the different sector models and finally harmonized at a level sufficient to reach the overall target of GHG-neutrality by 2050.

CO_2 prices on both markets in all scenarios are increasing over time. Lowest CO_2 prices are implemented in the EUBase scenario increasing from €24.7/t CO_2 to €161.1/t CO_2 in the EU

ETS 1 and from €95/t in 2030 to €216/t CO_2 in 2050 in the ETS 2. Significantly higher prices are implemented in the EUSupreme, where the CO_2 price in the ETS 1 increases from €24.7/t CO_2 in 2020 to €320/t CO_2 in 2050. In the ETS 2, it increases from €220/t CO_2 in 2030 to €320/t CO_2 in 2050. Highest CO_2 prices are determined and implemented in the EUTarget scenario. ETS 1 prices increase from €24.7/t CO_2 in 2020 to €390/t CO_2 in 2050, 20% higher than in the EUSupreme scenario. In the ETS 2 market, prices start at €300/t in 2030 and increase to €500/t CO_2 in 2050, 56% up compared to the EUSupreme scenario. Differences in CO_2 prices in the two target scenarios are difficult to interpret. They are mainly an indicator of the CO_2 price as a policy complementary to other policies also implemented. In case of the EUSupreme scenario, additional behavioural measures are implemented allowing for a lower CO_2 price, whereas the EUTarget scenario does not implement those behavioural measures. Hence, the CO_2 price and other measures need to develop a stronger impact on GHG emissions.

Main variables are summarized in Table 6. More details on and numbers for these and other overarching assumptions are given in Annex B.

Table 6: Main assumptions macro-economic drivers, CO_2 prices and hydrogen prices

Variable	Scenario	2020	2030	2040	2050
GDP [bn€15]	All scenarios	12.272	14.814	16.898	19.466
Population [m]	All scenarios	447.67	449.12	446.75	441.22
CO_2 price EU ETS 1 [€15 per t]					
	EUBase	24.7	108.8	141.3	161.1
	EUTarget	24.7	110	340	390
	EUSupreme	24.7	120	220	320
CO_2 price ETS 2 [€15 per t]					
	EUBase	---	95	171	216
	EUTarget	---	300	340	500
	EUSupreme	---	220	270	320
Hydrogen [€19 per MWh]					
	EUBase, EUTarget	207.7	100.3	82.4	64.5
	EUSupreme	297.7	95.3	74.4	55.3

3 Scenario definitions and results

3.1 Overview and central results

The following sections provide an overview of the EUBase scenario (section 3.1.1) and the two target scenarios EUTarget and EUSupreme (section 3.1.2) with a focus on cross-sectoral results and indicators for the EU27. We present findings for the GHG balance and compare them to target values established within the EU target framework, including a review of ETS (Emission Trading System) and ESR (Effort Sharing Regulation) targets. Additionally, we examine final energy demand and the share of renewable energy in both final energy demand and electricity generation. We also investigate non-fossil fuels, as the accounting approach in this analysis highlights its significance, in particular in view of future scenarios. The balance of hydrogen demand and production is also addressed in this context. Finally, the role of carbon is being analysed in detail.

The following terms play an important role in the discussion of the results:

- Generated CO_2: Generated CO_2 refers to the CO_2 generated within a combustion process or a chemical conversion process independent of whether this CO_2 is being emitted into the atmosphere or capture and stored
- Generated GHGs: Generated CO_2 plus other GHGs
- Gross CO_2/GHG emissions: generated CO_2/GHG minus amount of fossil CCS
- Net CO_2/GHG emissions: gross CO_2 /GHG emissions minus natural and technical sinks
- Negative emissions: storage of atmospheric and biogenic CO_2

For the interpretation of results, it is important to note that fuels derived from biological sources as well as synthetic fuels are accounted for in the energy balances, but their emissions factor for GHG balances is set to zero. This follows current accounting rules for biofuels in the national inventories under the United Nations Framework Convention on Climate Change (UNFCCC). It is also largely in line with the current accounting rules for RFNBOs in the EU. However, in some cases, figures include biogenic emissions and carbon contained in non-fossil fuels. In those cases, the corresponding CO_2 emissions from biomass combustion are reported for better understanding the amount of carbon that is still part of the energy and feedstock system.

Due to the interchangeability of synthetic and biological fuels in applications, liquid and gaseous biological and synthetic fuels in terms of accounting rules are classified as non-fossil fuels for purposes of GHG calculations in this project. It should be noticed that additional demand for biomass in the energy and other transforming sectors can lead to a net increase in emissions e.g. where no sustainable sourcing of raw material takes place or significant amounts of land use change are induced. Effects on the LULUCF sector within the EU are accounted for under the LULUCF sector, which is modelled separately. Where fuels of biological or synthetic origin are imported, these effects are not taken into account in the EU balance, following current accounting rules under the UNFCCC.

3.1.1 EUBase scenario

3.1.1.1 Scenario narrative and general description

The EUBase scenario serves as the reference scenario for the modeling work in this project. It starts with political and socio-economic developments from 2022 and models the impacts of economic development, population growth, energy prices, CO_2 prices and selected current policy packages on energy demand and supply[6], agricultural production, waste and the LULUCF sector along with related greenhouse gas emissions. Notably, it incorporates the effects of the Russian invasion into Ukraine on energy prices, as reflected in the energy price assumptions.

The EU policies considered include components of the energy and climate policy packages currently under discussion or recently agreed on in the European Fit-for-55 package and the EU REPower Package implemented in response to the European energy crisis. That includes CO_2 prices for industry and supply sector (EU ETS 1), but also for transport and buildings (EU ETS 2) as overarching policies. In addition, several sector-specific considerations are being applied. Here it is decided at a sector level which of the not yet implemented policies are being included in the scenario. For example, Minimum Energy Performance Standards (MEPS) for buildings, part of the revised Energy Performance in Buildings Directive (EPBD), are not included in this scenario as it had still not been finally decided at the time of calculating EUBase which building types would be addressed[7]. In contrast, the electricity and heat sector implement national targets for renewables or nuclear as presented in the MS's National Energy and Climate Plans (NECPs). That is despite the fact that they may lack implementation at the national level. Similarly, the targets of 10 Mt H_2 production (333 TWh) within the EU and an additional 10 Mt H_2-import into the EU by 2030 are not strictly implemented in this scenario. To align with strengthened European policies, the CO_2 price assumptions reflect relevant measures at the Member State level, as described in the NECPs. Also included are national support instruments for decarbonization in the industry and EU-wide fleet and fuel targets for the transport sector. Limited activities are implemented for a major part of the non-energy sectors. This reflects the current gap in legislative activities in these sectors. In particular, the LULUCF target for 2030 of providing a net sink of 310 Mt CO_2 is not implemented in the scenario, but different effects on the LULUCF sector stemming from interactions with other sectors, in particular the agriculture sector and the use of biomass as energy carrier are reflected here. Further information on all policies included as well as reasons for inclusion/exclusion of policies can be found in the sector sections of this report.

The scenario is designed to be technology-neutral, allowing for various options for decarbonizing the energy system, including CCS, CCU and nuclear power, reflecting different national approaches. The demand for CCS is determined model-endogenous (and is not found to be very relevant), industrial carbon removal technologies are not part of the modeling system. For the EUBase scenario, no further consideration of industrial carbon removals takes place for two reasons: first, their deployment depends on aspects such as technological advancements, increased public acceptance and sufficient regulatory support. Second, it is closely linked with the target of reaching net-zero and even net-negative emissions. Both are not implemented in the EUBase scenario CCU (also model-exogenous) is also not implemented in EUBase, mainly due to a lack of financial incentives in current legislation. Technological mitigation options in agriculture are not included[8]. A detailed description of the policies implemented is being provided in the sector chapters. Annex B provides an overview on the scenario assumptions in tabular format.

In contrast to the following target scenarios, the EUBase scenario does not require meeting either the 2030 or 2050 greenhouse gas targets in the EU. Where targets are met (as in the case of 2030 at the EU level), it results from the implementation of the described policies. At the same

[6] A detailed description and discussion of policy packages included or excluded can be found in the sector chapters

[7] In the end, only non-residential buildings are required by the recast EPDB (2024) to implement MEPS.

[8] This assumption is different in the more technically oriented EUTarget scenario where several technological abatement options for the agricultural sector are being discussed and their impact on GHG emissions is being modeled.

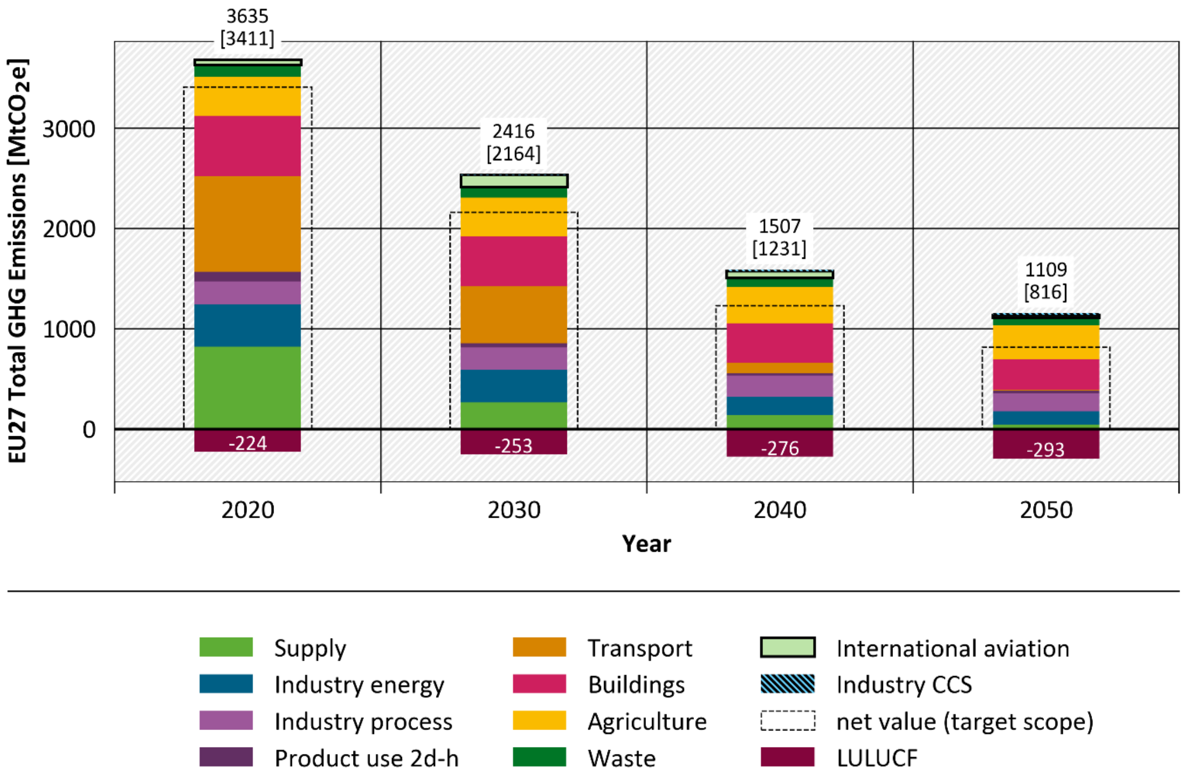
time, the EUBase scenario is not modelled as a classical current policies scenario, as it includes policies from the Fit-for-55 package and the REPower Package that are still in negotiation as well as targets and policies from the NECPs that may lack full implementation.

3.1.1.2 GHG balance

The following figures illustrate the GHG balance across all sectors within the European Union. For context, historical emissions data from 2020, as reported by the EEA, are also included. Emissions from all sectors including EU-related international aviation (marked as "outside of the official NDC") and maritime transport occurring outside the EU are fully accounted for[9], along with emissions related to carbon storage in the LULUCF sector and CCS in subsequent years. However, fugitive emissions resulting from the extraction and transportation of fossil fuels and synthetic fuels, as well as CO_2 leakage during the transport and storage of CO_2, are not included in this analysis (see section 2.2).

Figure 8 depicts the trajectory of modelled absolute GHG emissions from 2020 to 2050. The following discussion of GHG results focuses on total emissions excluding international aviation as it is not officially part of the EU's NDC.

Figure 8: Total GHG emissions for EU 27 in EUBase



Source: own calculations Fraunhofer ISI, Oeko-Institut

First number in box relates to total generated GHG emissions excl. int. aviation, number in brackets relates to net GHG emissions excl. int. aviation

Product use 2d-h contains data reported in categories 2D-H in international GHG inventories, categories 2A-C are reported under industry process

[9] Inconsistencies exist between the accounting of maritime emissions in the national inventory and the inclusion of international maritime emissions under the EU ETS. Values for this report build on the accounting under the national inventory for the UNFCCC.

In comparison to 2020[10], the generated GHGs projected in the EUBase scenario decrease by 1,215 Mt CO_2e, representing a 33% reduction from 3,635 to 2,420 Mt CO_2e by 2030. This downward trend continues into 2040, with a further decrease in generated GHGs by approximately 900 Mt CO_2e to 1,520 Mt CO_2e, which reflects a 58% reduction compared to 2020 levels. By 2050, the implementation of the policies included in the modeling lead to remaining generated GHGs of 1,126 Mt CO_2e, a reduction of 69% compared to 2020 levels.

The primary driver behind the reduction in generated GHGs by 2030 is a substantial decline in emissions from the energy supply sector, which drops from 821 Mt CO_2e to 266 Mt CO_2e. This shift is attributed to an almost doubling of the renewable energy share in the electricity sector, increasing from 39% to 71% between 2020 and 2030. Contributing factors include a strong CO_2 price, relatively high fossil fuel costs, decreasing technology costs for renewable electricity generation and optimistic assumptions regarding the fulfilment of Member States NECPs (see section 3.2.4.1.2 and Annex B.2). Additionally, the transport sector plays a significant role in emissions reductions, with emissions decreasing from 955 Mt CO_2e to 567 Mt CO_2e during the same period. This reduction is largely driven by a decline in road transport emissions, resulting from the increased adoption of BEV among passenger and commercial vehicles, spurred by strong CO_2 pricing and regulatory measures aimed at reducing emissions from the vehicle fleet.

In total, energy supply and transport contribute more than 940 Mt CO_2e of total reductions of the 1,215 Mt CO_2e between 2020 and 2030. With a share of almost 50% in 2020 generated GHGs these sectors contribute 78% of GHG emission reductions between 2020 and 2030. As a result, those sectors' share in 2030 decreases to 34%. Conversely, limited progress is observed in the industry, buildings and non-energy related sectors.

From 2030 to 2040 the continued decline in generated GHGs is predominantly fuelled by further reductions in the transport sector. These decreases stem from further enhanced electrification of road transport and reduced emissions in international transport due to the adoption of non-fossil fuels. With reductions in the order of 465 Mt CO_2e between 2030 and 2040, the transport sector contributes slightly over 50% of all emission reductions between 2030 and 2040. While contributions from the industry and buildings sectors are smaller, they also show progress in emission reductions with slightly increasing absolute emission reductions between 2030 and 2040 compared to the timeframe 2020 to 2030.

By 2050, generated GHGs decrease further to 1,126 Mt CO_2e. Notably, significant additional savings are observed not only in the energy supply and transport sectors, which are projected to be nearly fully decarbonized by 2050, but also in the industry sector, where energy-related emissions decrease by 60% and total industry emissions by 40% between 2030 and 2050 (69%, respectively 49% between 2020 and 2050). Furthermore, the waste sector achieves a 34% reduction over the same period (46% between 2020 and 2050). The extended timeframe allows implemented policies in these sectors to yield greater effectiveness than by 2030.

Generated emissions are slightly reduced in this scenario by CCS in the industry sector. The overall amount of CCS in industry reaches 13 Mt in 2040 and 17 Mt in 2050. Resulting gross emissions are 1,507 Mt CO_2e in 2040 and 1,109 Mt CO_2e in 2050.

Gross GHG emissions are partly balanced by sinks. In the EUBase scenario, the LULUCF sector serves as the primary carbon storage, through the forest ecosystems and partly through continued storage of carbon in wood products. Total net removal capacity of the LULUCF sector (i.e. including positive as well as negative emissions from LULUCF activities) is expected to rise

[10] 2020 figures used for comparison are taken from the models to cover for existing differences in sector definition between official data sources and the scope of the models used in this project. A comparison of 2020 data from EEA and the models is provided in section 2.2 and Annex A.3

from 224 to 293 Mt CO_2 between 2020 and 2050 according to our modeling results. By definition, the scenario does not include technical sinks.

Net emissions in the EU, i.e. gross emissions minus sinks, are projected to be 2,164 Mt CO_2e in 2030, 1,247 Mt CO_2e below 2020 levels in the EUBase scenario. They decrease further to 1,231 Mt CO_2e by 2040 and ultimately reach 816 Mt CO_2e by 2050. Thus, in the EUBase scenario, the EU's 2030 net GHG emissions are 55 Mt CO_2e higher than the EU's 2030 target[11], equalling a reduction of 54% below 1990 levels. EU-wide net GHG emissions in 2040 and 2050 are considerably above the discussed 90% reduction target for 2040 and the climate neutrality target for 2050: in 2040 net-emissions are 763 Mt CO_2e above a 90% reduction (equalling a reduction of 74% below 1990 levels); in 2050 emissions reach 816 Mt CO_2e, a reduction of 83% below 1990 levels. These results indicate that the currently implemented and discussed policies, as modelled here, are not at all in line with the EU's pathway towards climate neutrality.

Figure 9 and Figure 10 present the emission balance as a flowchart in the form of a Sankey diagram for the years 2020 and 2050. In addition to GHGs as included in the national total, the figures also visualize emissions from biogenic or carbon-containing non-fossil fuels. The figures illustrate a shift in the relative importance of sectors. While generated GHGs in total are reduced by close to 70%, the agriculture and waste sectors generated GHGs show significantly different developments: generated GHGs in the waste sector decrease by only approximately 40%, while generated GHGs in the agriculture sector even decline by only 12%. In contrast, the transport and energy supply sectors have largely been de-fossilized. The buildings sector achieves more substantial generated GHG reductions of close to 50%, yet it remains a major source of emissions in 2050, with slightly more than 300 Mt CO_2. The industrial sector makes strides towards de-fossilization; however, significant emissions persist, particularly from but not restricted to process emissions. Also included are remaining energy-related emissions from processes that use e.g. used tires (included in other fossil), but also natural gas, oil and coal in sectors where a switch to non-fossil energy is not incentivized by current legislation. The LULUCF sector, with its carbon sink capacity increasing by 30% between 2020 and 2050, becomes increasingly relevant in the overall emission balance. Generated GHGs from international shipping contribute only marginally to total generated GHGs. Although outside the EU's NDC, generated GHGs in international aviation also decrease significantly due to the switch from fossil fuels to synthetic non-fossil fuels, an effect of the EU's ReFuel aviation legislation.

As a result of the differences in generated GHG developments sector shares shift notably by 2050. Agriculture contributes a significant share of 30% in 2050, starting from 11% in 2020. The buildings sector accounts for 27% of 2050 generated GHGs, a more modest increase from 17% in 2020. The industrial sector contributes a total of 30%, up from 18% in 2020. This is divided into 18% from process-related generated GHGs (6% in 2020) and 12% from energy-related generated GHGs (12% in 2020). Smaller shares are noted from the waste sector at 6% (up from 3% in 2020) and the transport sector with 0% (down from 23%), which is almost completely de-fossilized.

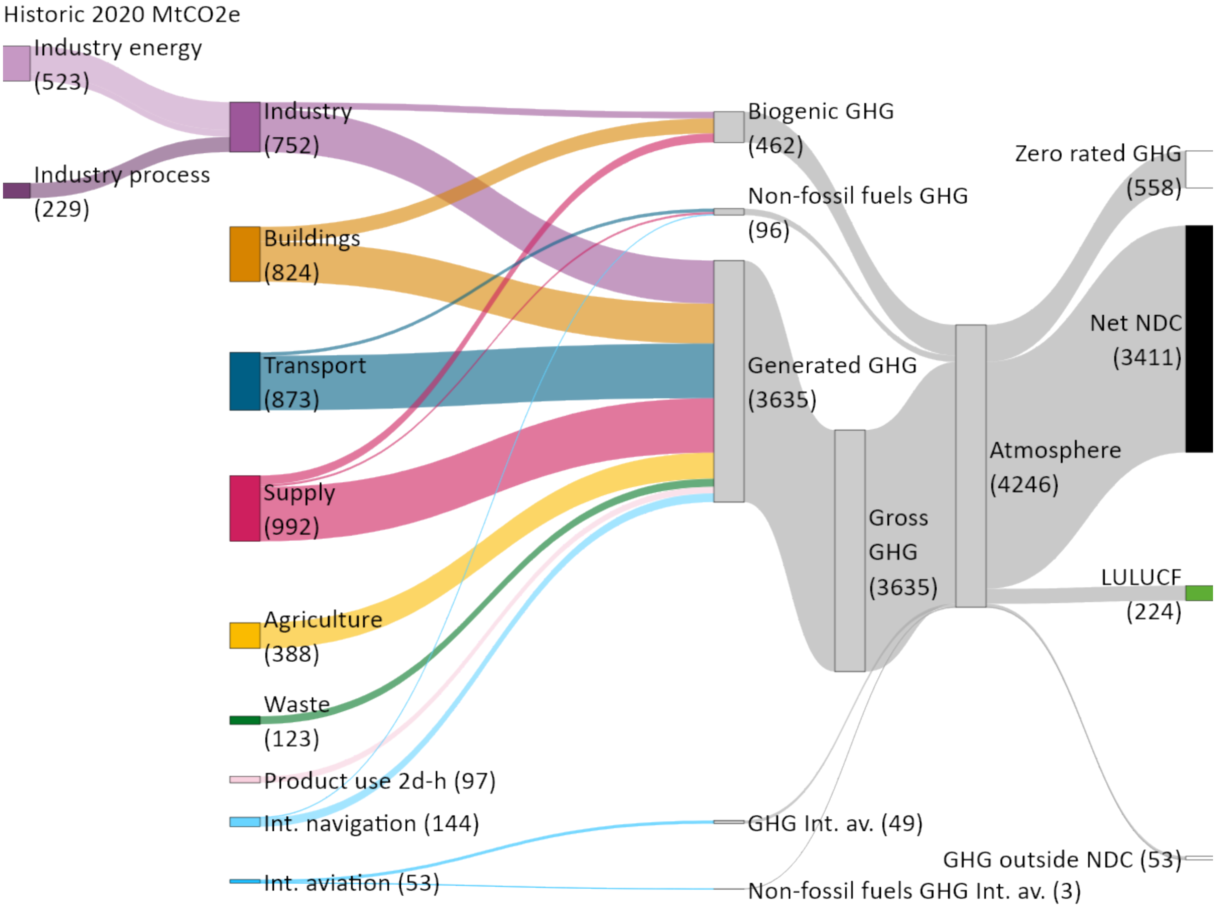
Emission reductions in the agricultural sector are constrained by natural limits, as long as assumption to not change dietary preferences and the continued consumption of meat and dairy products, as well as the exclusion of technological mitigation options in this scenario are not altered. This reflects the lack of legislative measures in that direction in current policy. Remaining emissions in the buildings and industry sectors are a result of the interpretation of current policies in the EUBase scenario. CO_2 prices not sufficient to create strong incentives for fuel switch in connection with non-monetary barriers, lacking policies for the development of

[11] a total reduction in emissions of 55% below 1990 levels, being translated for our calculations into an absolute emissions value of 2,109 Mt CO_2e

CCS and relevant CO_2 transport infrastructure as well as slow developments in the heating sector in the past regarding both, renovation rates and levels as well as the uptake of renewable heat sources are key factors for these settings. Timely and ambitious mitigation efforts in the waste sector are crucial to reduce remaining emissions by 2050, especially considering the long lifespan of emissions from landfilling waste. The chosen scenario setting and its results reflect the lack of current policy activity.

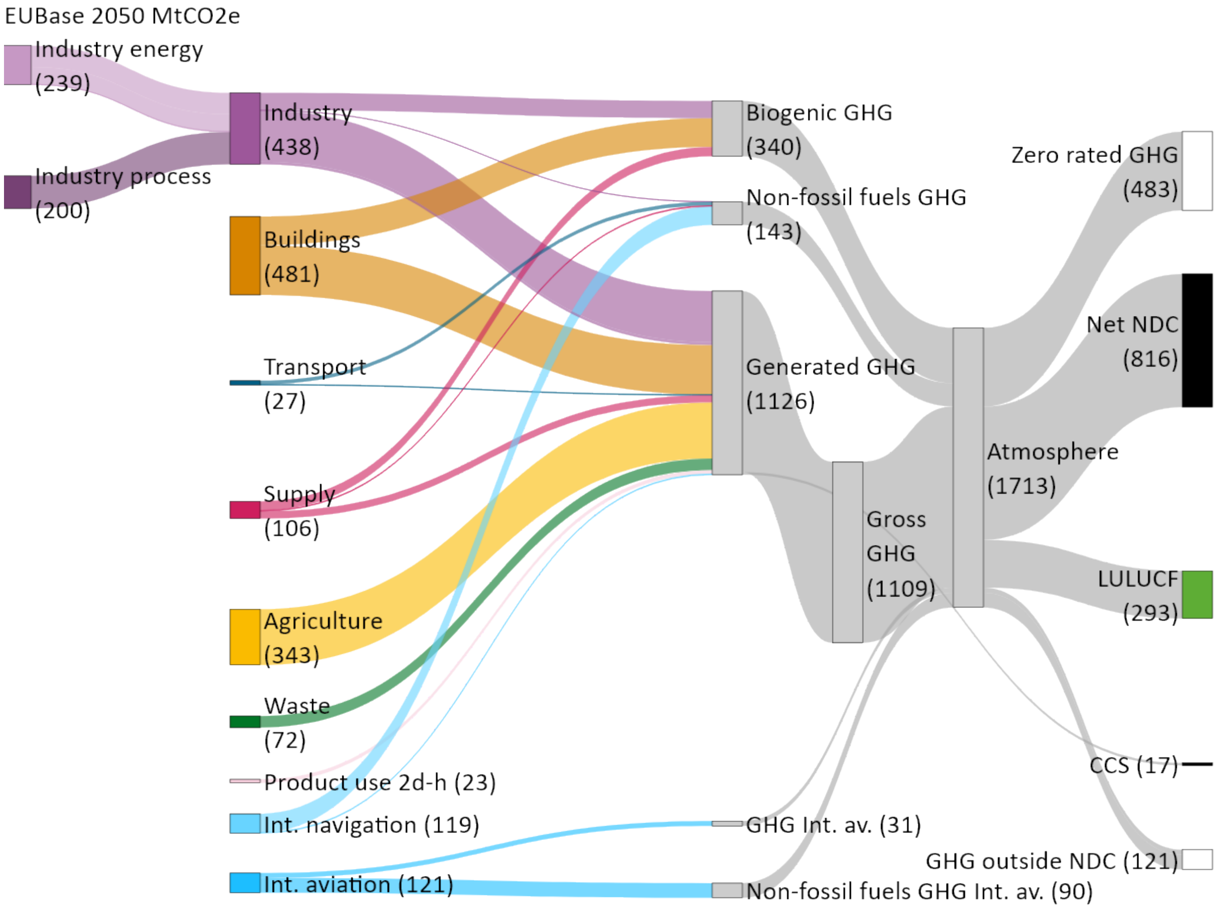
Visualization of zero-rated emissions from biomass and synthetic fuels shows two things: first, some sectors, in particular the buildings sector but also to lesser degrees industry and transport, emit significantly more CO_2 than visible in the inventory data today due to the zero-rating of biomass in biomass using sectors. For buildings, biogenic emissions today are more than 1/3 of accounted emissions. Second, significant zero-rated emissions remain for the sectors buildings, industry and international transport as those sectors continue to burn carbon containing fuels.

Figure 9: Flowchart of GHG emissions in EUBase for EU27 in 2020 (Mt CO_2e)



Note: Biogenic emissions are nominally already accounted for in the LULUCF sector
Source: own calculations Fraunhofer ISI, Oeko-Institut

Figure 10: Flowchart of GHG emissions in EUBase for EU27 in 2050 (Mt CO_2e)



Note: Biogenic emissions are nominally already accounted for in the LULUCF sector

Source: own calculations Fraunhofer ISI, Oeko-Institut

3.1.1.3 ETS, ESR and LULUCF emissions

The overarching EU target of 55% reduction in GHG emissions by 2030, compared to 1990, is split: between those sectors governed by the EU ETS (EU Emissions Trading System; most of industry, electricity and centralized heat generation, refining, EU internal aviation and maritime), the LULUCF sector, which has its own target of 310 Mt CO_2e sink capacity in 2030 and remaining sectors governed by the Effort Sharing Regulation (in particular buildings, transport and industry not covered by the EU ETS)[12].

This sectoral split and the corresponding emission reductions are shown in Figure 11. The 2030 ESR target value of a 40% reduction below 2005 levels is translated into 1,494 Mt CO_2e based on (EEA 2023a). The ETS sectors are associated with a target of 62% reduction relative to 2005. This is translated into a value of 774 Mt CO_2 in 2030 for ETS sectors (EEA 2024). In case of the ESR, questions related to the split between countries cannot be discussed within the scope of this project.

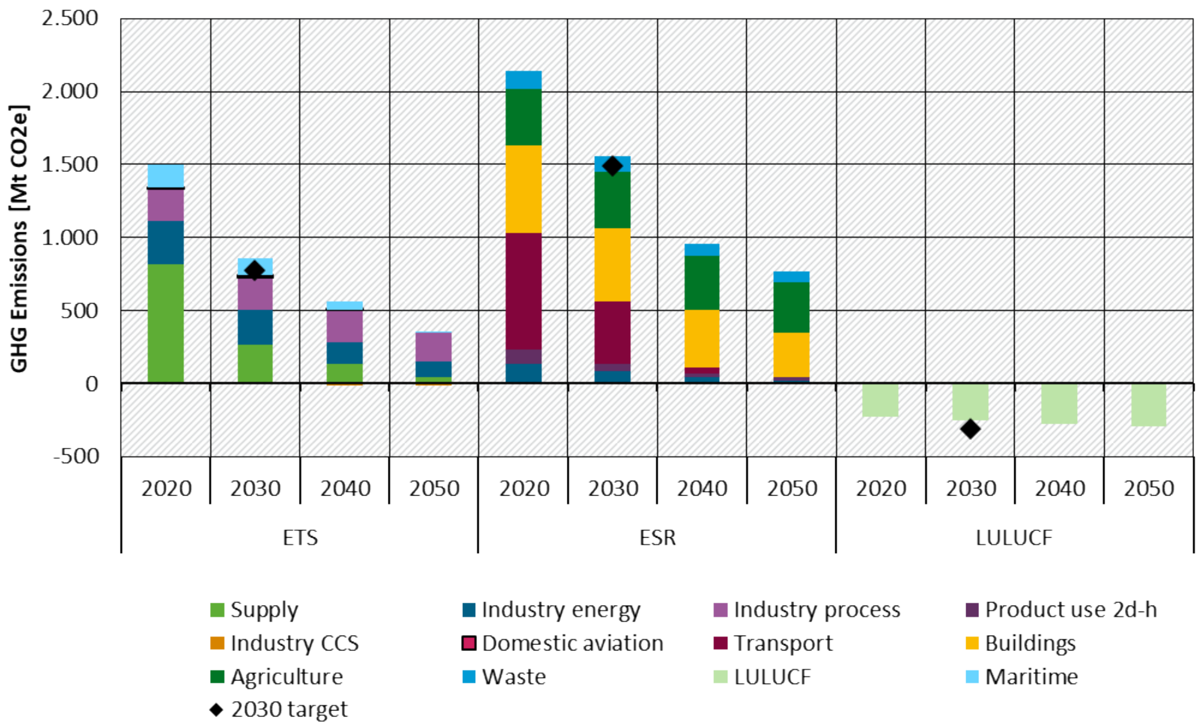
Based on our modeling, all three targets for the ETS, ESR and the LULUCF sector for 2030 are missed in the EUBase scenario. For the EU ETS, emissions are about 82 Mt CO_2e higher than the target value, translating into a reduction of 58% below 2005 levels; despite strong emission reductions in the supply sector For the ESR sectors, emissions are about 66 Mt CO_2e higher than the target value, translating into a reduction of 37% below 2005 levels. In particular the

[12] International aviation, covered by the overall target of 55% reduction, is not covered by the ETS or the ESR regulation. LULUCF has its own target. Therefore, the target values of ETS and ESR sectors do not add up to the total value.

buildings and agriculture sectors show high remaining emissions, while the transport sector shows strong reductions. For the LULUCF sector, the target is being missed by 57 Mt CO_2e due to continuing high emissions from organic soils and an insufficient enhancement of sinks, e.g. through forests.

For 2040, emissions in the ETS sectors reach 546 Mt CO_2e, corresponding to a reduction of 73% below 2005 levels. That is, compared to a reduction to close to zero as currently implemented under the ETS Directive, there is a significant reduction gap in this scenario. For ESR sectors, remaining emissions in 2040 amount to 961 Mt CO_2e, a reduction of 61% compared to 2005 levels. By 2050 the reduction increases to 83% below 2005 levels for the ETS sectors and 69% below 2005 levels for the ESR sectors. Consequently, in both sectors, the remaining emission levels are significant. At the same time, carbon storage in the LULUCF sector does not even reach the 2030 target level of -310 Mt CO_2e by 2050. Hence, storage capacities are far off from being able to compensate for remaining emission levels in the ETS and ESR sectors in this scenario.

Figure 11: Emissions of EU 27 in EUBase scenario allocated to ETS, ESR and LULUCF sectors with corresponding 2030 target



Source: own calculations Fraunhofer ISI, Oeko-Institut

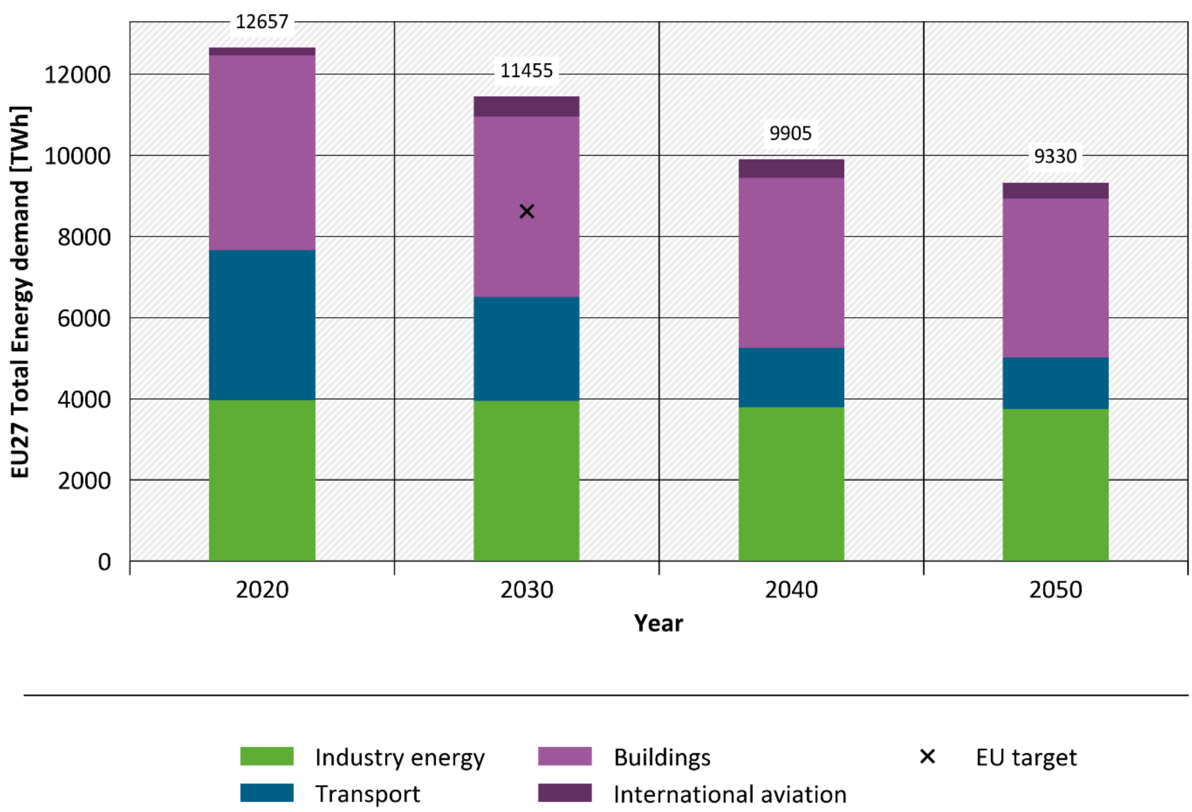
3.1.1.4 Energy demand and supply

The results on final energy demand are illustrated in Figure 12. In contrast to the GHG figures, this and all following discussions on energy carriers cover all sectors including international aviation, following the accounting logic of energy balances. The figures also include demand for feedstocks.

Total demand for final energy decreases by 26% over the modeling period from 12.7 PWh in 2020 to 9.3 PWh in 2050. Contributions from the different sectors vary significantly. Energy demand from industry decreases by 6% (3.97 PWh in 2020 to 3.75 PWh in 2050) due to efficiency improvements, the adoption of advanced technologies, and a slight decrease in primary production volume compared to 2018 levels. Energy demand from buildings decreases by 18% in the EUBase scenario (4.81 PWh in 2020 to 3.92 PWh in 2050), primarily driven by a reduction in energy demand for space heating. Additionally, energy demand in the aggregated transport sector[13] drops by 57% from 3.88 PWh in 2020 to 1.66 PWh in 2050. The increase in energy efficiency is mainly achieved through the electrification of road transport for passenger cars as well as for heavy-duty vehicles and buses.

In total, the energy demand decreases by 9% in 2030 compared to 2020. The EU27 target of 8,626 TWh final energy demand in 2030 (11.7% reduction compared to the reference value)[14], is not achieved in the EUBase scenario, where energy demand from the different sectors sums up to 11,456 TWh in 2030.

Figure 12: Final energy demand for the different end-use sectors for EU 27 in EUBase



Source: own calculations Fraunhofer ISI, Oeko-Institut

Figure 13 shows the development of energy carriers in the EUBase scenario for the EU27. We consider non-fossil fuels such as biofuels, synthetic fuels and hydrogen to be fully renewable.[15] For hydrogen produced locally within the EU – as is the case in this scenario – corresponding demand for renewable electricity is integrated in the modeling. For import hydrogen – occurring in the target scenarios – this is an assumption for the imported hydrogen to be renewables-based. Biomass from within the EU is accounted for in the LULUCF sector. Imported biomass is assumed to be sustainable.

In the EUBase scenario, renewables are projected to reach a share of 35% in final energy demand by 2030, up from 19.2% in 2020. However, this 2030 value falls short of the EU target of

[13] a separate assessment for international transport and the remaining transport sub-sectors was not possible due to special effects in the aviation sector in 2020

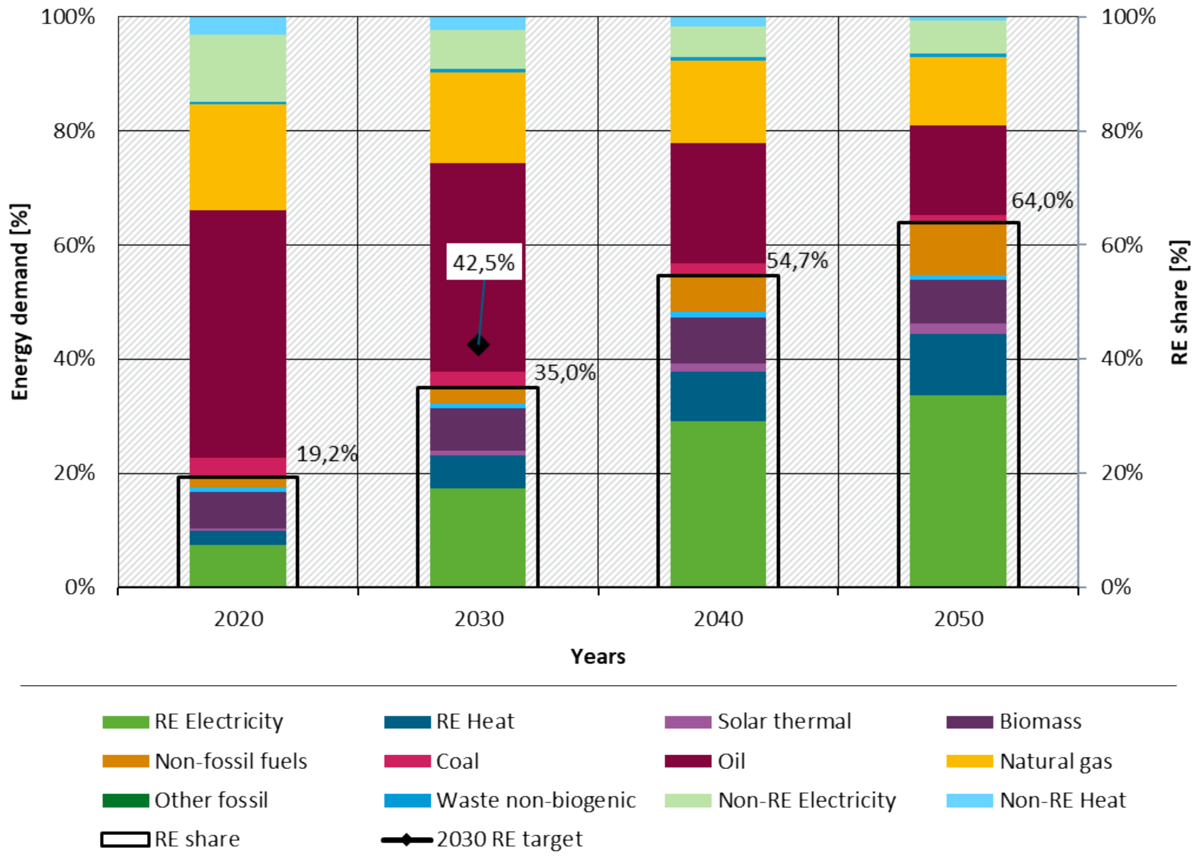
[14] Target value has been calculated from 2020 PRIMES reference scenario for 2030 (840011 ktoe), applying a percentage reduction of 11.7%.

[15] Non-renewable hydrogen as produced and used today in the industry sector is reported as natural gas in the industry sector. It is not part of the category hydrogen

42.5% outlined in the Fit-for-55 package. It is important to note that these values cannot be directly compared, as the target employs statistical accounting methods that are not mirrored in the demand and supply figures from our modeling.[16] These statistical differences typically inflate the share of renewable energy in the reported values, thereby bringing the EUBase scenario closer to the target value in nominal terms.

By 2040, the share increases to 54.7% and reaches 64% by 2050. Remaining fossil fuels in 2050 are small amounts of coal in industry, oil use partly in industry with larger amounts in buildings and international transport and natural gas use in industry and buildings. For electricity and centralized heat generation nuclear energy and waste remain as non-renewable fuels in the system.

Figure 13: Shares of energy sources in final energy demand for EU27 in EUBase



Note: Electricity and heat are split into renewable and non-renewable shares based on generation.
Source: own calculations Fraunhofer ISI, Oeko-Institut

The share of renewable energy in electricity is an essential prerequisite for assessing the overall share of renewable energy (see Figure 14).[17] Starting from a share of 38.8% in 2020, the modelled system reaches a share of 71.4% in 2030 and 85.3% in 2050. By 2050, electricity generation relies entirely on renewable energy sources, except for nuclear power plants. Coal is almost entirely phased out from electricity generation already by 2030. While the share of

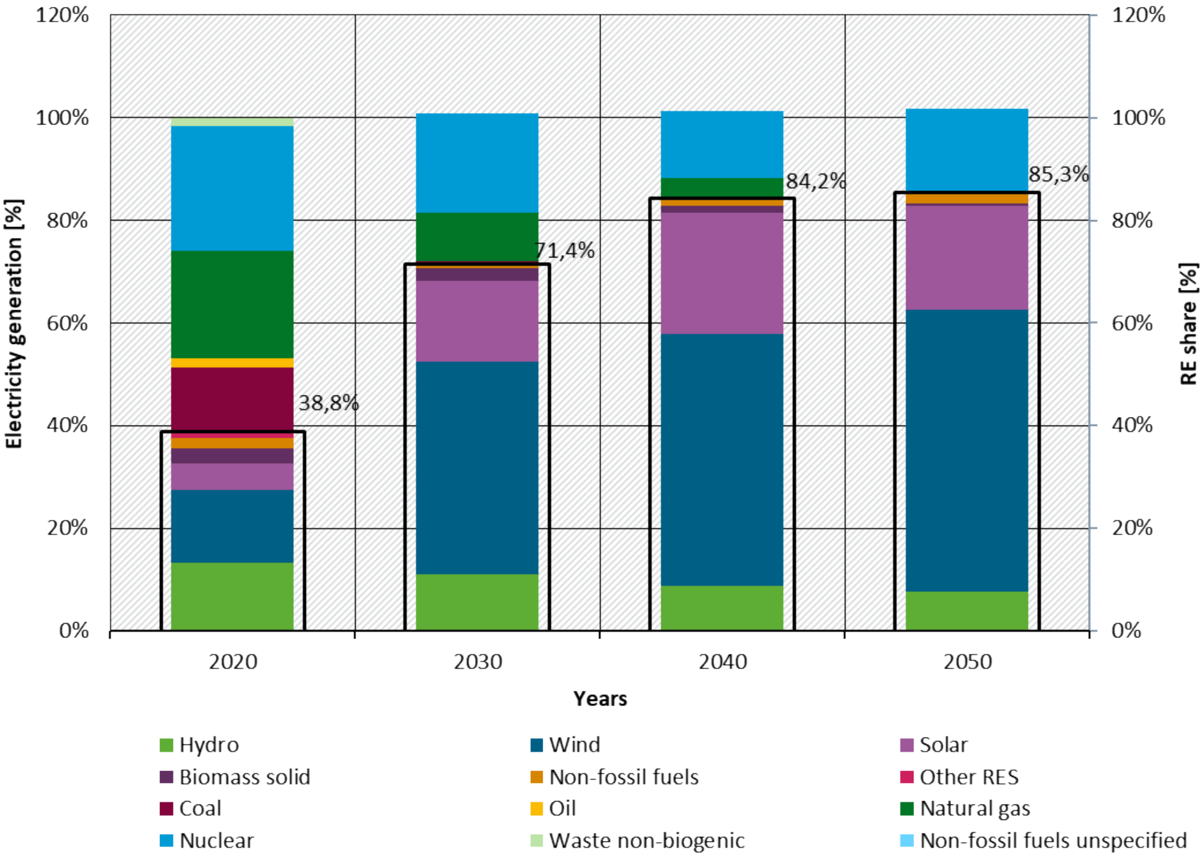
[16] E.g., the renewable energy directive sets out certain multipliers for the use of biofuels and for the use of electricity in certain transport modes.

[17] This is equally true for district heating (as a final energy carrier consumed by the energy demand sectors, not generated within these sectors). For readability, we limit ourselves to electricity here. The renewable energy share for centralized heat generation reached in the EUBase scenario for the EU27 is 29.7%, 64.8%, 76.3% and 94.6% for the years 2020, 2030, 2040 and 2050, respectively. This is not to be confused with thew RE share in heating, which is a combination of district heating and heating and cooling demand in the buildings sector.

natural gas is being more than halved between 2030 and 2040 and less than one quarter compared to 2020, small amounts of natural gas are still used in 2040. Those amounts are completely replaced by renewable energy sources and nuclear by 2050.

It is important to note that these values cannot be directly compared to Eurostat statistics, as those statistics employ a slightly different metric (comparing generated renewable electricity to consumed electricity) and average over recent years for specific technologies. Nevertheless, we utilize these values as input for determining the overall share of renewable energy, which will be discussed in the following sections.

Figure 14: Energy sources for electricity generation (% of total generation) in EUBase



Note: Values above 100% for generation are an effect of small trading and storage losses

Source: own calculations Fraunhofer ISI, Oeko-Institut

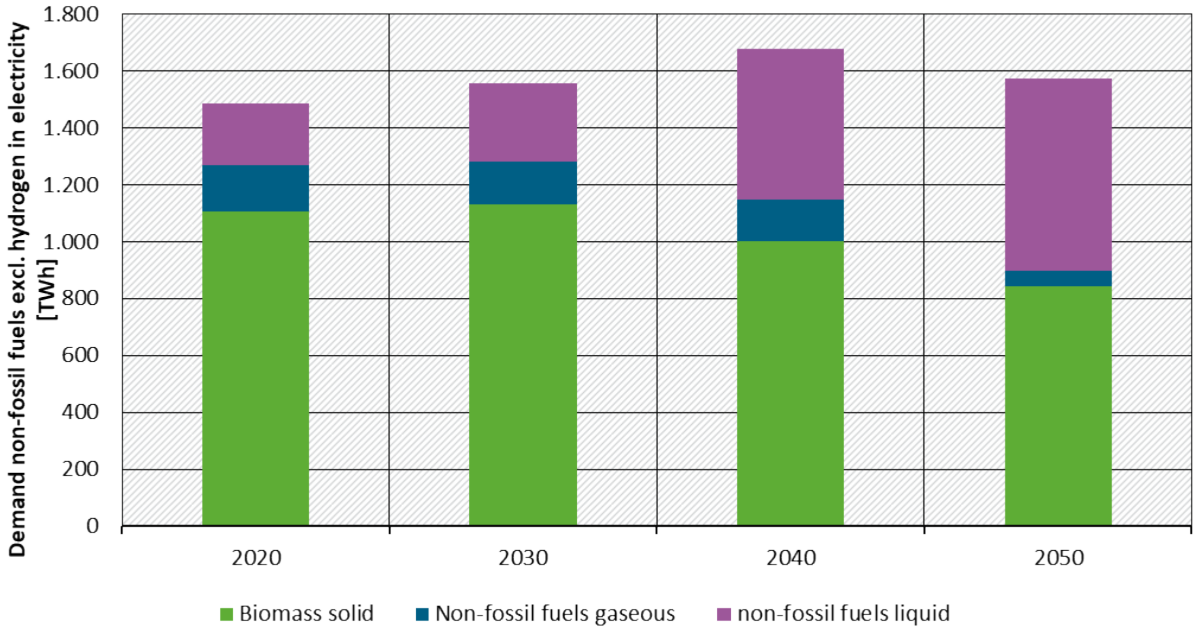
3.1.1.5 Non-fossil fuels balance

To decarbonize the energy system, non-fossil fuels, such as hydrogen, synthetic fuels and biomass, will play a significant role in future energy supply. We first examine the sum of non-fossil fuels and then discuss hydrogen separately. As before, energy demand includes the demand from international bunkers and feedstocks. Hydrogen and non-fossil fuels are assumed to be produced sustainably from renewable sources.

From a technical perspectives, synthetic fuels and biofuels can be substitutable in most applications. To take into account this substitutability, we define two groups: liquid non-fossil fuels including liquid biofuels as well as liquid syn-fuels and gaseous non-fossil fuels including gaseous biofuels and gaseous syn-fuels except for hydrogen demand from industry and electricity. Hydrogen demand from industry and electricity needs to be hydrogen and is not easily substitutable with alternative gaseous non-fossil fuels. Solid biomass remains separate.

Figure 15 shows the demand for solid biomass and other non-fossil fuels except hydrogen in the EUBase scenario. The total amount of non-fossil fuels and feedstocks increases from 1,485 TWh in 2020 to 1,555 TWh in 2030 and further rises to 1,575 TWh in 2050. Demand peaks in 2040 with 1,680 TWh. The amount of non-fossil fuels (liquid or gaseous) increases from 379 TWh in 2020 to 730 TWh in 2050. This demand mainly originates from the transport sector, where non-fossil fuels are required to meet the RED II requirements and demand particularly arises from international bunkers. In contrast, the amount of solid biomass decreases from 1,106 TWh in 2020 to only 845 TWh in 2050. This is a result from limited availability of solid biomass. In early years, the demand is met by imports. In later years, demand for biomass decreases in demand sectors. This decrease is an effect of the assumption that only domestic biomass shall be used to include effects on the LULUCF sector and increase the probability that the biomass is sustainable.[18] The supply sector is only allowed to use excess biomass in later years. The amount of excess biomass is determined as difference between supply of solid biomass and demand. This results in a significant decline in the use of biomass in electricity and heat generation over time as we see strong imports of solid biomass in earlier years. Hydrogen, nuclear and additional renewable capacities replace the biomass. In total, the share of solid biomass decreases from 74% in 2020 to 54% in 2050, while the absolute amount declines by 24% over the same period.

Figure 15: Demand for non-fossil fuels (excl. hydrogen for industry, feedstocks and electricity and heat generation) for the EU27 in EUBase

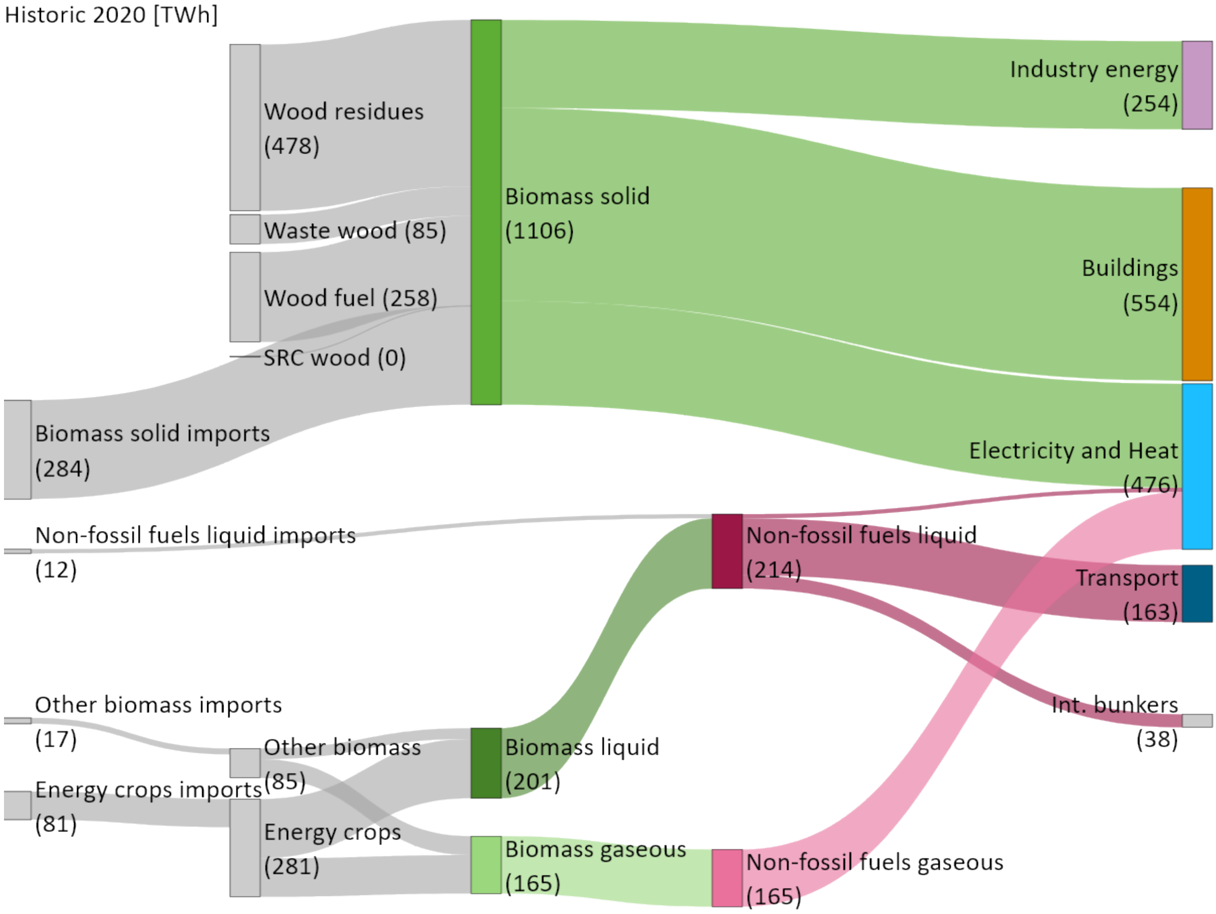


Source: own calculations Fraunhofer ISI, Oeko-Institut

Figure 16 shows the distribution of energy supply and demand in a flowchart for the EUBase scenario. This format facilitates the analysis of sources, the transition away from bio-based energy sources to alternative non-fossil fuels and demand sectors. The sources are presented in terms of final energy, eliminating the need to account for losses in the figures. Note that these flows represent only bioenergy and non-fossil fuels, the overall energy demand is higher. As before, non-fossil fuels liquid or gaseous can be sourced from biogenic sources as well as be synthetic using atmospheric carbon.

[18] Sustainability of biomass is a highly complex topic and was not looked at in detail in this study. However, the developments in the LULUCF sector are modelled in a way to allow for a certain amount of biomass to be used for energetic purposes despite an increasing forest sink and effects from the harvest of domestic biomass on the LULUCF sink are fully accounted for.

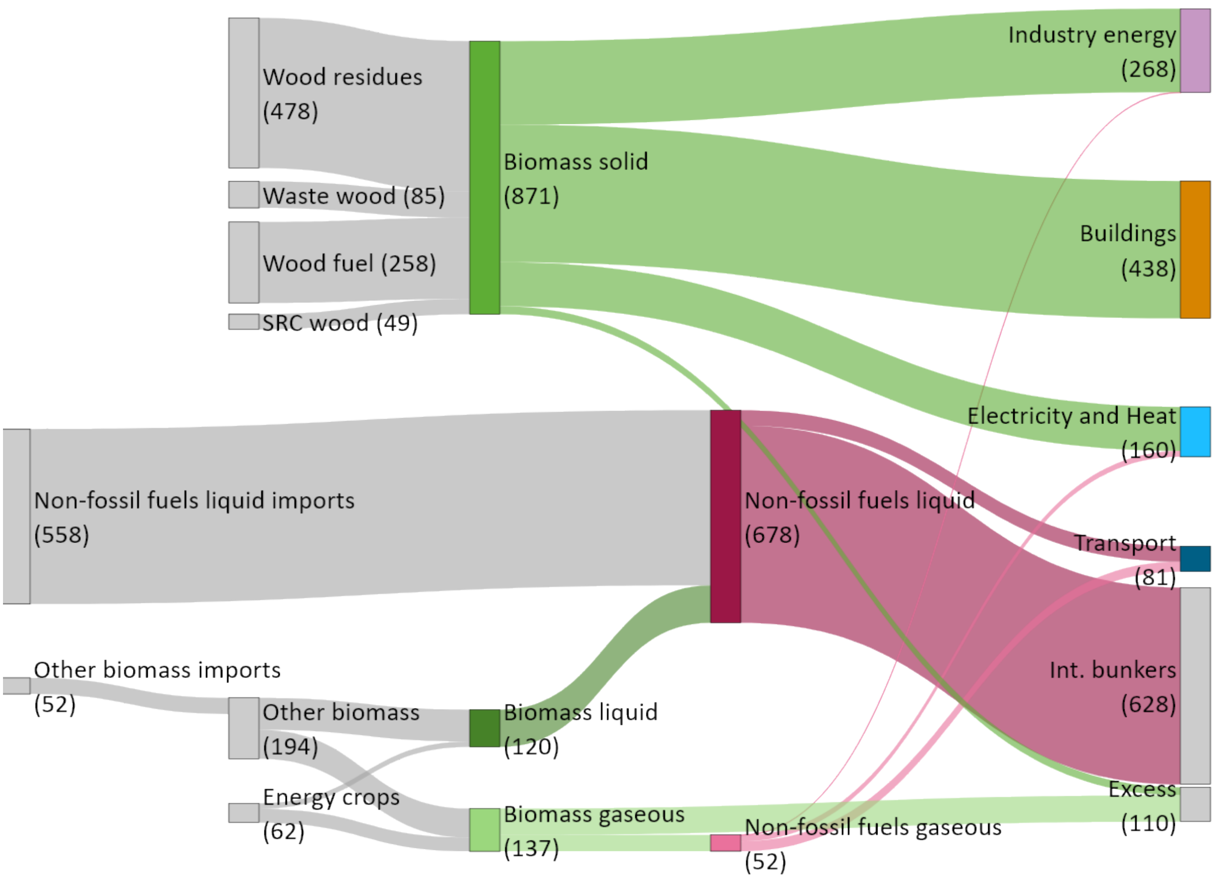
Figure 16: Flowchart of non-fossil fuels (excl. hydrogen demand from supply and industry) for the EU 27 for EUBase for 2020 (in TWh)



Source: own illustration based on own calculations Fraunhofer ISI, Oeko-Institut

Note: non-fossil fuels liquid imports may include synthetic as well as biogenic liquid fuels

Figure 17: Flowchart of non-fossil fuels (excl. hydrogen demand from supply and industry) for the EU 27 for EUBase for 2050 (in TWh)



Source: own illustration based on own calculations Fraunhofer ISI, Oeko-Institut

Note: non-fossil fuels liquid imports may include synthetic as well as biogenic liquid fuels

The main sectors utilizing solid biomass are the industry and buildings, with some use for electricity and heat supply. Demand from the buildings sector decreases over time from 554 TWh in 2020 to 438 TWh in 2050. In contrast, demand from industry increases slightly from 254 TWh in 2020 to 306 TWh in 2040 before declining again to nearly 2020 levels at 268 TWh in 2050. Use of solid biomass electricity and centralized heat production drops from 298 TWh in 2020 to 160 TWh in 2050. Currently, the supply with domestic solid biomass cannot meet demand, this situation is projected to persist for years to come driven by the assumption that biomass use for energy continues to be subsidized and promoted in EU Member States. Over time, demand for solid biomass decreases, in both, the buildings sector but, in particular, in the electricity and heat sector. This leads to a small, expected surplus by 2050. This development is driven by a strong restriction of biomass use in the electricity and heat sector to reduce use of biomass in that sector to the amount available domestically. This surplus could be exported or, depending on the source, potentially used in construction or as carbon for the production of carbon-containing synthetic fuels.

The balance of non-fossil fuels other than solid biomass is dominated by the demand from international bunkers, with smaller amounts also going to other modes of transport. During the interim period from 2020 to 2030, demand for liquid non-fossil fuels increases due to CO_2 regulations in road transport, but it declines after 2030 as a result of further electrification. The type of non-fossil fuel utilized is heavily influenced by the sector in which it is applied, as well as the availability and cost developments. At the moment, it is challenging to predict which specific types of non-fossil fuel will be demanded in which sectors. E-kerosine appears to be a likely option, particularly for international aviation, which is why we decided to assume demand for liquid non-fossil fuels as a conservative assumption in this project. However, other options like ammonia, methanol, hydrogen, e-diesel, and e-methane are being discussed especially for maritime transport and aviation as well. Simultaneously, if sustainable biomass is available and politically accepted, it is likely that biofuels will also be partially utilized to meet the demand for non-fossil fuel energy carriers. In light of already high consumption of biomass and unclear fulfilment of sustainability criteria, however, use of biomass is likely to decrease if restricted to sustainable sources. Limited amounts need to be distributed between sectors, likely resulting in redistribution compared to today to sectors lacking GHG-mitigation options such as direct use of electricity. In addition to the significant amount of liquid non-fossil fuels going into transport, industry and centralized heat generation also contribute to the demand for non-fossil energy carriers. Excess amounts of gaseous biomass are utilized in electricity and centralized heat production in addition to the use of solid biomass. Feedstock demand from industry in this scenario is purely supplied by fossil naphtha and natural gas. A change of feedstock only occurs in the two target sectors.

As a result, from supply side modeling, we find that all gaseous and liquid non-fossil fuels are imported within this scenario. This is a result of (i) complying with the EU targets of domestic hydrogen production but finding (ii) no significant additional RES potential that could be used for the production of non-fossil fuels. Moreover, we find in the target scenarios with higher demand for hydrogen that hydrogen needs to be imported in addition to non-fossil fuels.

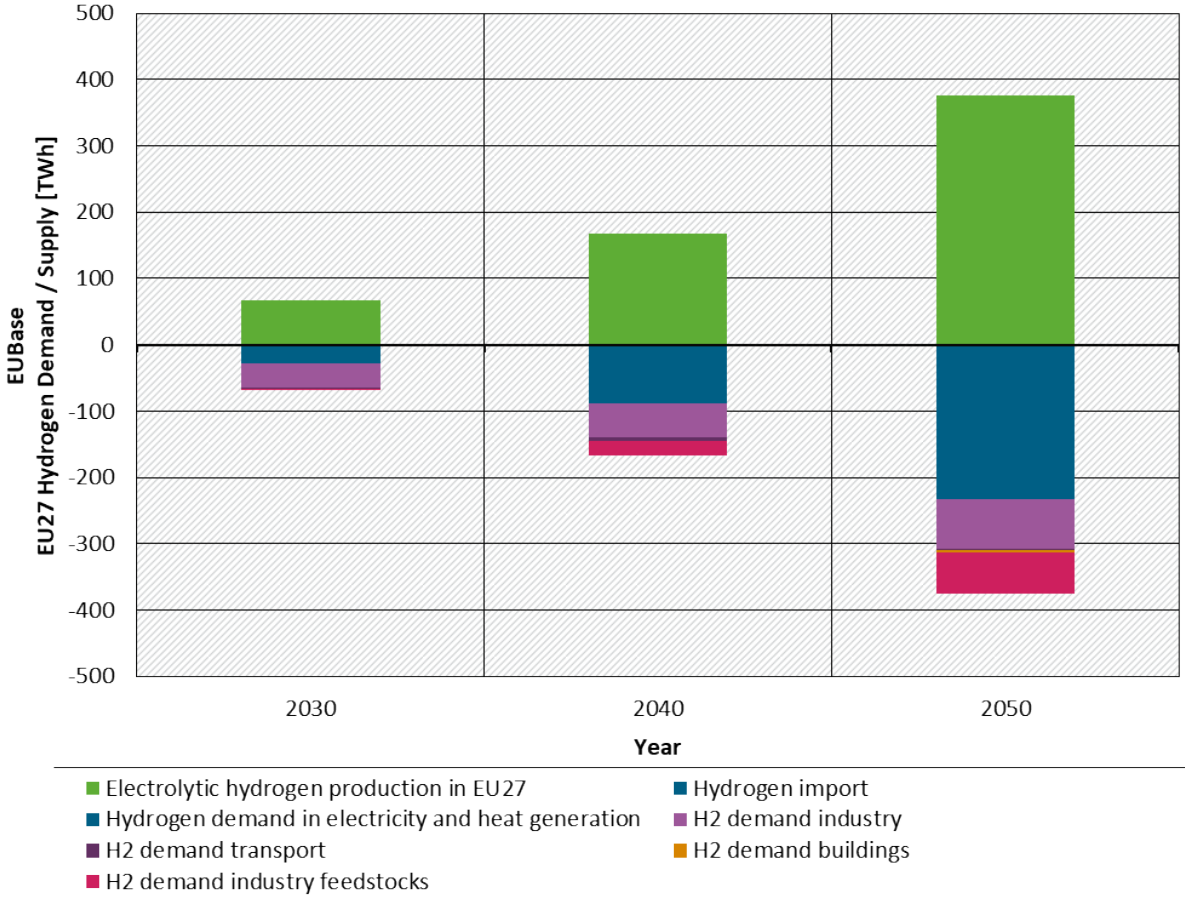
While classified as non-fossil fuels, for certain sectors and applications our models indicate a clear preference for hydrogen if available. In contrast to other non-fossil fuels hydrogen is more efficient and does not require additional inputs such as carbon or nitrogen. Figure 18 shows demand and supply of hydrogen in the EUBase scenario where models strongly favor hydrogen over other non-fossil fuels. This is particularly the case in industry where a limited number of production sites require large amounts of hydrogen (direct reduction of iron, chemical industry) and in the supply sector, where hydrogen is used for supplying electricity and heat in times of limited availability of renewable electricity and high demand. Hydrogen demand in the scenario reaches 66 TWh in 2030, 167 TWh in 2040 and 376 TWh in 2050. While in 2030 only about 43% of that are going into the supply sector, by 2050 the share of the supply sector has increased to 62%. Remaining amounts are almost completely used in industry, as feedstock or for energy supply.

Although the scenario models a slow and not very drastic uptake of hydrogen in the energy system, it needs to be kept in mind that currently the development of hydrogen infrastructure as well as hydrogen production sites, in particular, within the EU are at their very beginning. From a current perspective, it seems unlikely that already by 2030 a hydrogen infrastructure system exists that allows to provide supply to all major industry locations within the EU (EU hydrogen backbone). Also, while in our model hydrogen demand can be met with domestic supply, currently hydrogen import projects are also being developed. In this scenario, we abstract from real project development. The modeling shows that with the slow uptake of hydrogen in the EUBase scenario it would in principle be possible to meet demand with domestic sources.

As reminder: for calculation of GHG emissions, an emission factor of zero is assumed for the hydrogen used in this (and the following) scenarios as hydrogen does not contain carbon and thus combustion of hydrogen does not lead to CO_2 or CH_4 emissions. The hydrogen demand is met by local production (i.e. production within Europe, not necessarily in the Member State that uses the hydrogen) solely from renewable energy sources within the EU in the EUBase scenario.

The amount of renewable electricity required for this hydrogen production is reported in section 3.2.4. For hydrogen imports, hydrogen is assumed to be no-carbon hydrogen.

Figure 18: Hydrogen demand and generation in the EUBase scenario for the EU 27



Source: own calculations Fraunhofer ISI, Oeko-Institut

3.1.1.6 Carbon demand and technical CDR

The demand for carbon in sectors such as industry and production of energy carriers, particularly carbon-containing non-fossil fuels, necessitates specific supplies of carbon to meet those needs. The EUBase scenario shows - under the specific assumptions for the build-up of synthetic fuels production infrastructure in the EU, see also section 3.2.4 - no production of synthetic fuels in the EU[19]. As demand for non-fossil fuels is increasing over time, so are imports of non-fossil fuels.

Table 7 shows the origin of liquid and gaseous non-fossil fuels and their carbon content. Non-fossil fuels contain bio-based as well as synthetic fuels. Domestic production of liquid and gaseous non-fossil fuels decreases over time (only bio-based fuels) from 390 TWh in 2030 to 172 TWh in 2050. In contrast, the imports of liquid and gaseous non-fossil fuels increase significantly from 32 TWh in 2030 to 558 TWh in 2050.

To estimate the carbon content of liquid and gaseous non-fossil fuels, we assume that liquid non-fossil fuels in the transport sector are kerosene and gaseous non-fossil fuels in industry and the supply sector has an equivalent structure to natural gas. Gaseous non-fossil fuels going into the transport sector is assumed to be hydrogen. Please note, that hydrogen demand from the supply sector is not included in the demand for gaseous non-fossil fuels. Based on those assumptions,

[19] There is no demand for green naphtha in EUBase

the carbon content of liquid and gaseous non-fossil fuels excl. hydrogen is increasing over time from 107 Mt CO_2 in 2030 to 196 Mt CO_2 in 2050. This increase is particularly driven by the demand for liquid non-fossil fuels from the transport sector, while demand for gaseous non-fossil fuels in the supply sector is decreasing over time.

In the context of basic chemicals, a limited amount of production processes is changed to MTO/MTA. Here, naphtha as input is replaced by electricity and CO_2. The resulting amount of carbon required in the EUBase scenario amounts to 3 Mt CO_2 in 2040 and 9 Mt CO_2 in 2050. For the resulting products to be carbon-neutral, this carbon needs to be sourced from the atmosphere or from sustainable biomass. In case of capture from air (direct air capture - DAC), the additional energy demand would amount to 1,37 TWh electricity in 2040 and 4,14 TWh electricity in 2050. The heat demand amounts to 5,5 TWh in 2040 and 16,7 TWh in 2050. Although the heat and electricity demand are not taken into account in the calculations for the supply sector, the amounts are minor compared to total electricity and heat demand[20]. Demand could also be met with recycled CO_2 which is already accounted for in other sectors (or accounting could be shifted) without altering the overall outcome on GHG emissions.

As EUBase is no classical target scenario, no demand for technical CDR arises from the target setting. Small amounts of BECCS may arise from the use of CCS technology in the cement and lime industry in combination with the use of biomass as energy carrier. However, this regards the smaller amount of the – already low – amount of CCS in industry and is not analysed within the scenario or identified in the presented figures.

Table 7: Overview of carbon demand and technical CDR

	2030	2040	2050
Non-fossil fuels gaseous and liquid – domestic production [TWh]	390	310	
Non-fossil fuels gaseous and liquid – imports [TWh]	32	370	558
Non-fossil fuels gaseous and liquid imports – carbon content [Mt CO_2]	107	178	196
Demand for CO_2 from domestic chemical sector [Mt CO_2]	0	2.98	9.0
Technical CDR [Mt CO_2]	---	---	---
Total CO_2 demand (domestic and imports)	107	181	205
Electricity demand for DAC [TWh]	49.5	83.7	94.9
- For domestic demand	0	1.4	4.2
- Contained in imports	49.5	82.3	90.7
Heat demand for DAC [TWh]	198	334.9	379.3
- For domestic demand	0	5.6	16.7
- Contained in import	198	329.3	362.6

[20] Total electricity demand amounts to 2771 TWH in 2030, 3427 TWh in 2040 and 3690 TWh in 2050. Space heating demand in buildings amounts to 2695 TWh in 2030, 2454 TWh in 2040 and 2160 TWh in 2050. Additional demand for heat is coming from industry for processes.

3.1.2 Target scenarios EUTarget and EUSupreme

3.1.2.1 Scenario narratives and general description

In addition to the EUBase scenario, the modeling exercise includes two target scenarios, designed to achieve the EU's climate goal of net-zero emissions by 2050. These scenarios are structured around specific mitigation strategies that facilitate the EU's attainment of this target. While the achievement of the intermediate target for 2030 is not pre-defined, the scenario results can indicate whether current targets are met under the scenario specifications. Member State specific targets under the Effort Sharing Regulation (ESR), EU Emission Trading System (ETS), and renewable energy and energy efficiency targets are also not pre-defined and are only partly evaluated for this report. Values for 2040 are being provided to allow for an assessment in light of the discussions on a climate architecture for the year 2040.

The two target scenarios employ distinct mitigation strategies to achieve the 2050 climate target:

- The EUTarget scenario adopts a classical technology-oriented approach. It builds upon the assumptions of the EUBase scenario, remaining technology-open and allowing for various mitigation strategies tailored to Member States based on their NECPs. In this scenario, the CO_2 price serves as a critical mechanism for reaching the 2050 climate target with separate prices for ETS 1 and ETS 2 sectors. The two prices and their development over time is determined within the modeling framework rather than being predefined as it is in the EUBase scenario. Meeting the 2050 target is the main determinant. However, determined prices are streamlined between sector models. The stronger CO_2 prices as well as assumptions on a stronger uptake of mitigation technologies to allow for meeting the 2050 target are main drivers in this scenario. The focus on technical mitigation measures is also applied in the agriculture sector (although not implemented via a CO_2 price), introducing a variety of additional technical mitigation measures compared to the EUBase scenario. Not implemented are strong behavioural changes compared to EUBase.
- In contrast, the EUSupreme scenario envisions the implementation of a comprehensive EU-wide mitigation strategy that emphasizes strong sustainability criteria, enhanced circularity, and non-technical behavioural changes. This scenario significantly limits the use of nuclear power and reduces biomass utilization in the energy system. It further visualizes a mitigation pathway without CCS. Instead, the scenario introduces stringent sufficiency and circular economy assumptions in the industry sector allowing for lower primary production levels and thus adding an additional mitigation lever. Additionally, it aims to lower energy demand more strongly than the EUTarget scenario and puts increased effort into fossil fuel phase-out such as coal phase-out by 2040 in the industry sector and a strict ban on the use of fossil fuels in 2050. For the agriculture sector, strong sufficiency assumptions allow to significantly reduce animal stocks and related emissions instead of applying technical mitigation measures. In combination with a stronger increase in organic farming and other robust assumptions on land use, the scenario allows for a pronounced increase of the natural carbon sink.

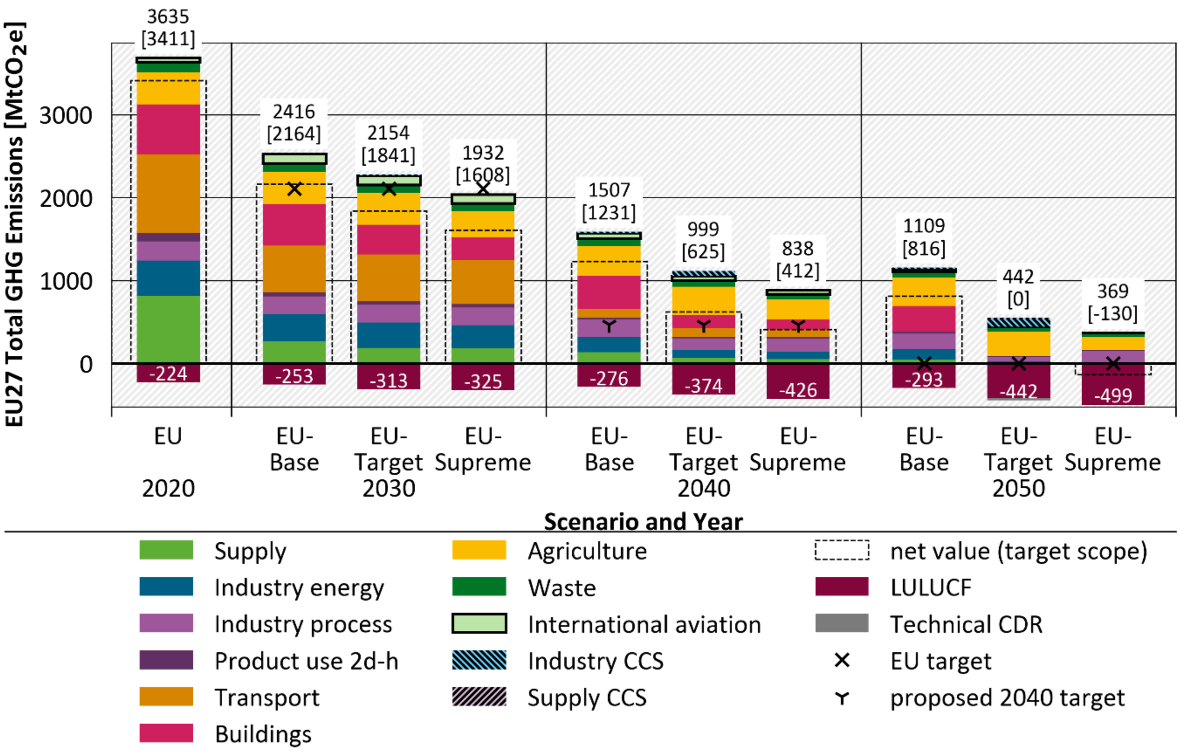
3.1.2.2 GHG balance

The following figures illustrate the GHG balance across all sectors for the European Union under different scenarios, compared to 2020. Emissions from international aviation[21] (marked as "outside of the official NDC" and not discussed in total GHG emissions) and maritime transport

[21] International aviation here refers to all flights except for domestic flights within individual EU countries as reported in the countries' GHG inventories under the UNFCCC

are fully included, as well as emission storage in the LULUCF sector and CCS in later years for the EUTarget Scenario. As before, fugitive emissions from extraction and transport of fossil fuels are not included, nor are fugitive emissions or leakages associated with the transport of novel fuels or the transport or injection of carbon into geological formations.

Figure 19: Total GHG emissions in three modelled scenarios for key target years for EU27



Source: own calculations Fraunhofer ISI, Oeko-Institut

First number in box relates to total generated GHG emissions excl. int. aviation, number in brackets relates to net GHG emissions excl. int. aviation

Figure 19 depicts the development of absolute GHG emissions from 2020 to 2050. As anticipated, net emissions decrease significantly more in the two target scenarios compared to the EUBase scenario. This effect is more pronounced in later years and is notably stronger in the EUSupreme scenario than in the EUTarget scenario. By 2030, net emissions in the EUTarget scenario reach 1,841 Mt CO_2e, about 323 Mt lower than in the EUBase scenario. The EUSupreme scenario further reduces emissions to around 1,608 Mt CO_2e, a decrease of an additional 233 Mt CO_2e compared to the EUTarget scenario. By 2040, the EUTarget scenario achieves a level of 625 Mt CO_2e, 606 Mt CO_2e lower than the EUBase scenario. In contrast, the EUSupreme scenario reaches a level of 412 Mt CO_2e, resulting in an additional reduction of 213 Mt CO_2e compared to the EUTarget scenario. By 2050, the gap in emissions between EUBase and EUTarget scenario widens to 816 Mt CO_2e, with the EUTarget scenario reaching net-zero emissions with the help of natural and technical CDR. The amount of technical CDR needed is small with 28 Mt CO_2. The EUSupreme scenario, however, reaches levels of -130 Mt CO_2 by 2050 in the absence of technical CDR. Notably, the gap in net emissions between the two target scenarios is smaller compared to 2030 and 2040, not only due to the introduction of technical CDR. One effect triggering this result is the nearly complete phase-out of fossil fuels in both, the buildings and transport sector, in both scenarios. Another effect is the role of CCS in the EUTarget scenario over time, which generates additional emission reductions by 2050 in the order of 100 Mt CO_2 compared to the

EUSupreme scenario. Without the utilization of CCS EUTarget would be missing the EU 2050 target.

In total, both target scenarios meet the 2030 target. For 2030, emissions in the EUTarget scenario are approximately 268 Mt CO_2e below the target, while the EUSupreme scenario more significantly exceeds it, achieving an additional reduction of around 301 Mt CO_2e. This is a result of an increase in natural sinks and significantly higher emission reductions compared to the EUBase scenario, in particular in the buildings sector and in agriculture. Emission reductions via CCS play a minor role in 2030 in the EUTarget scenario. By 2040, the EUTarget scenario misses a reduction of 90%[22] by 156 Mt CO_2e. In contrast, the EUSupreme scenario overachieves a reduction of 90% by 57 Mt CO_2e, equalling a reduction of 91% below 1990 levels.

Additional reductions in generated GHGs in the EUTarget scenario by 2030 are primarily observed in the buildings sector, where emissions are 141 Mt CO_2e lower compared to the EUBase scenario, largely due to the implementation of a stronger uptake of heat pumps and higher renovation rates and energy efficiency levels reached within buildings. Also, a stronger uptake of renewable energies in the supply sector contribute to reductions in generated GHGs with 80 Mt CO_2e. In the EUSupreme scenario, reductions from the buildings sector are even more substantial with an additional decrease of 86 Mt CO_2e, amounting to further emission reductions of 227 MtCO_2e in the buildings sector in EUSupreme compared to the EUBase scenario in 2030. This is especially due to higher energy efficiency efforts and additional sufficiency measures, such as less floorspace per person. Remaining generated GHGs in the buildings sector amount to 55% of the sector’s emissions in the EUBase scenario for that year. Moreover, the agricultural sector contributes significantly in the EUSupreme scenario, with additional reductions of around 67 Mt CO_2e by 2030. This is primarily due to the effects of adopting behavioural mitigation strategies, such as dietary changes. Slightly higher emission reductions can also be noted in the transport sector in the EUSupreme scenario, with an additional 30 Mt CO_2e reduction by 2030 as a result of higher sufficiency measures in this scenario in contrast to the EUTarget scenario.

Despite already high emission reductions in the supply sector, additional reductions in generated GHGs in the order of 80 to 85 Mt CO_2 can be found in the EUTarget, respectively the EUSupreme scenario. That is despite the fact that the demand for electricity increases significantly due to mitigation efforts via the utilization of electricity in the demand-side sectors, in particular buildings and transport.

By 2040, the GHG emission reduction effects found for 2030 are more pronounced. In particular in the buildings sector, emissions are significantly lower in both target scenarios compared to the EUBase scenario. In contrast, additional contributions from the transport sector occur only in the EUSupreme scenario and at a lower intensity Again higher sufficiency measures drive down emissions. In light of already low emission levels in 2040 in the EUBase scenario, this effect is however limited. For agriculture, the trend from 2030 is continued in 2040 with significantly lower emissions in the EUSupreme scenario due to the change in mitigation strategies. In contrast, emissions in the EUTarget scenario are only slightly lower compared to the EUBase scenario.

Mitigation via CCS is only allowed in the EUTarget scenario. Here, reductions in the order of 11 Mt CO_2e can be found in 2030, increasing to 63 Mt CO_2e in 2040, 50 Mt CO_2e above the levels in the EUBase scenario. By 2050 mitigation via CCS in both, industry and supply sector (i. e. in waste incineration), amount to 106 Mt CO_2e, up by 89 Mt CO_2e compared to the EUBase scenario. The EUSupreme scenario forgoes the use of CCS for mitigation of fossil or geogenic emissions.

[22] Being translated into an emissions level of 469 Mt CO_2e

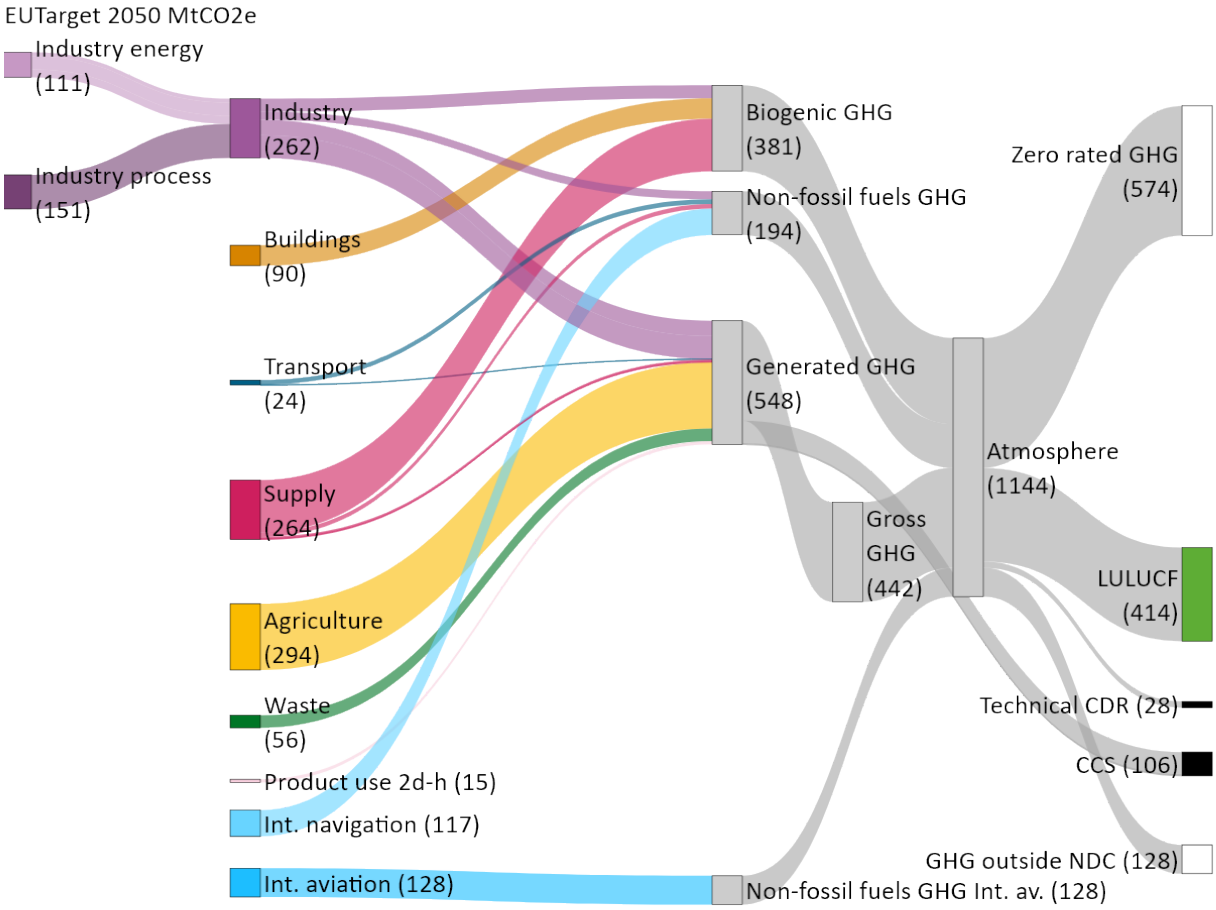
Natural sinks for emissions in the LULUCF sector are significantly higher in both target scenarios EUTarget and EUSupreme compared to EUBase, with limited differences between the two target scenarios in 2030. Additional storage amounts to 60 (EUTarget) and 72 Mt CO_2 (EUSupreme) in 2030 (EUBase: 253 Mt CO_2). In 2040, this increases to an additional emission storage of 98 (EUTarget) and 150 Mt CO_2 (EUSupreme, EUBase: 276 Mt CO_2) in the two target scenarios, amounting to 121 (EUTarget) and 206 Mt CO_2 (EUSupreme) by 2050 (EUBase: 293 Mt CO_2). To reach net-zero emissions in the EUTarget scenario, additional technical carbon removals[23] are needed in the order of 28 Mt CO_2 in 2050. In contrast, the additional behavioural mitigation measures in industry and agriculture in the EUSupreme target allow to reach a net-negative emission balance in 2050 without the help of technical CDR.

Figure 20 and Figure 21 show again emission balances as a flowchart in a Sankey diagram. We focus on the year 2050 to highlight differences between the three scenarios. The figure illustrates the roles of agriculture and waste in the target scenarios, as well as the additional reductions from industry compared to the EUBase scenario. A comparison highlights significantly higher emission reductions in the EUSupreme scenario due to assumptions on behavioural changes in diet. The comparison also shows that mitigation via CCS is used to reduce industry emissions in the EUTarget scenario, resulting in higher generated emissions but allowing to reach lower gross emissions from industry in the EUTarget scenario compared to the EUSupreme scenario. Additional emission reductions in the EUSupreme scenario are realized by lowering production levels and by implementing a complete ban of fossil fuels in the industry sector by 2050. Similarly remaining fossil emissions in the transport sector were mitigated via a ban on fossil fuels in 2050.

Both pictures also highlight, that a significant number of emissions remains in both target scenarios, which is zero-rated (biofuels, biomass, synthetic fuels). For domestic biogenic and electricity-based fuels, effects on land-use and LULUCF sink are accounted for and it is taken into account that hydrogen is produced from renewable electricity. For imports, this can only be an assumption as related emissions are outside of the accounting limits of our models.

[23] Technical CDR is not part of the modelled system. The amount of technical CDR is calculated to fill the gap between the GHG target for 2050 and remaining net-emissions in the absence of technical CDR.

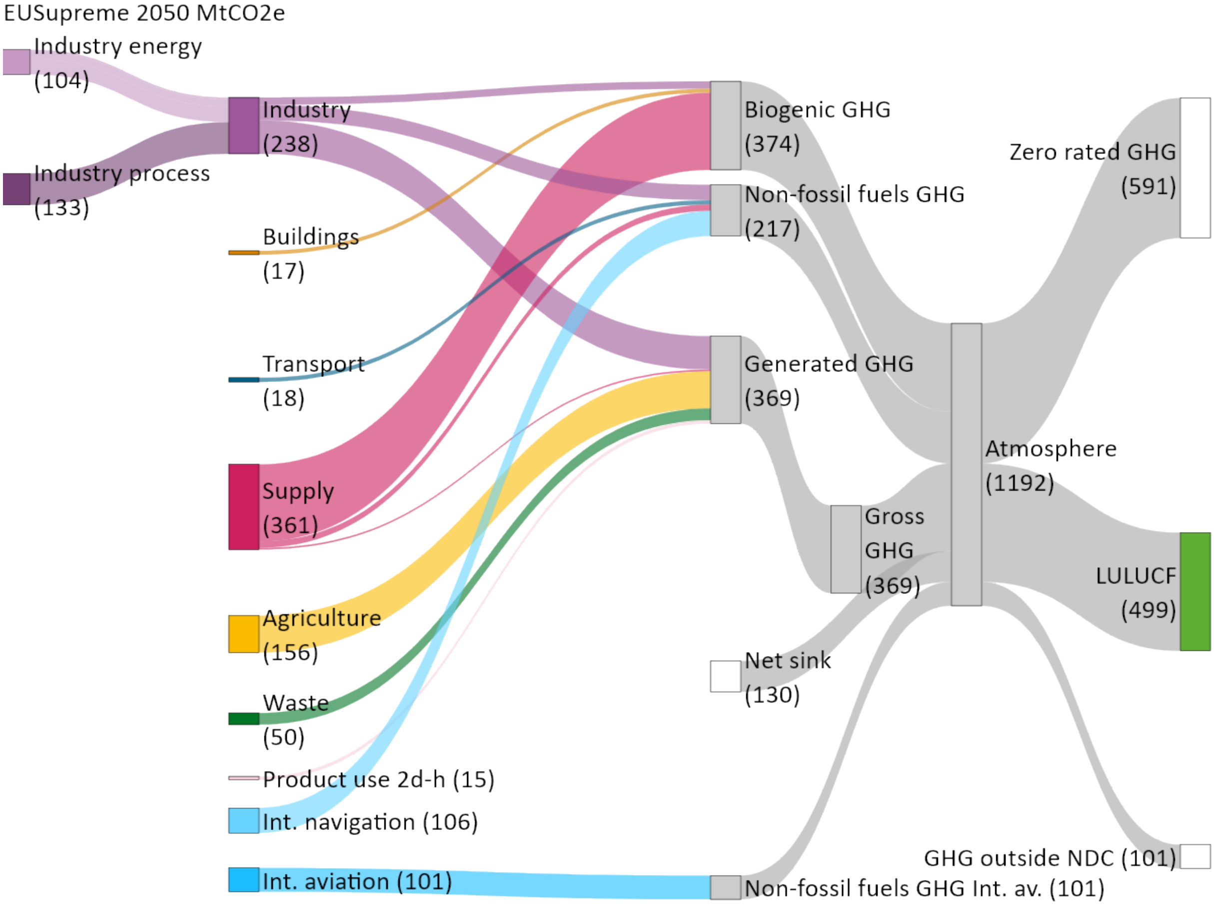
Figure 20: Flowchart of GHG emissions in EUTarget in 2050



Note: Biogenic emissions for domestic biomass are nominally already accounted for in the LULUCF sector

Source: own illustration based on calculations by Fraunhofer ISI, Oeko-Institut

Figure 21: Flowchart of GHG emissions in EUSupreme in 2050



Note: Biogenic emissions for domestic biomass are nominally already accounted for in the LULUCF sector
Source: own illustration based on calculations by Fraunhofer ISI, Oeko-Institut

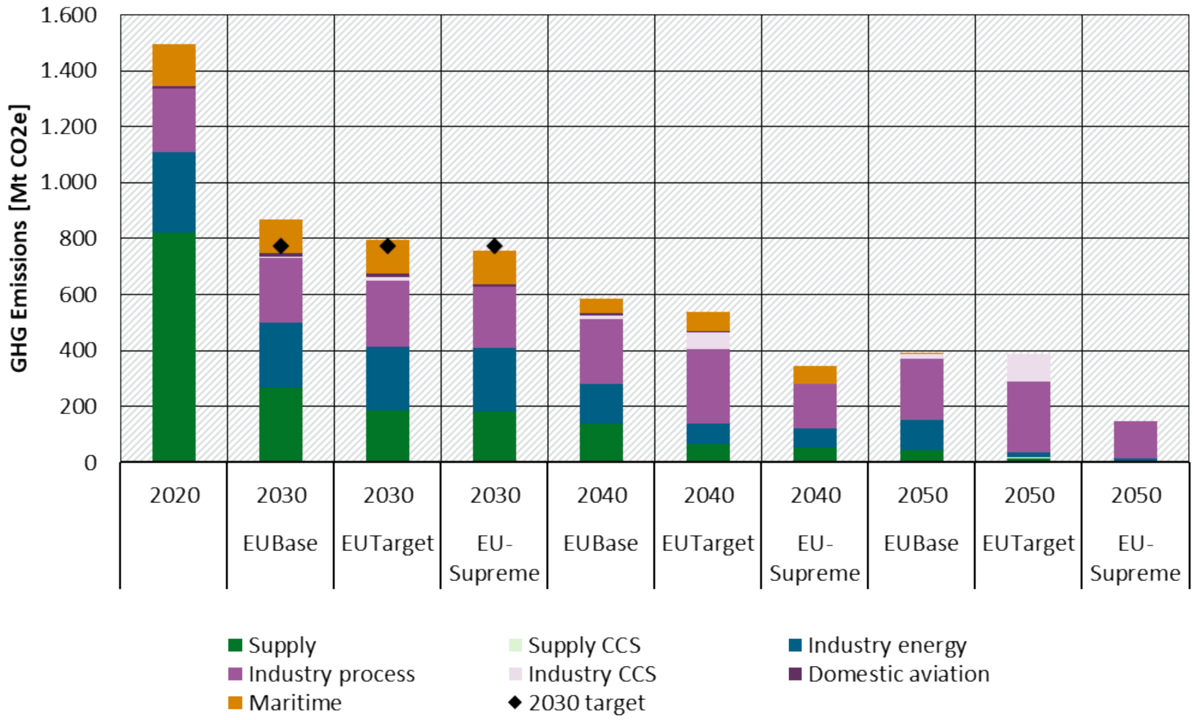
3.1.2.3 ETS, ESR and LULUCF emissions

Figure 22 shows the development of ETS emissions in the different scenarios. In contrast to the EUBase scenario where the 2030 target[24] was missed by 82 Mt CO_2e, the target is being met in both target scenarios. In the EUTarget scenario, emissions in the ETS sector reach 760 Mt CO_2e, a reduction of 63% below 2005 levels. In the EUSupreme scenario the level reached is even slightly lower with 755 Mt CO_2e, again a reduction of 63% below 2005 levels. However, while our figures indicate that the target could be met, there is no clear over-fulfilment of the 2030 targets.

For 2040, emissions in the ETS sectors decrease further to 348 and 345 Mt CO_2e in the EUTarget and EUSupreme scenario (corresponding to a reduction of 83% below 2005 levels). Although this is a significant further reduction in emissions, it is still far from reaching zero emissions under the ETS as is required by the current linear reduction factor and cap development. By 2050 remaining emissions in the ETS sectors reach 71 Mt CO_2e in the EUTarget scenario and 156 Mt CO_2e in the EUSupreme scenario. The lower emission levels in the EUTarget scenario are a result of the use of CCS in both, the industry and the supply sector (waste incineration). Total emission reductions by CCS amount to 63 Mt CO_2e in 2040 in the EUTarget scenario and 106 Mt CO_2e in 2050.

[24] a reduction of 62% below 2005 levels or an absolute emissions level of 774 Mt CO_2e

Figure 22: Development of ETS emissions in scenarios

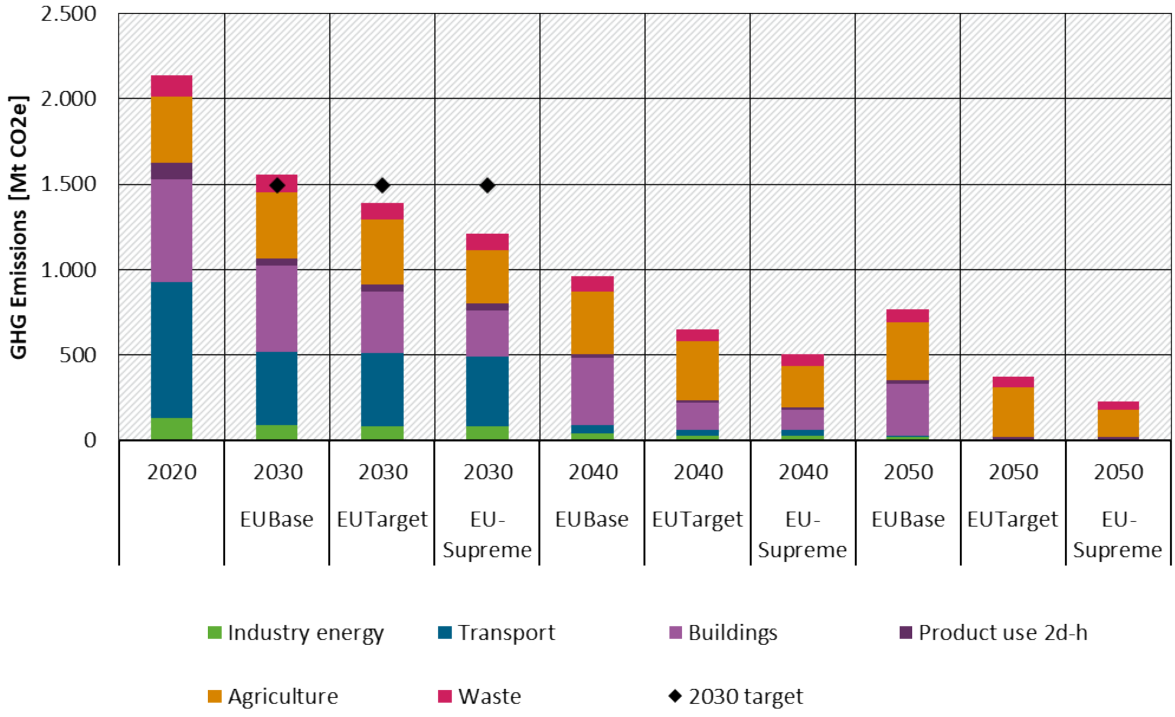


Source: own calculations Fraunhofer ISI, Oeko-Institut

Similar to ETS sectors, ESR sectors show higher emission reductions in the target scenarios compared to the EUBase scenario. By 2030, both target scenarios meet the 2030 target – a reduction of 40% below 2005 levels or an absolute emissions level of 1,494 Mt CO_2e. With an absolute emission level of 1,394 Mt CO_2e (44% reduction below 2005 levels) already the EUTarget scenario clearly meets the target. With even lower emission levels of 1,211 Mt CO_2e (51% reduction below 2005 levels) the over-fulfilment of the target in the EUSupreme scenario is even stronger. In particular, the ambitious emission reduction measures in the buildings and transport sector allow for this development.

Further emission reductions are being realized by 2040 and 2050 in the two target scenarios. By 2040, reductions reach 74 and 80% below 2005 levels, respectively. While emissions within the buildings and transport sector as well as the industry are close to zero in 2050, the remaining emissions stem in particular from the agriculture and the waste sector. Emission reductions in the ESR sectors reach 85% in the EUTarget scenario and 91% in the EUSupreme scenario.

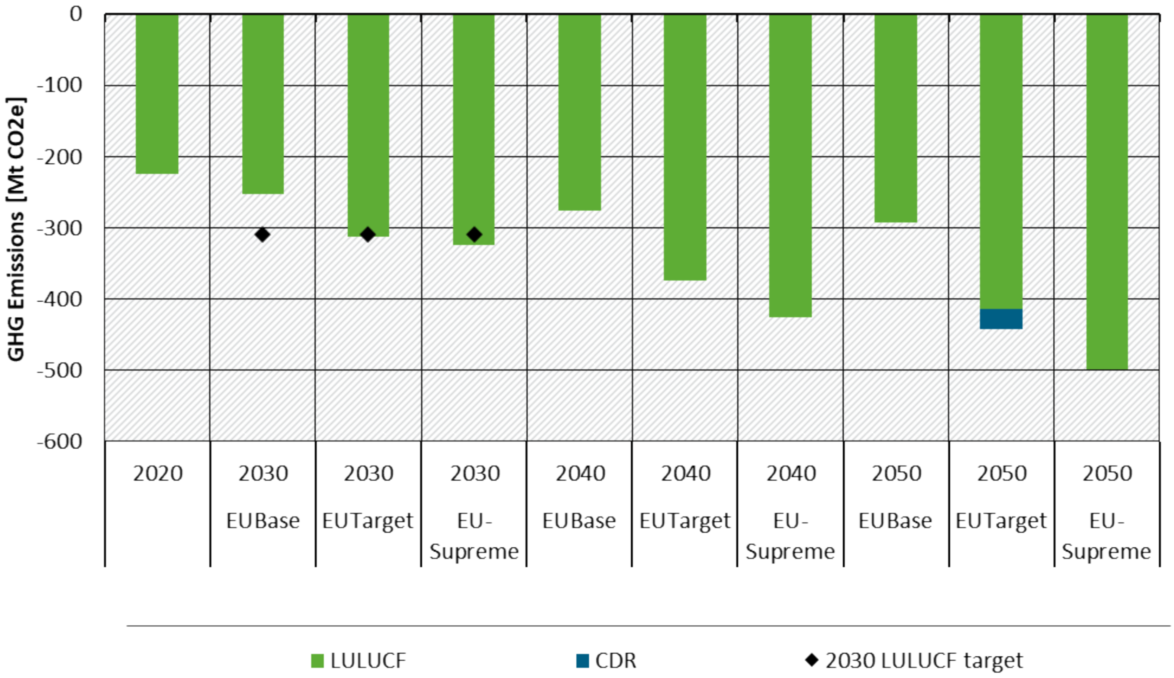
Figure 23: Development of ESR emissions in scenarios



Source: own calculations Fraunhofer ISI, Oeko-Institut

To cover for the remaining emissions in both, the ETS and the ESR sectors, LULUCF and, partly, technical CDR play an important role. In the LULUCF sector, similar to ETS and ESR, targets exist for 2030. As Figure 24 shows, the LULUCF sink in both target scenarios is significantly larger compared to the EUBase scenario, in 2030. As a result, the target of reaching net-negative emissions of 310 Mt CO_2 by 2030 is met in both target scenarios. In the EUTarget scenario, the sink reaches 313 Mt CO_2, in the EUSupreme, it is slightly higher with 325 Mt CO_2. Until 2040 and 2050 this trend continues, allowing to reach a net-sink of 414 Mt CO_2 in the EUTarget scenario and even 499 Mt CO_2 in the EUSupreme scenario, both by 2050. While this sink is sufficient to reach the overall target of GHG-neutrality by 2050 in the EUSupreme scenario, it is not sufficient to cover for all remaining emissions in the EUTarget scenario. As a result, to close the gap and meet the 2050 target, the EUTarget scenario requires additional carbon dioxide removals in the order of 28 Mt CO_2. Hence, the total sink of LULUCF and technical CDR adds up to 442 Mt CO_2.

Figure 24: Natural and technical CDR in scenarios



Source: own calculations Fraunhofer ISI, Oeko-Institut

3.1.2.4 Energy demand and supply

The development of final energy demand by sectors in the target scenarios is illustrated in the following Figure 25. Both target scenarios demonstrate a significantly strong decrease in final energy demand, particularly pronounced in later years. In 2030, the additional decrease in final energy demand[25] amounts to 167 TWh in the EUTarget scenario and 492 TWh in the EUSupreme scenario. That corresponds with an additional 2% (EUTarget) and 4% (EUSupreme) reduction below 2020). By 2040, absolute savings reach an additional 469 TWh (EUTarget) and 1.099 TWh (EUSupreme). That equals an additional 3% and 8% compared to 2020. By 2050, final energy demand in the EUTarget scenario is about 851 TWh lower than in the EUBase scenario, representing about 7% lower demand. In the EUSupreme scenario this difference increases to 1858 TWh. Compared to the EUBase scenario, where final energy demand in 2050 was reduced by 26% it is now 41% below 2020 levels.

The most significant contributions to the additional reduction in final energy demand come from the buildings sector. By 2050, final energy demand in the EUTarget scenario is 851 TWh lower than demand in the EUBase scenario for that year: 8,479 TWh in EUTarget compared to 9,330 TWh in EUBase This difference is even more pronounced in the EUSupreme scenario, where final energy demand in the buildings sector in 2050 is 7,473 TWh. This is a result from a reduced energy demand for space heating driven by increasing renovation rates and standards, and in case of the EUSupreme scenario also sufficiency measures. Moreover, energy demand for electrical appliances in the buildings sector decreases slightly, however there is also a slight increase in energy demand for hot water, space cooling and ventilation. For the industry sector, the more pronounced role of CCS in the EUTarget scenario even results in a slight increase in final energy demand in 2040 and 2050 compared to the EUBase scenario. In the transport sector, final energy demand is only slightly reduced in the EUTarget scenario relative to the

[25] Final energy demand in 2030 amounts to 11,455 TWh in EUBase, 11,288 TWh in EUTarget and 10,964 TWh in EUSupreme

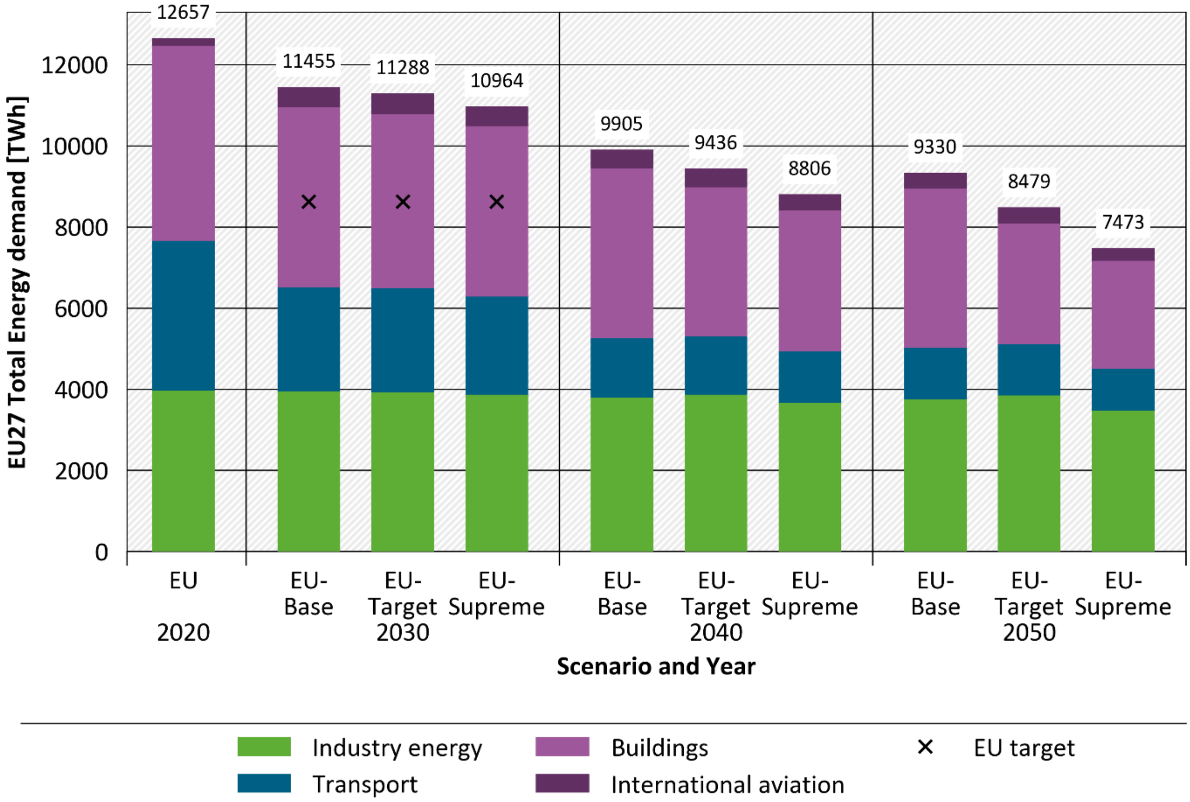
EUBase scenario, but significantly lower in the EUSupreme scenario due to reductions in traffic volume.

Despite the higher decline in final energy demand in the two target scenarios compared to the EUBase scenario, the energy efficiency target of 8,626 TWh for final energy demand in 2030 is not met in either target scenario.

Two effects are evident when looking at the mix of energy carriers in the system: the phase out of fossil fuels is more pronounced in the two target scenarios compared to the EUBase scenario, and the share of non-fossil fuels increases significantly. The first effect is particularly strong in the target scenarios, primarily due to a more significant phase out of fossil-fuels in the buildings sector of the target scenarios resulting from the increased use of heat-pumps and district heating for space heating compared to the EUBase scenario. However, this effect is somewhat mitigated by the sufficiency assumptions in the EUSupreme scenario.

Limited differences can be observed in the final demand for electricity, indicating that the substantial increase in electricity demand from various sectors remains consistent across different overall ambition levels. This is a combined effect of a slight decrease in electricity demand from the buildings sector (excluding heat pumps), which is more than offset by the increase in final electricity demand from the transport sector (in all scenarios) and a significant rise in final electricity demand from industry. The latter is notably high in all three scenarios, with particularly pronounced increases in the two target scenarios.

Figure 25: Final energy demand by sectors for EU 27 in three modelled scenarios

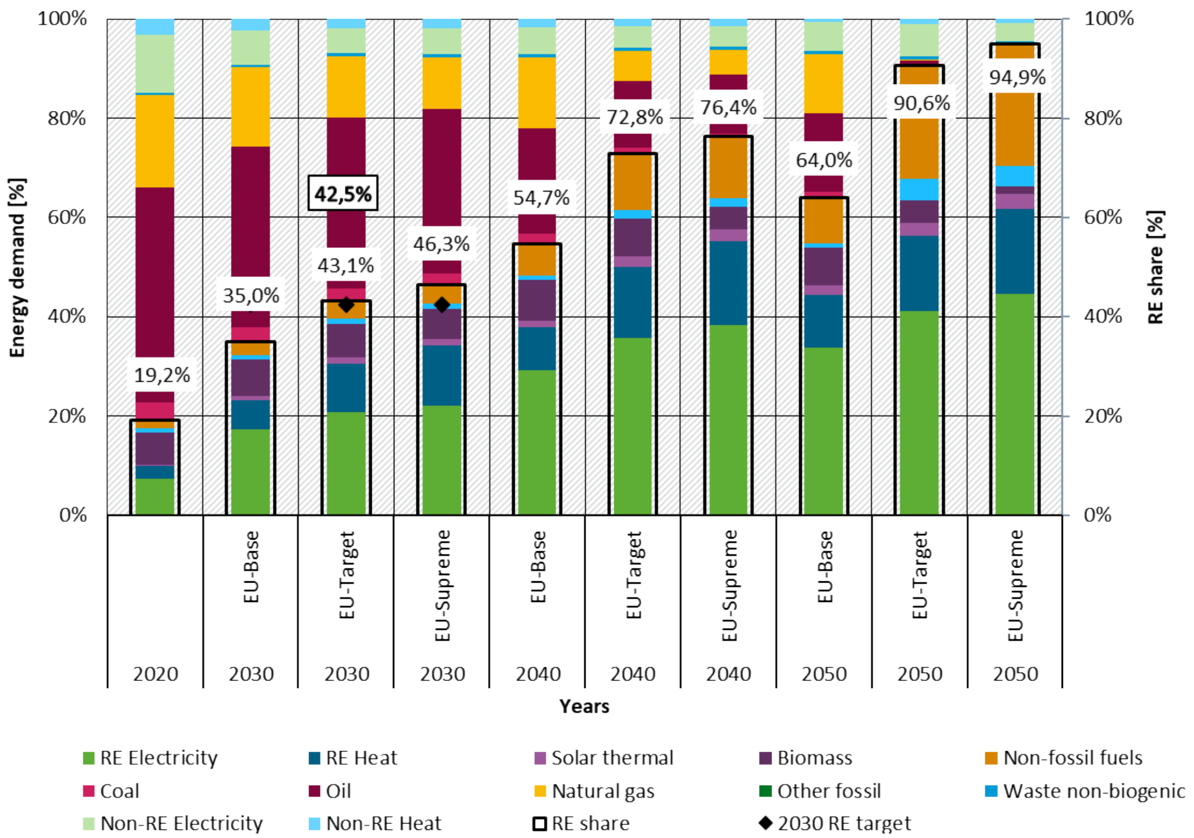


Source: own calculations Fraunhofer ISI, Oeko-Institut

Figure 26 depicts the share of renewable energy in the two target scenarios with non-fossil fuels assumed to be fully renewable.

The differences of the target scenarios compared to the EUBase scenario are substantial in 2050, with 90.6% (EUTarget) and 94.9% (EUSupreme) versus 64% in the EUBase scenario. By 2030, the values in the target scenarios exceed the EU target of 42.5%. By 2040, the values in the two target scenarios are already higher than those in the EUBase scenario by 2050.

Figure 26: Shares of energy sources in final energy demand for EU27 in three modelled scenarios

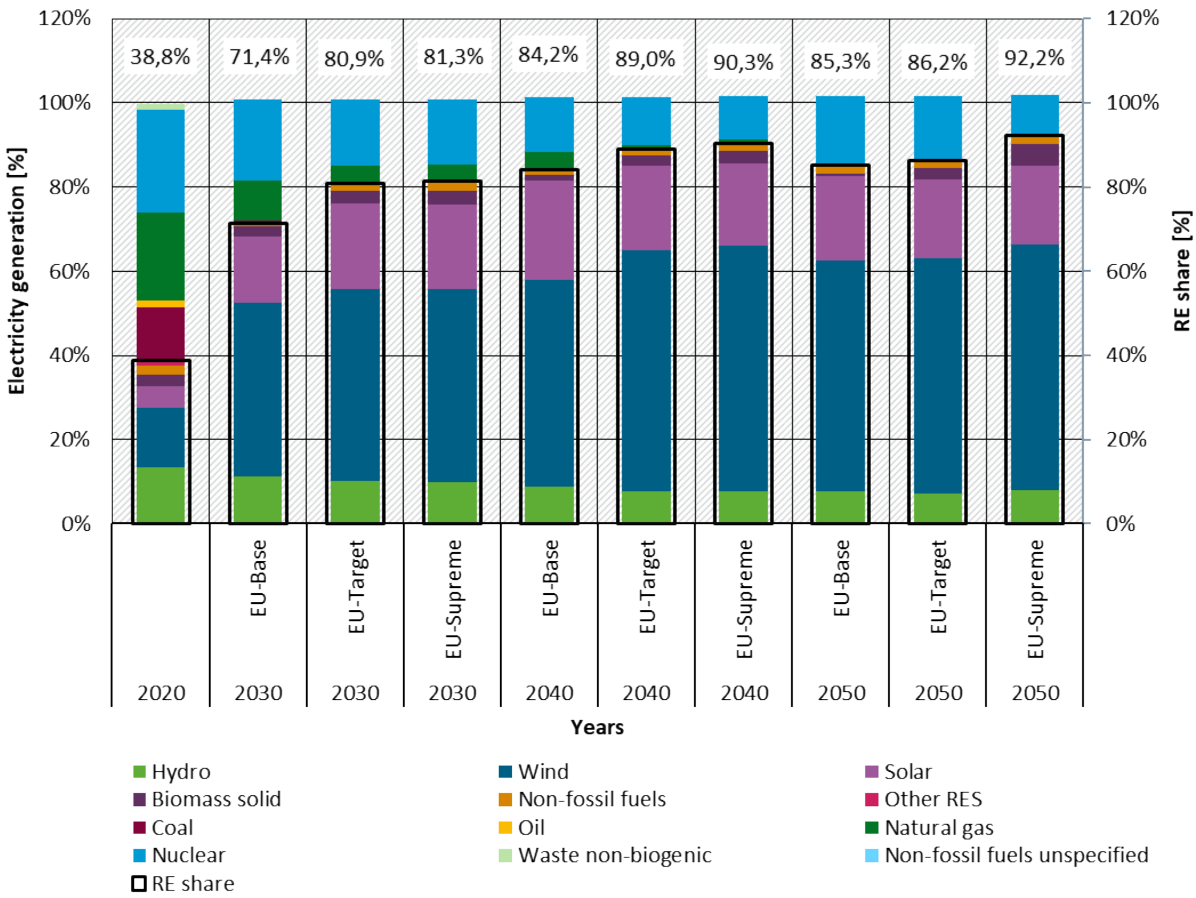


Note: Electricity and heat are split into renewable and non-renewable shares based on generation.
Source: own calculations Fraunhofer ISI, Oeko-Institut

Figure 27 shows the share of renewable sources for electricity generation. Differences to the EUBase scenario are small. In the EUTarget scenario a strong increase in electricity demand and demand for non-fossil fuels and an already strained electricity system in the EUBase scenario prevent affect the renewable electricity shares. Nevertheless, in 2030 and 2040 RES shares are higher in the EUTarget scenario compared to EUBase the same in the two scenarios. In 2030 by 10 percentage points, in 2040 still by 5 percentage points. In 2050, the RES share in EUTarget is only 1 percentage point compared to EUBase. Remaining electricity is provided by nuclear power in 2050, which has a share of 15 percent in EUBase and 14% in EUTarget.

The lower electricity demand in the EUSupreme scenario as well as stricter restrictions on the development of nuclear help to increase the RES share. The effects are limited in 2030 and 2040, where shares are almost the same in EUTarget and EUSupreme. An effect can be found in 2050, where the RES share reaches 92% in EUSupreme, an additional 6 percentage points compared to EUTarget. In turn, the share of nuclear in 2050 in the EUSupreme scenario is only 8% compared to 14% in the EUTarget scenario.

Figure 27: Energy sources for electricity generation (% of total generation) in target scenarios



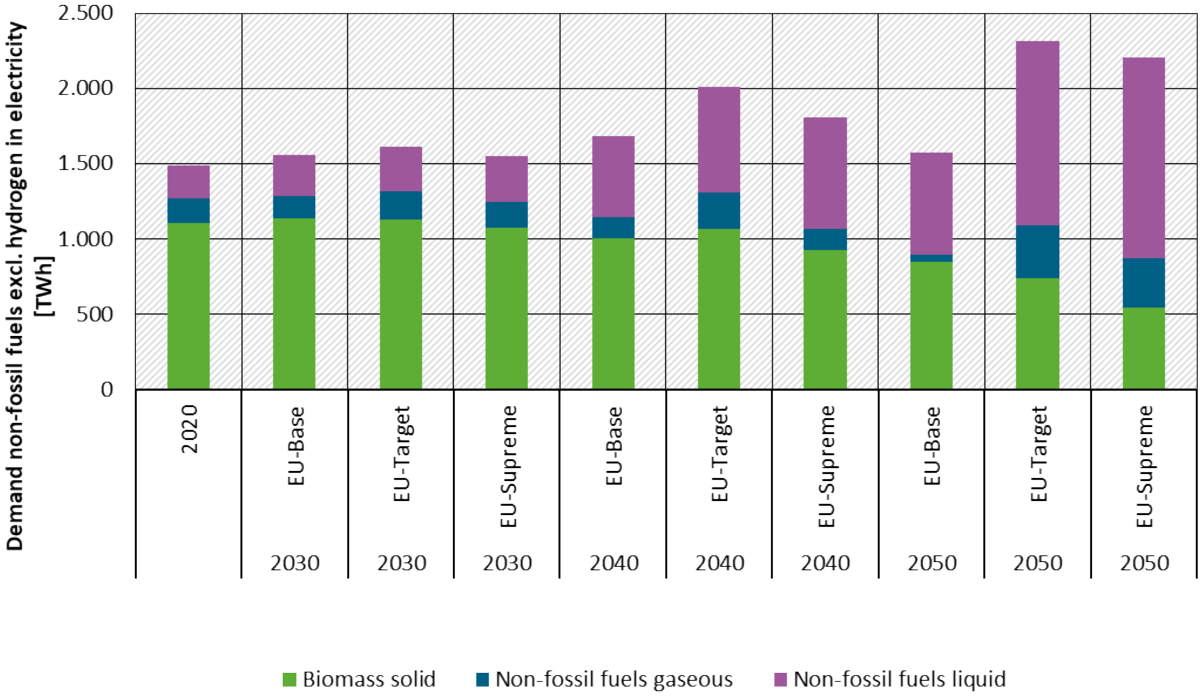
Source: own calculations Fraunhofer ISI, Oeko-Institut

3.1.2.5 Non-fossil fuels balance

Figure 28 illustrates the demand for solid biomass and other non-fossil fuels across all three scenarios. In the EUTarget scenario, demand for non-fossil fuels increases further compared to the EUBase scenario, primarily due to demand from industry and transport. By 2050, demand for non-fossil fuels in the EUTarget scenario is approximately 740 TWh higher than in the EUBase scenario, representing a 56% increase compared to 2020.

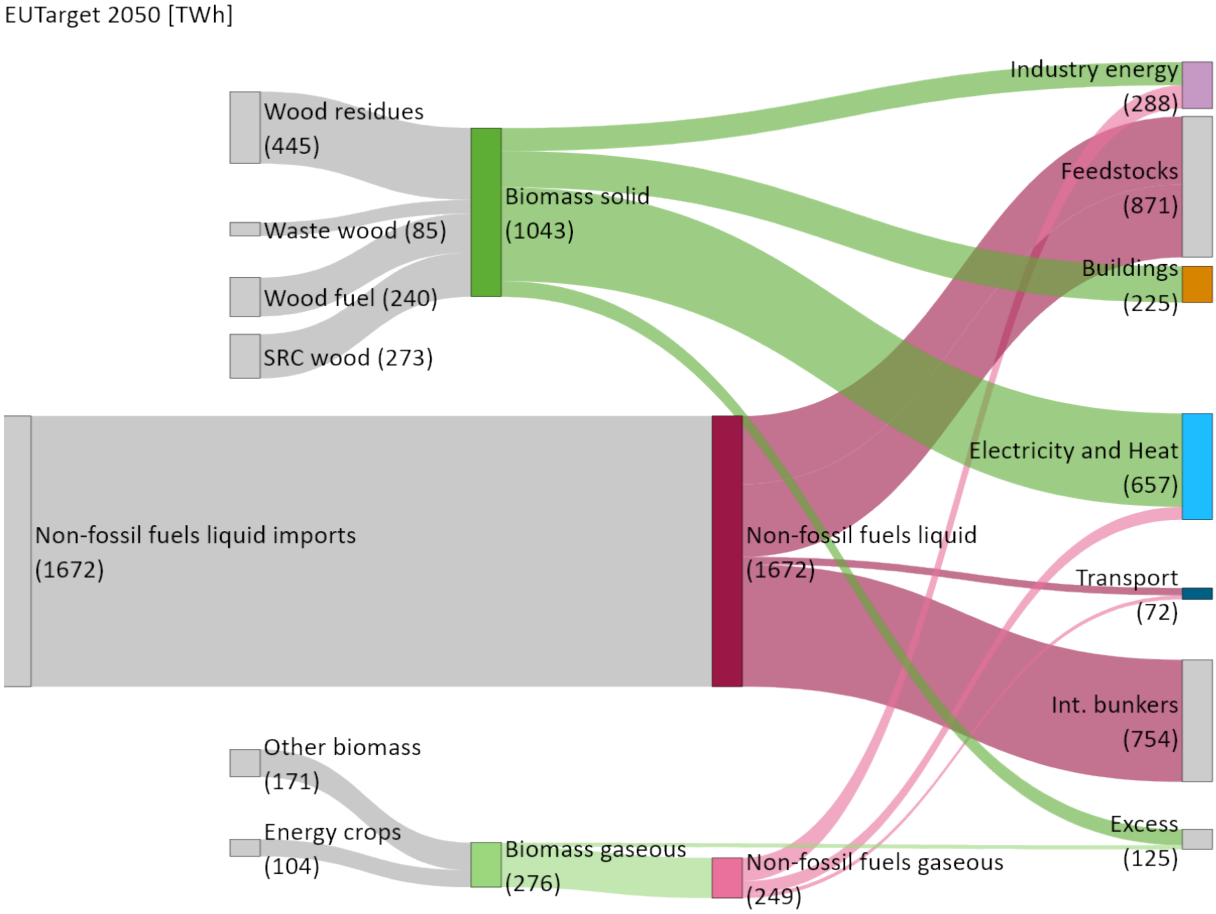
Similarly, the EUSupreme scenario shows higher demand for non-fossil fuels compared to the EUBase scenario by 2040 and 2050. The sufficiency and efficiency assumptions in this scenario, however, limit the increase in demand. Overall, demand for non-fossil fuels in 2050 is roughly 340 TWh higher than in the EUBase scenario, but also 400 TWh lower than in the EUTarget scenario.

Figure 28: Demand for non-fossil fuels for energy use and feedstocks (excl. hydrogen for industry, feedstocks and electricity and heat generation) for the EU27



Source: own calculations Fraunhofer ISI, Oeko-Institut

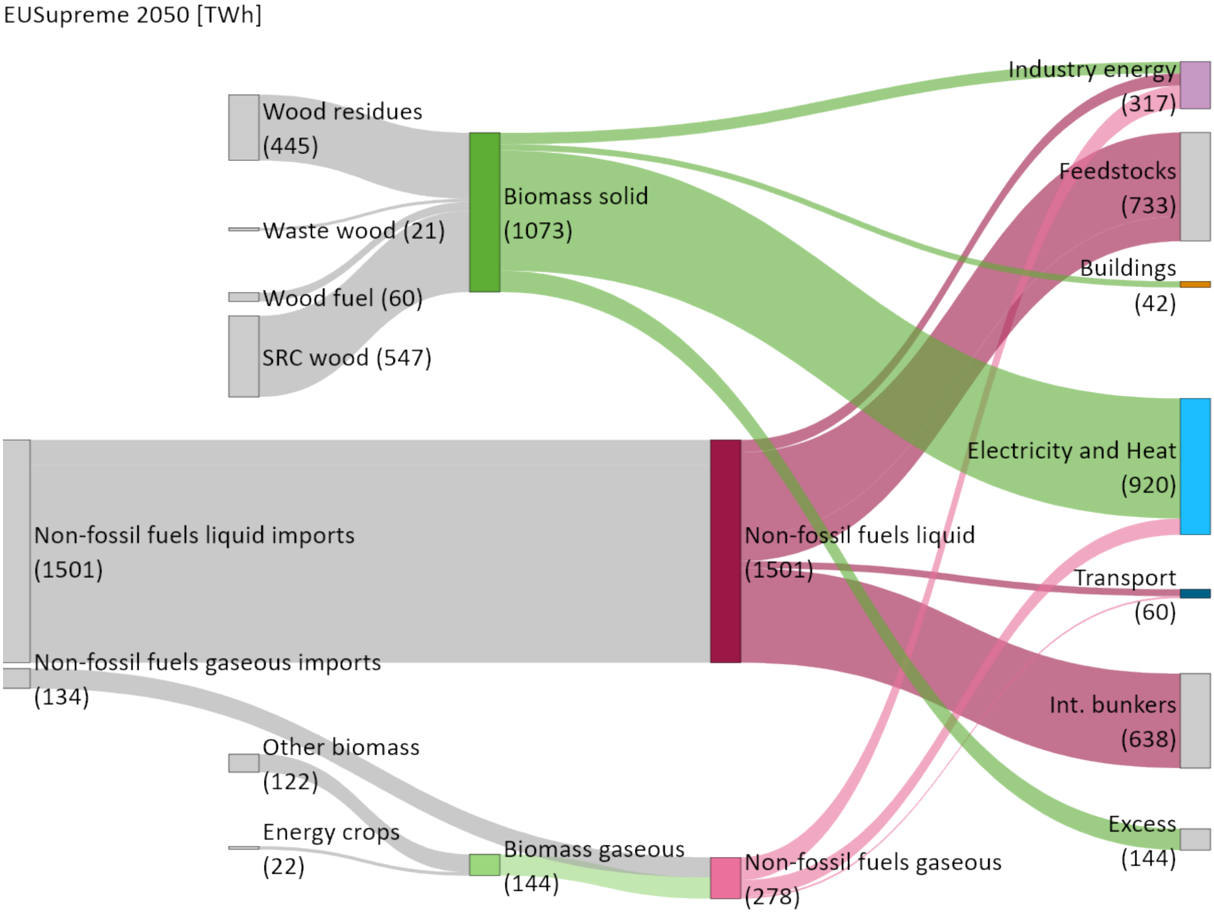
Figure 29: Flowcharts of non-fossil fuels (not hydrogen) for the EU 27 for the EUTarget scenario for 2050 (in TWh)



Source: own illustration based on own calculations Fraunhofer ISI, Oeko-Institut

Note: non-fossil fuels liquid imports may include synthetic as well as biogenic liquid fuels; excess means that more solid biomass is being produced than is used in solid form

Figure 30: Flowcharts of non-fossil fuels (not hydrogen) for the EU 27 for the EUSupreme scenario in 2050 (in TWh)



Source: own illustration based on own calculations Fraunhofer ISI, Oeko-Institut

Note: non-fossil fuels liquid imports may include synthetic as well as biogenic liquid fuels; excess means that more solid biomass is being produced than is used in solid form

Figure 29 shows the distribution of energy supply and demand for non-fossil fuels in a flowchart format. The use of solid biomass in the industry and buildings sector is significantly reduced, particularly in the EUSupreme scenario. The excess biomass is used as far as possible for flexible generation of heat and power. This reduces the demand for hydrogen.

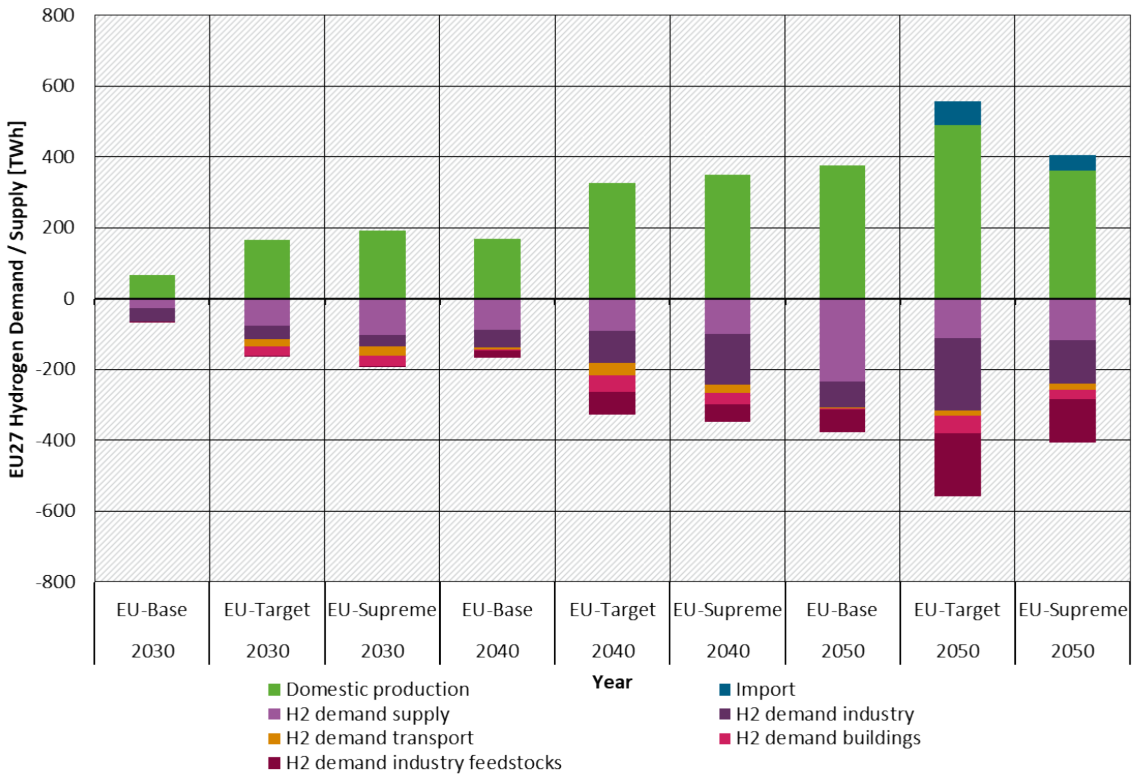
Demand for liquid non-fossil fuels arises from the industry (for both feedstocks and energy demand) and from international transport. As a result of the modeling in the energy sector, we find that this demand is completely met by imports. Liquid non-fossil fuels are at no time produced within the EU.

Gaseous non-fossil fuels are primarily supplied from biogas, with smaller import shares in the EUSupreme scenario due to more restrictive assumptions regarding the agricultural sector, resulting in a lower supply of biogas.

Figure 31 illustrates the demand for hydrogen across different applications and supply. In the EUBase scenario, the amounts of liquid biomass are reduced from the overall demand for liquid non-fossil fuels. As shown, the demand for chemical non-fossil feedstocks leads to a high demand for hydrogen and non-fossil synthetic hydrocarbons in both target scenarios, mainly from the industry (1,049 TWh in EUTarget and 869 TWh in EUSupreme by 2050) and the energy supply sector, which add to the demand from international transport and direct hydrogen use.

Local production of hydrogen increases significantly in the two target scenarios compared to EUBase in all years between 2030 and 2050. Moreover, while the demand for hydrogen could be met domestically in all years in EUBase, we find significant amounts of hydrogen imports in 2050 in both EUTarget and EUSupreme. The share of hydrogen imports amounts to 12% in EUTarget and 11% in EUSupreme. As hydrogen needs to be imported in later years, we do not allow for the production of carbon-containing non-fossil fuels in the EU to prevent hydrogen imports for the production of non-fossil fuels. This is despite the fact that in 2030 and 2040 syn-fuel production potential could exist within the EU. However, we assume that building up the production infrastructure for a limited amount of time is not cost-efficient.

Figure 31: Demand and supply of hydrogen



Source: own calculations Fraunhofer ISI, Oeko-Institut

3.1.2.6 Carbon content of fuels and naphtha and technical CDR

Like EUBase, EUTarget and EUSupreme - under the specific assumptions for the build-up of synthetic fuels production infrastructure in the EU, see also section 3.2.4 – see build-up of production capacities for synthetic fuels or green naphtha in the EU. As demand for non-fossil fuels is increasing over time, so are imports of non-fossil fuels. The increase is stronger in the EUTarget scenario as behavioural changes and sufficiency measures lead to lower demand in EUSupreme. The higher increase in demand in the EUTarget scenario results in a higher increase in non-fossil fuel imports in this scenario compared to EUSupreme.

Table 8 summarizes the main insights into carbon content and technical CDR for the EUTarget and EUSupreme scenario. Domestic production of liquid and gaseous non-fossil fuels shows different developments in the two target scenarios. In the EUSupreme scenario, as was the case in the EUBase scenario, the domestic production of (bio-based) non-fossil fuels decreases over time from 168 to 144 TWh between 2030 and 2050. The decrease is significantly lower in EUSupreme than in EUBase. However, the total amount of domestic production in EUSupreme is only 43% of the value in EUBase in 2050. In 2050 domestic production is still lower in

EUSupreme with 144 TWh compared to 172 TWh in EUBase, but the difference is significantly smaller.

The imports of liquid and gaseous non-fossil fuels increase significantly in both target scenarios (545 TWh in 2030 to 1672 TWh in 2050 in EUTarget and 541 TWh in 2030 to 1547 TWh in 2050 in EUSupreme) and are significantly higher compared to the EUBase scenario (32 TWh in 2030 to 558 TWh in 2050). This result is mainly driven by the increased demand for non-fossil fuels in industry and in particular feedstocks that were not needed in the EUBase scenario.

The carbon content of imported non-fossil fuels increases over time in both target scenarios with a slightly lower increase in EUSupreme from 182 to 344 Mt CO_2 compared to 187 to 388 Mt CO_2 in the EUTarget scenario. It is in both target scenarios significantly higher than in the EUBase scenario where it peaked at 196 Mt CO_2 in 2050, an effect mainly driven by industry feedstocks.

The amount of CO_2 needed for domestic purposes (i.e. either chemical industry demand from MTO/MTA or technical CDR) in the two target scenarios is also significantly higher than in the EUBase scenario, due to a complete switch from fossil naphtha to non-fossil production routes and inputs. Starting at 4 Mt in 2030 in the EUTarget scenario, the CO_2 demand increases to 54 Mt in 2040 and 149 Mt in 2050. In case of CO_2 being sourced via DAC a significant energy demand for both electricity and heat arises for capturing the CO_2: 25 TWh electricity in 2040 and 69 TWh electricity in 2050 in EUTarget and 100 TWh heat in 2040 and 276 TWh heat in 2050.

In EUSupreme, the amount of CO_2 needed is slightly lower in 2050 due to demand reductions in that scenario: 101 Mt CO_2. The uptake of MTO/MTA route is however faster than in the EUTarget scenario. Therefore, CO_2 demand in 2030 and 2040 is higher compared to EUTarget amounting to 9 Mt CO_2 in 2030 and 74 Mt CO_2 in 2040. Electricity demand for direct air capture amounts to 34 TWh in 2040 and 47 TWh in 2050. Heat demand amounts to 137 TWh in 2040 and 187 TWh in 2050.

Instead of using DAC, the CO_2 could – at least partly – also be sourced from processes burning biomass. Our analysis of biogenic emissions shows that in general both sectors, electricity and heat supply and industry could contribute. It seems reasonable to assume that installations that have already installed a carbon capture system are particularly likely to provide carbon removals if possible. That would include – in our scenario – cement and lime production sites as well as large heat and power generation sites. Another possibility is the use of additional carbon capture systems in the paper industry, where large amounts of biomass are being processed. Of a total of 148 Mt biogenic emissions in the scenario, about 7 Mt come from non-metallic minerals, another 21 Mt can be found in the pulp and paper industry. High amounts are also available in the supply sector even with capture rates significantly below 100%.

Table 8: Overview of carbon demand and technical CDR

	EUTarget			EUSupreme		
	2030	**2040**	**2050**	**2030**	**2040**	**2050**
Non-fossil fuels gaseous and liquid – domestic production [TWh]	189	240	249	168	140	144
Demand for carbon-containing fuels and materials						
Non-fossil fuels gaseous and liquid – imports [TWh]	545	1170	1672	541	1107	1547

	EUTarget			EUSupreme		
Non-fossil fuels gaseous and liquid imports – carbon content [Mt CO_2]	187	245	388	182	232	344
Demand for CO_2 from domestic chemical sector [Mt CO_2]	4	54	121	9	74	101
Technical CDR [Mt CO_2]	---	---	28	---	---	---
Total CO_2 demand (domestic and imports)	191	299	537	191	306	445
Related electricity and heat demand						
Electricity demand for DAC [TWh]	88	138	248	88	142	206
- For domestic demand	2	25	69	4	34	47
- Contained in imports	86	113	179	84	107	159
Heat demand for DAC [TWh]	353	553	9893	353	566	823
- For domestic demand	7	100	276	17	137	187
- Contained in import	346	453	718	337	429	636

3.2 Sector results

3.2.1 Industry

Industrial production forms the backbone of modern economies, providing essential materials like steel, chemicals, and cement, as well as machinery and goods that drive infrastructure development, technological progress, and innovation. European industry is also important for economic stability and prosperity, contributing 20.5% to the EU's Gross Value Added (GVA)[26] and employing over 32 million people [27]. However, these contributions come with significant environmental costs. In 2022, the EU industry sector was responsible for 25% of the total final energy demand [28] and approximately 20% of the EU's total GHG emissions, corresponding to 684 Mt of CO_2 equivalent [29].

The European Union has set targets to reduce overall GHG emissions by 55% by 2030 compared to 1990 levels and to achieve climate neutrality by 2050. Central to achieving these targets is the decarbonization of the industrial sector. Supporting this effort are policy frameworks European Green Deal and the Fit for 55 package, which include measures like revisions to the EU Emissions Trading System (ETS) and the Carbon Border Adjustment Mechanism (CBAM). The necessity for a transition to sustainable and renewable energy sources has been further highlighted by the challenges related to energy dependency and increasing prices, as addressed by REPowerEU. Additional recent initiatives, such as the Figure 35Green Deal Industrial Plan and its accompanying Net Zero Industry Act and Critical Raw Materials Act reflect broader efforts to strengthen industrial innovation and support circular economy.

[26] Eurostat (2023): *National accounts and GD.* Available online

[27] Cedefop (2023). *Skills intelligence: Sector employment and occupations (2022, EU).* Available online

[28] Eurostat (2023). *Final energy consumption in industry – detailed statistics.* Available online

[29] European Environment Agency (EEA) (2023). *Greenhouse gas data viewer.* Available online

Decarbonizing the industrial sector requires a mix of transformative technologies and systemic changes to address the unique challenges posed by high-temperature processes and process-related emissions. Key strategies include electrification, hydrogen adoption, circular economy (CE), as well as Carbon Capture Utilization and Storage (CCUS). Electrification and hydrogen offer viable solutions for industrial heat, with electrification suitable to low- and medium-temperature processes and hydrogen for temperatures exceeding 500°C. CCUS can be an option for managing process-related emissions that are otherwise difficult to eliminate.in sectors like cement and petrochemicals. The success of these strategies relies heavily on the development of robust infrastructure. Furthermore, CE reduces the reliance on primary resources by extending product lifecycles, enhancing recycling and promoting reuse. However, CE requires systemic transformation of production and consumption models. These strategies will require redesigning entire production systems, which is capital-intensive and necessitates long-term planning. The scenarios explored in this analysis (EUBase, EUTarget, and EUSupreme) illustrate different levels of reliance on these strategies, highlighting trade-offs between technological innovation and the redesign of value chains for CE.

3.2.1.1 EUBase scenario

3.2.1.1.1 General description

The EUBase scenario provides a baseline for assessing the current European policy landscape, capturing existing measures at both EU and member state levels. However, it excludes some proposed or debated instruments, such as elements of the 'Fit for 55' package[30]. Technologically, the scenario assumes moderate electrification, supported by carbon pricing under the EU Emissions Trading System (ETS) and incentives for energy-efficient technologies, such as electric furnaces and industrial heat pumps for low- and medium-temperature processes. Targeted hydrogen deployment focuses on applications with high Technology Readiness Levels (TRL) and cost-effectiveness, particularly in iron and steel industrial clusters, aligning with the EU Hydrogen Strategy. Additionally, the scenario assumes ambitious improvements in energy efficiency, consistent with the Energy Efficiency Directive (EED).

3.2.1.1.2 Main assumptions[31]

Economic framework and production data

The economic forecasts (GDP and industrial gross value added) used in the EUBase scenario are defined in line with the most recent EU reference scenario (2020). An average annual growth rate in (gross) value added of around 1.6 % p.a. is assumed for the industry until 2030, afterwards, the growth rate declines to 0.8% p.a. The equipment goods industry (engineering) is projected to be growing at a steady higher pace compared to the energy-intensive basic industries. In addition, in the long run, a moderate decoupling of the value added and the physical production volumes in the basic industry is projected, consistent with the trends in the EU Reference Scenario.

CO_2 and energy carrier prices

The model FORECAST-Industry makes choices for fuels, investments, or energy efficiency measures largely **based on cost-competitiveness**. Therefore, a key exogenous input to the model is energy carrier prices, which include current taxes and levies for industrial users as well as CO_2 prices. The electricity and natural gas prices were updated based on the latest Eurostat

[30] Not included are for example the CBAM and the EU Taxonomy but also instruments such as the modernisation fund, as they were either not yet legally adopted, lacked sufficient data, or could not be consistently integrated into the modeling framework at the time of scenario development.

[31] Unless otherwise stated, the assumptions presented in this chapter are based on experts' opinions and modeling experience developed in close coordination with the project team.

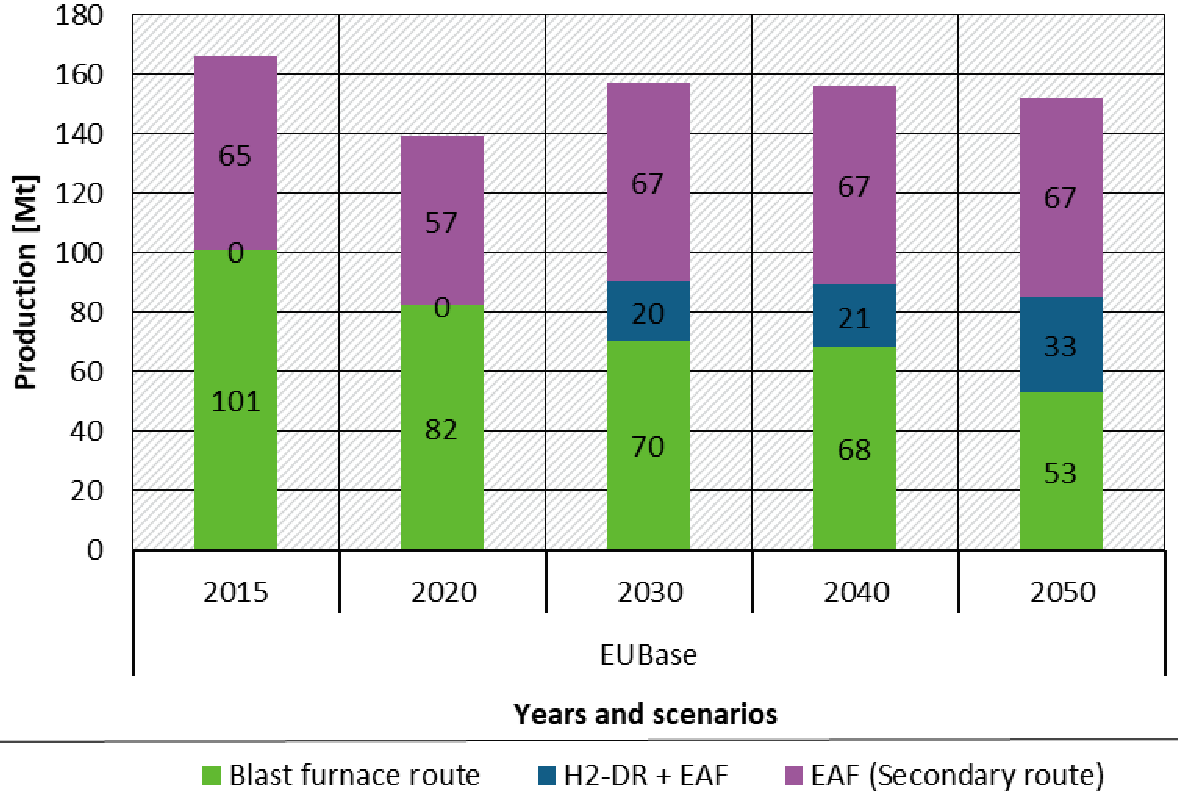
available statistics until 2022; the future evolution of international energy prices follows the trends (see section 2.4). Towards 2050, prices for most fossil energy carriers show an increasing trend, while the electricity price decreases starting from 2030.

The CO_2 price is an exogenous assumption, which affects the speed of fuel switching. Furthermore, we assume separate prices for the EU ETS I and the newly introduced ETS II based on the Reference scenario 2020 for more information, refer to chapter 2.4. EU ETS I is at around €109/tCO_2e in 2030, €141/tCO_2e in 2040 and €161/tCO_2e in 2050. The trajectory of the ETS II CO_2 price is assumed to be higher than the ETS I price. ETS II: around €95/tCO_2e in 2030, €171/tCO_2e in 2040 and €216/tCO_2e in 2050. This is needed to drive fuel switches towards low-carbon energy carriers in the less energy-intensive industries like machinery, food and others.

3.2.1.1.3 Sub-Sector specific assumptions

Iron and steel industry

Figure 32: EU 27 Crude steel production in EUBase by production route (2015-2050).



We assume a gradual recovery in steel production and demand from 2022 to 2025 following the reductions triggered by the COVID-19 pandemic. In the **EUBase,** the total crude steel production will decrease by around 9% by 2050, compared to 2015 levels, a reduction of approximately 13,7 Mt. The secondary steel production in the EU27 is assumed to gradually increase from 65,5 Mt in 2015 to approximately 68,5 Mt by 2050. The share of secondary steel in EUBase is projected to reach 45% by 2050 (see Figure 32).

In EUBase, the transformation of primary steel production is assumed to proceed gradually through the shift from blast furnaces-basic oxygen furnaces (BF-BOF) to direct reduction of iron using hydrogen (H2-DRI). By 2030, H2-DRI capacity is projected to reach approximately 20 million tons, increasing to 33 million tons by 2050 and accounting for 45% of primary steel production. The assumptions on material efficiency and secondary steelmaking represent a continuation of existing trends. The increased share of secondary steel production is driven by improved recycling of municipal waste and gradual advances in circular economy. In parallel, incremental gains in material efficiency due to product optimization are assumed to reduce the overall steel demand by 8% compared to 2015. These developments are aligned with current industrial commitments and current policy frameworks. An overview of the key assumptions for the iron and steel sector in the EUBase scenario is provided in Table 9.

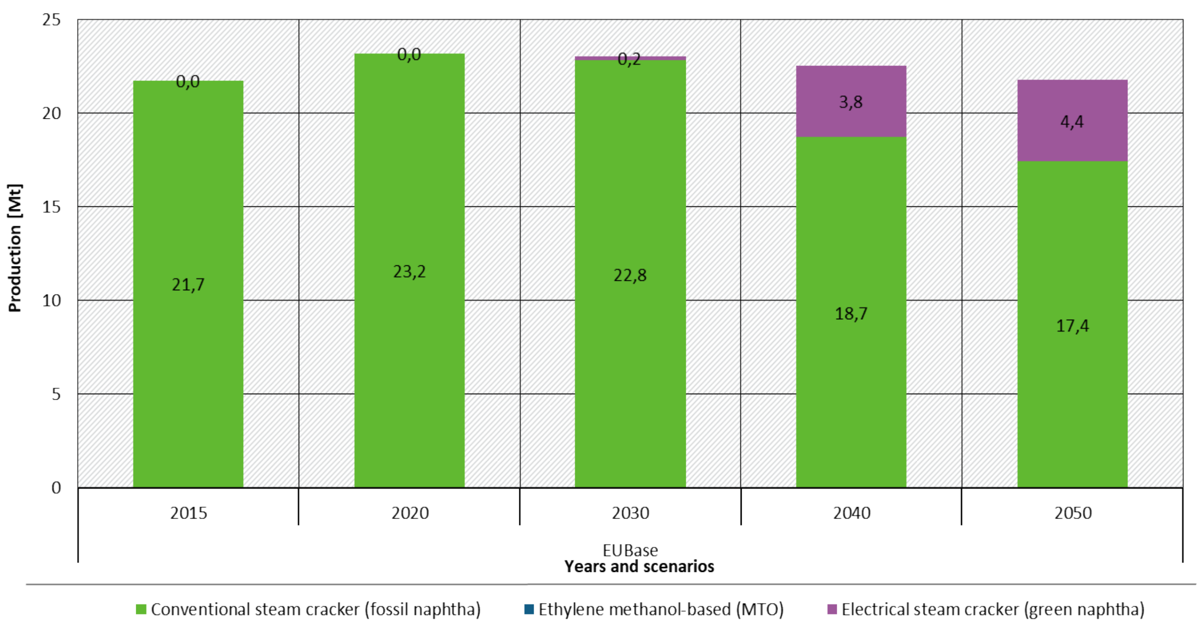
Table 9: Overview of the major assumptions for the iron and steel industry in 2050

Measure	EUBase
Material efficiency	More efficient steel use and substitution result in decreasing production by about 8% (13 Mt) compared to 2015
Circular economy	Increase secondary steel (EAF) share from 39% (65 Mt) by 2015 to 45% (69 Mt) by 2050
Process switch	19.5 Mt Direct Reduction route by 2030 and 33 Mt by 2050

(Petro-) Chemical industry

In the EUBase scenario, a slight increase in the recycling and more efficient use of plastic products leads to a slight decrease in High-Value Chemicals (HVCs) (e.g. ethylene) production of about 5% by 2050 compared to 2015 levels, a reduction of approximately 1 Mt. Whereas, ammonia (NH_3) production in the EUBase increases by around 8% by 2050 compared to 2015 (Figure 33).

Figure 33: EU 27 assumed High-Value Chemicals (Ethylene (C_2H_4), Olefine) production in EUBase by production route (2015-2050)



In the EUBase scenario, the conventional steam cracker (CSC) route remains the primary method for producing HVC. In this scenario, approximately 20% of ethylene production is assumed to shift to electrical steam crackers (ESC) and imported green naphtha. This scenario reflects a moderate adaptation, constrained by the cost difference between conventional and innovative sustainable production routes.

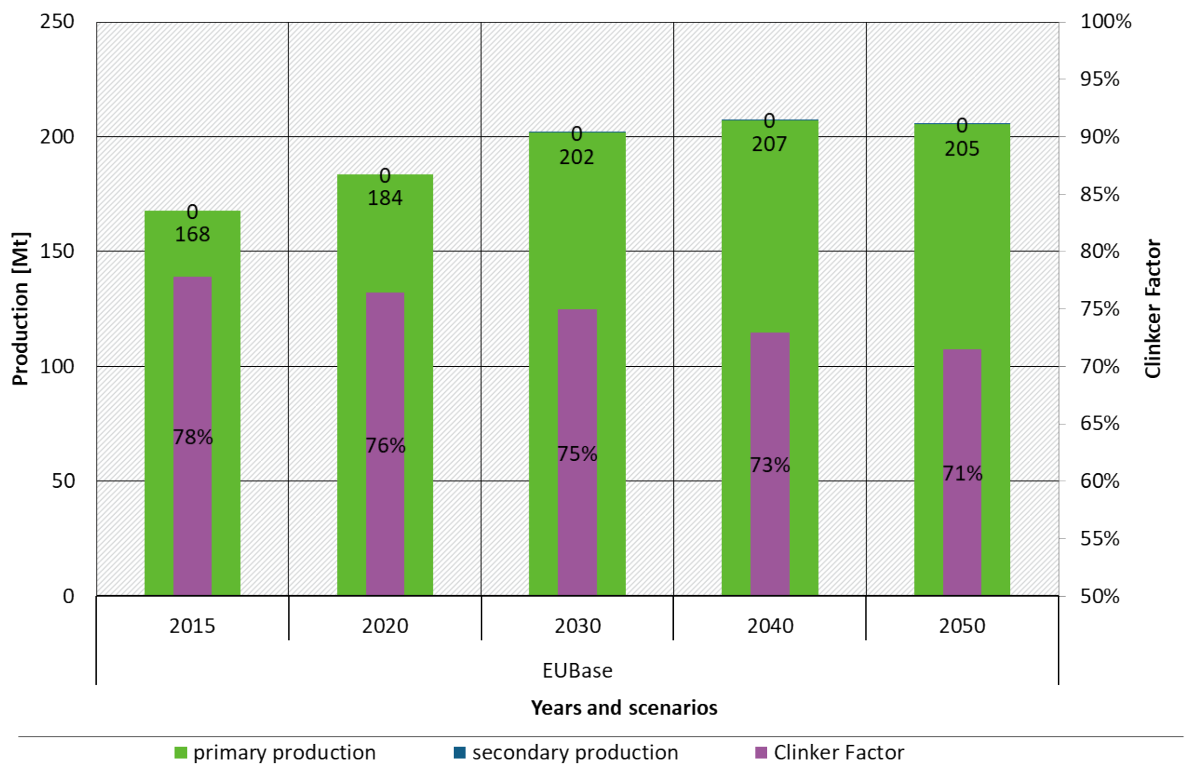
Table 10: Overview of the major assumption for the (petro-) chemical industry by 2050

Measure	EUBase
Material efficiency	A slow increase in plastic recycling
Process switch Ammonia	33% Feedstock H2 for ammonia
Process switch HVC	20% Electrical Steam cracker (ESC), No switch to the methanol-to-olefins (MtO)
Primary Feedstock	Fossil-based (Naphtha)
Feedstock availability	Crude oil import

Non-metallic minerals industry

In the EUBase scenario, cement production increases significantly (by approximately 30 Mt), leading to a total output of 205 Mt by 2050. This trend aligns with the macroeconomic framework data (GVA), which assumes a Compound Annual Growth Rate (CAGR) for non-metallic minerals of 2.4% during this period, however, annual growth rates are higher in the early years and decline toward 2050, (Figure 34).

Figure 34: EU 27 cement production by production route and scenario (2015-2050)



Around two-thirds of emissions in cement production are process-related and originate directly from clinker production, making the reduction of the clinker share a key mitigation strategy. Although there are already cement types with a significantly lower clinker share (e.g. blast furnace cement with as little as 19% clinker), their future application is limited. On the one hand, the availability of established clinker substitutes such as blast furnace slag or fly ash is expected to decline due to structural changes in the steel and power sectors. On the other hand, low-clinker cement types often face limitations in technical performance and structural applications (e.g. due to corrosion risk). While some global scenarios assume a clinker share as low as 0.6, this is strongly dependent on the large-scale availability of alternative materials such as calcined clays. Consequently, we assume a moderate reduction in the clinker share from 0.77 in 2015 to 0.71 by 2050 (147 Mt of clinker) in the EUBase scenario.

Secondary production routes, such as alternative binders and recycling of construction materials are not included in the EUBase scenario due to their currently limited role in practice, the absence of clear industrial implementation plans, and the high avoidance costs associated with these production routes. Instead, current research and development efforts are primarily focused on enabling Carbon Capture and Storage (CCS). In this scenario, CCS deployment remains limited to selected countries and industrial sites with high CCS potentials or made explicit target announcements. The future success of these technologies will depend on both technological progress and enabling political, regulatory, and societal conditions.

Table 11: Overview of the major assumption for the cement and lime industry by 2050

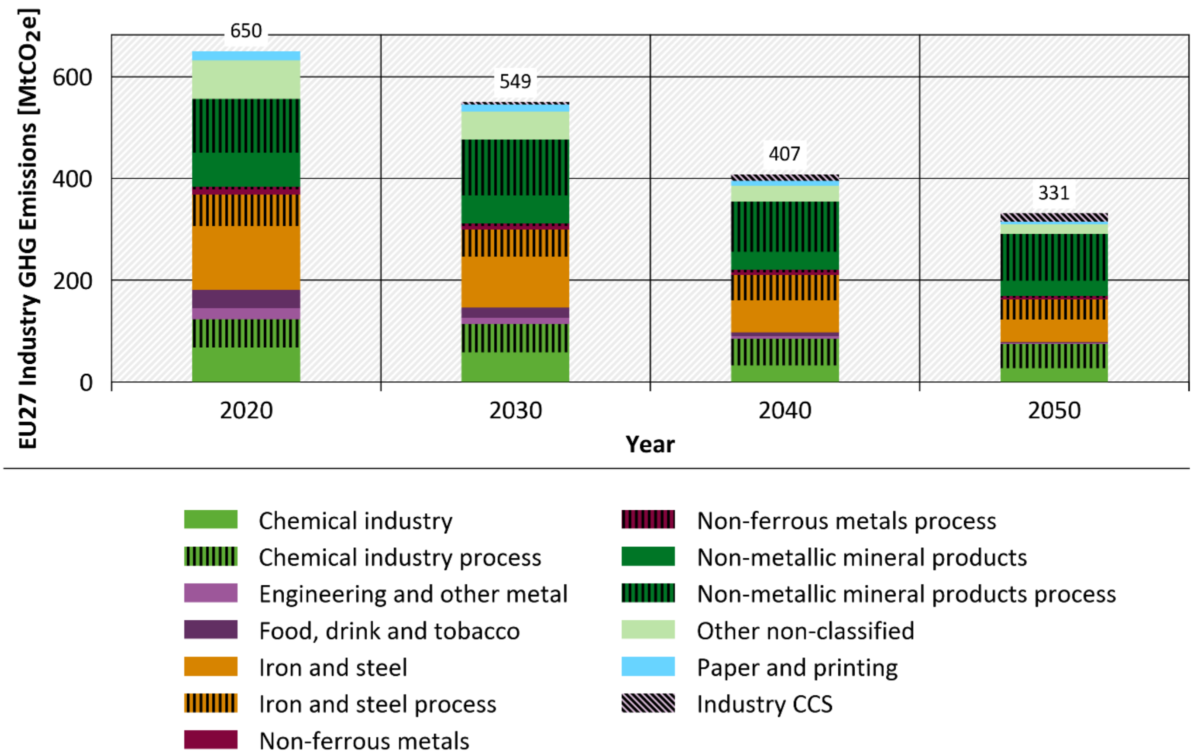
Measure	EUBase
Material efficiency	Increase by 18% in total cement production compared to 2018
Clinker Factor	Decrease in the clinker share from 0.77 in 2015 to 0.71 by 2050
Process switch	No low-carbon types of cement
CCS	CO_2 capture at limited sites

3.2.1.1.4 Results

The EUBase scenario fails to meet the 2050 GHG emissions reduction targets, achieving a 54% by 2030 and 73% reduction by 2050 compared to the 1990 levels (Figure 35). By 2050, process-related GHG emissions account for about 65% of the remaining 329 $MtCO_2eq$ emissions, while energy-related emissions decline more sharply due to electrification and efficiency improvements. Around 50% of the remaining process emissions originate from the non-metallic minerals sector, mainly from clinker and lime production.

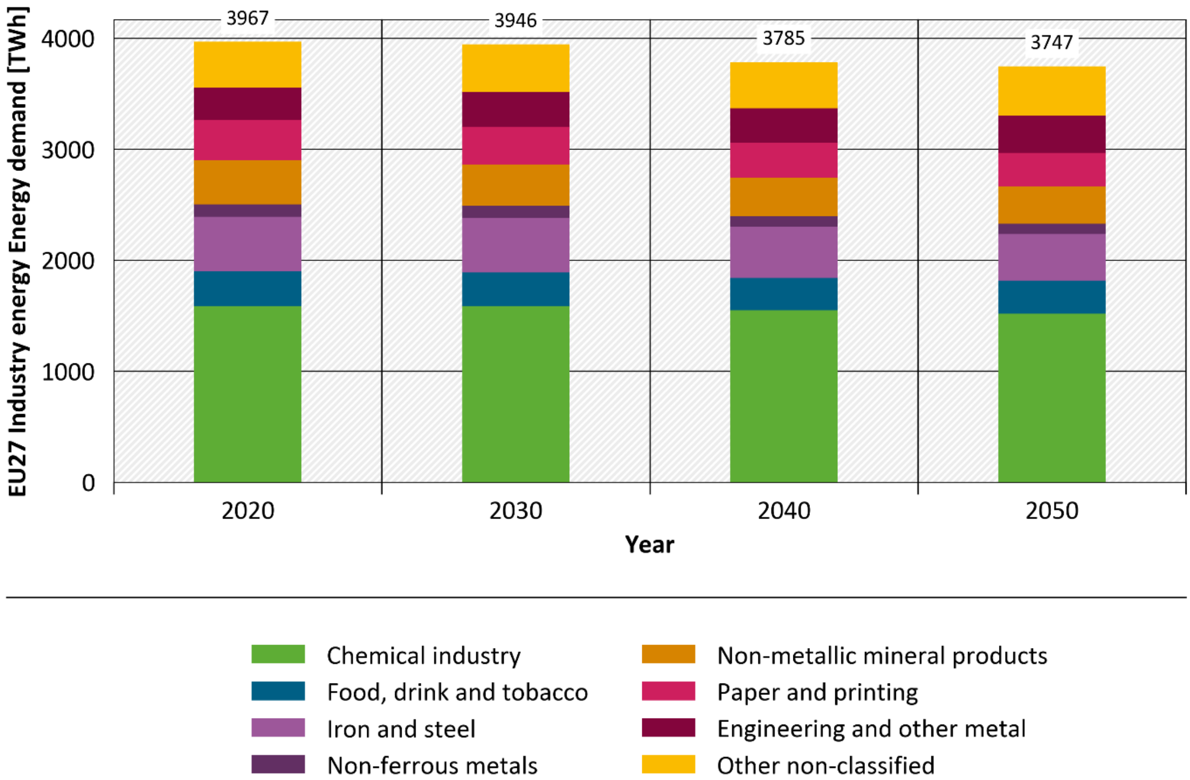
Process-related GHG emissions account for about 65% of the remaining 329 $MtCO_2$ eq GHG emissions by 2050. Notably, 50% of the process-related GHG emissions by 2050 originate from non-metallic minerals such as cement clinker, and lime (Figure 35).

Figure 35: Overview of the development of total EU 27 industry GHG emissions by sources in the industry sector (incl. energy-related, process-related emissions and CO_2 sequestration via CCS)



Source: own illustration based on Eurostat and own calculations Fraunhofer ISI

Figure 36: Overview of the development of total EU 27 industry total energy demand by sub-sector in the industry sector in EUBase scenario (including final energy and feedstock use)



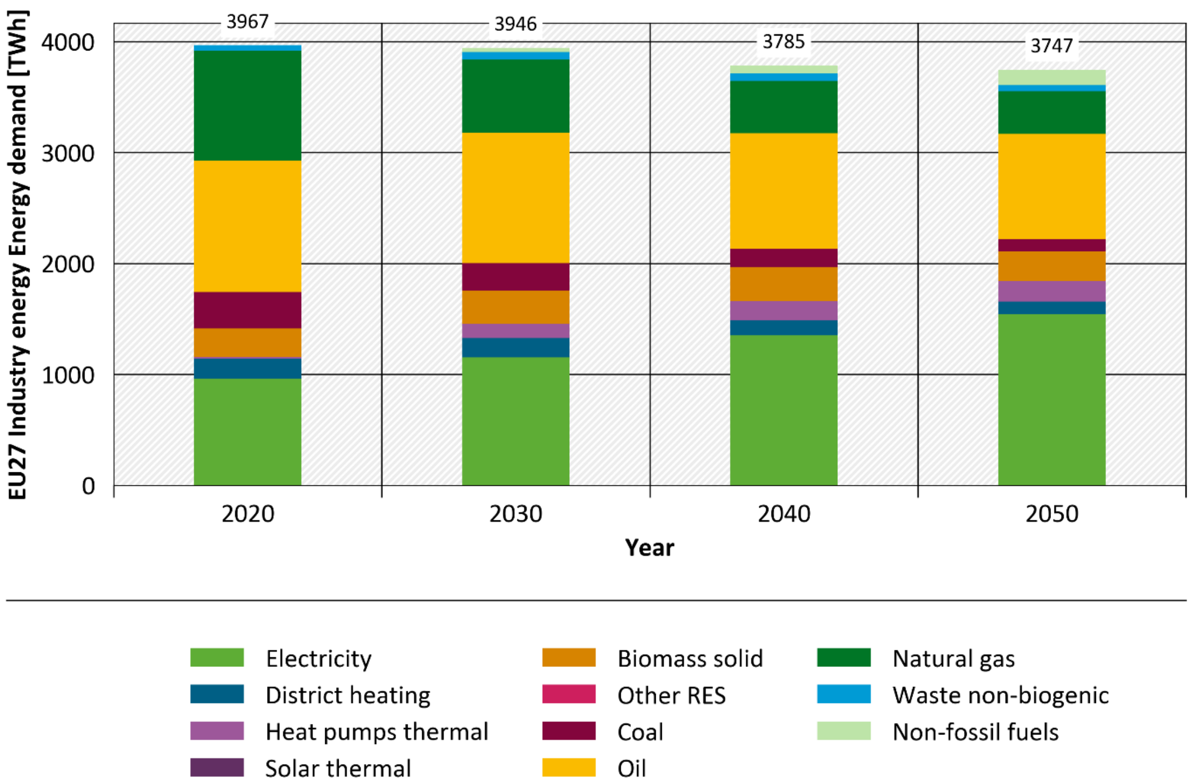
Source: own illustration based on Eurostat and own calculations Fraunhofer ISI

In this report, the total energy demand (TED) for the industry sector includes the final energy demand (FED) as defined by Eurostat, plus the demand for energy carriers used as raw materials (feedstock) in the industry. In the calibration year 2018[32] the TED for the EU27 industry was 4,056 TWh. The chemical industry had the highest energy demand, accounting for 39% of the TED, followed by the iron and steel industry (14%) and the non-metallic mineral products sector (10%).Figure 36 Figure shows the development of the TED for the EU27 industry sub-sectors in the EUBase scenario.

The TED steadily decreases from 3,967 TWh in 2020 to 3,747 TWh by 2050, driven by efficiency improvements, the adoption of advanced technologies, and a slight reduction in primary production compared to 2018 levels. Among energy-intensive industries, the iron and steel sector shows the most significant and consistent reduction, declining from 561 TWh in 2018 to 418 TWh by 2050. This is primarily attributed to the increased share of secondary steel production and more efficient steel usage in downstream sectors. In contrast, the chemical industry shows only a small decrease, with a 4% reduction by 2050 compared to 2018. Unlike most sectors, engineering and other non-classified industries TED increases by 2050, which is mainly driven by higher projected growth in GVA.

[32] The year 2018 is used as the calibration year to ensure that the data provides a more representative baseline for energy demand and emissions in the industry, unaffected by the disruptions caused by the COVID-19 pandemic.

Figure 37: Overview of the resulting EU27 total energy demand in EUBase scenario for the industry sector by energy carrier



Source: own illustration based on Eurostat and own calculations Fraunhofer ISI

In the EUBase scenario, the electricity demand increases from 958 TWh in 2018 to 1,544 TWh by 2050 (Figure 37) due to the electrification of industrial process heat (see Figure 36). Ambient heat [33], increases to 183 TWh by 2050, driven by the adoption of heat pump technologies, which are efficient and cost-effective across multiple industrial applications in low-temperature process heat applications e.g. in the food, chemical and paper industries.

Hydrogen[34] becomes a significant energy carrier starting in 2030, with (non-fossil) hydrogen demand increasing from ~40 TWh to ~140 TWh by 2050.This increase is primarily driven by its use in H2-DRI for iron and steel production (~75 TWh) and ammonia synthesis (~ 65 TWh).

In EUBase scenario fossil fuel consumption declines significantly but remains important for specific applications. Natural gas usage decreases from 1,042 TWh in 2018 to 383 TWh by 2050. The continued use of natural gas in the EUBase scenario is due to the comparatively high CO_2 abatement costs of available low-carbon alternatives, which limits their uptake in the absence of stronger incentives. Coal demand decreases from 360 TWh to 112 TWh, mainly limited to iron and steel production. Other fossil fuels, predominantly naphtha, decreased from 651 TWh to 481 TWh, due to efficiency improvements and partial substitution. In the EUBase scenario, the transition to low-carbon technologies is limited, resulting in continued reliance on fossil energy carriers. Natural gas and naphtha remain prominent, particularly in the chemical sector, due to high CO_2 abatement costs and the absence of targeted policy interventions. As a result, the scenario falls short of achieving the required emission reductions for climate neutrality by 2050.

[33] Heat pumps thermal in Figure 37

[34] Non-fossil in Figure 37

3.2.1.2 EUTarget and EUSupreme scenarios

3.2.1.2.1 General description

The EUTarget and EUSupreme scenarios outline a pathway that achieves the long-term goal of at least 95% GHG reduction by 2050 compared to 1990 for the industry sector. Both scenarios assume a strong expansion of policy support and regulation to meet this target. In terms of the technological outlook for energy efficiency, the scenarios leverage the Best Available Technology (BAT) even with a long payback time. Furthermore, we assume a strong diffusion of innovative technologies with a Technology Readiness Level (TRL) above 4. This implies that technical challenges have been overcome, and technologies are ready for scaling up and deployment.

The EUTarget scenario primarily focuses on technology-driven pathways (technological development and efficiency improvement) to achieve GHG emissions reductions. Drawing on a relatively balanced mix of mitigation strategies including energy and material efficiency, electrification, hydrogen and non-fossil gas such as PtX products and bio-based gases as well as CCS. The EUSupreme scenario extends beyond technical solutions to embrace a comprehensive expansion of sustainable practices. The scenario assumes that the European industry development is oriented toward long-term sustainable well-being rather than the traditional growth paradigm driven by overproduction and consumption. This reorientation places the industry at the center of transformative change, requiring a shift from linear production models to systems that is built around a circular economic model focusing on resource efficiency and reducing dependencies on finite materials.

3.2.1.2.2 Main assumptions

Economic framework and production data

The economic forecasts (GDP and industrial gross value added) used in the **EUTarget scenarios** are defined in line with the most recent EU reference scenario (2020). An average annual growth rate in (gross) value added of around 1.6 % p.a. is assumed for the industry until 2030, afterwards, the growth rate declines to 0.8% p.a. The equipment goods industry (engineering) is projected to be growing at a steadily higher pace compared to the energy-intensive basic industries. In addition, in the long run, a moderate decoupling of the value added and the physical production volumes in the basic industry is projected.

The **EUSupreme scenario** uses the same economic framework, however, the scenario assumes a fundamental shift in how economic growth is achieved. The EUSupreme scenario assumes a faster decoupling between value-added and physical production for energy-intensive industries. Industrial growth focuses on delivering resource-efficient, longer-lasting solutions rather than increasing material throughput. This means optimizing industrial processes to minimize resource input, supported by enhanced recycling and reuse of materials across production cycles. The shift is further driven by the transition to service-oriented models, such as repair, reuse, and remanufacturing (based on (European Commission: Directorate-General for Climate Action, Fraunhofer ISI, ICF, Herbst, A., Langkau, S. et al. 2024)).

For example:

- Steel Industry: advanced alloy sorting and increased use of post-consumer scraps improve recycling efficiency while extending vehicle lifespans by 4–6 years and reusing structural steel lower overall demand. Lightweight product designs and better space utilization further enhance material efficiency, complemented by the substitution of steel with wood in specific construction applications.

- Cement Industry: reducing cement use through optimized material mixes and alternative binders, extending building lifetimes, and improving floor space utilization to reduce construction demand. Increased adoption of wood in housing and small office buildings replaces concrete in some applications.
- Chemicals Sector: Adopts waste-based and biomass feedstocks, reducing dependency on fossil-derived raw materials. Reducing single-use plastics with measures like bans on single-use water bottles and a transition to reusable or recyclable packaging formats

CO_2 and energy carrier prices

In the EUTarget scenario, the CO_2 price for the EU ETS I is at around 110€/tCO_2-eq in 2030, 340€/tCO_2-eq in 2040 and 390€/tCO_2-eq in 2050. The EUSupreme uses different CO_2 prices for the ETS I: around 114€/tCO_2-eq in 2030, 164€/tCO_2-eq in 2040 and 305€/tCO_2-eq in 2050. Furthermore, we assume in addition to the ETS I CO_2 price a CO_2 price for the ETS II industry sector. The trajectory of the ETS II CO_2 price is assumed to be similar in both scenarios and is higher than the EU ETS price. ETS II: around 300€/tCO_2-eq in 2030, 340€/tCO_2-eq in 2040 and 500€/tCO_2-eq in 2050. Although these high prices may not be strictly necessary for achieving fuel switching in the industrial sector, they are aligned with the marginal abatement costs (MAC) in other sectors, such as transport (on general assumptions see also 2.4).

Table 12: Overview of the major technology assumptions for the industry

Measure	Scenario assumptions		
	EUBase	**EUTarget**	**EUSupreme**
GHG target	55% GHG reduction target by 2030	At least 55% by 2030 and net zero industry by 2050	
Energy Efficiency	A continuation of current trends	Ambitious progress (Broad diffusion of best available technology in terms of energy efficiency (even with long payback time)	
Process innovation	No fundamental break-through; some technologies at high TRL above (6-7) will become available soon (e.g. H2- DRI steelmaking)	Diffusion of innovative technologies with a Technology Readiness Level (TRL) above 4	
Material strategies	A continuation of current trends in recycling		Ambitious progress in circularity and material efficiency measures
CCS	Limited carbon capture to cement and lime plants only in countries with announced plans or high potentials; no CCS	Carbon capture at most Cement and lime plants by 2050 (no climate neutral technical alternative with TRL higher than 4 available)	No CCS
Fuel switch	Driven by costs and prices	Prioritize direct use of electricity over indirect use	

3.2.1.2.3 Sub-Sector-specific assumptions

Iron and steel industry

Production Trends:

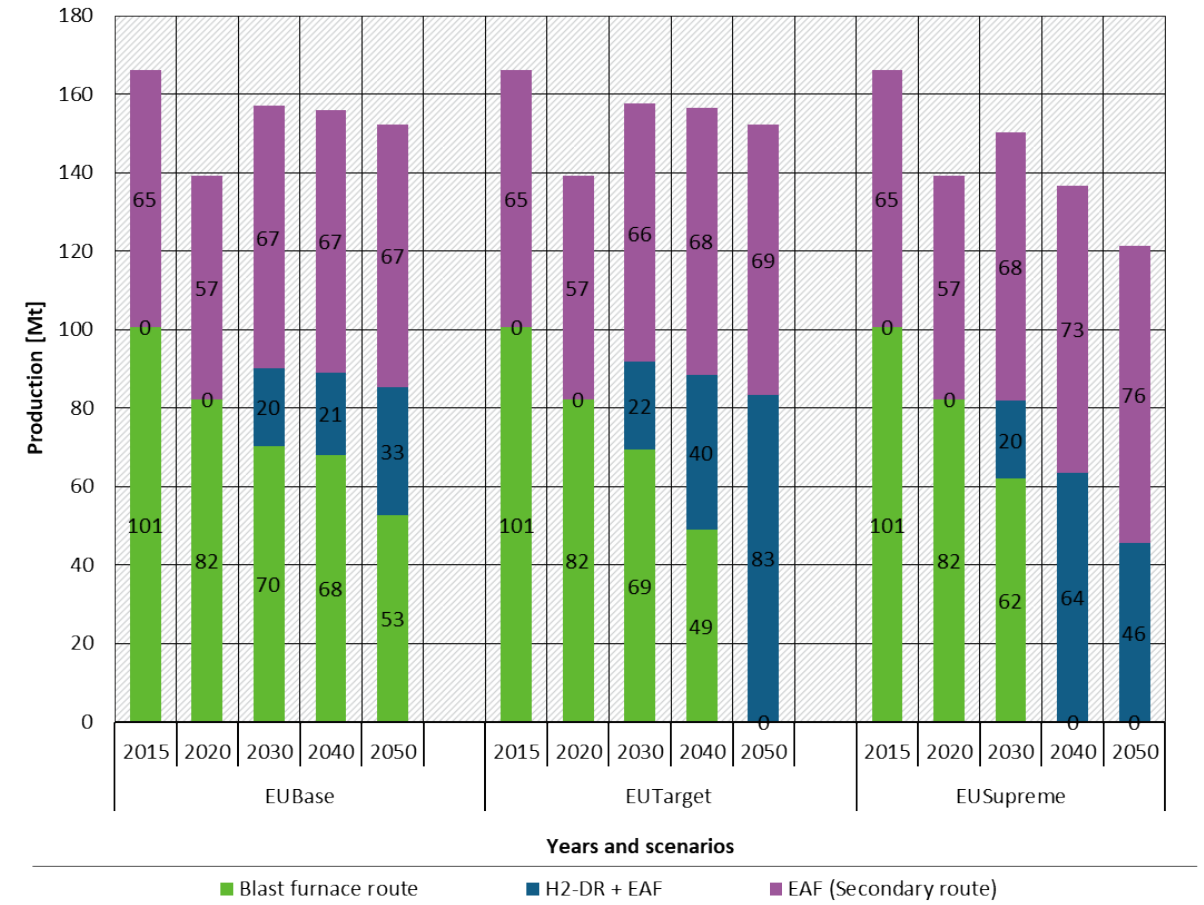
A gradual recovery in steel production and demand is assumed from 2022 to 2025, following the reductions triggered by the COVID-19 pandemic. In 2015, total crude steel production was 165 Mt. In the EUTarget scenario, this is projected to decrease by approximately 8% to 142 Mt by 2050 compared to 2015. Due to incremental gains in material efficiency due to product optimization. The EUSupreme scenario assumes a more significant reduction, with crude steel production decreasing by 20% compared to the EUTarget scenario, declining further to 120 Mt by 2050 (see Figure 38). This significant reduction in crude steel production and consumption is driven by a shift towards higher circularity and more efficient use of steel and steel products along the value chains, behavioural changes and material substitution.

Shift to secondary production routes:

In the EUTarget, the secondary steel production via EAF in the EU27 is assumed to gradually increase from 65.5 Mt in 2015 to approximately 68.5 Mt by 2050 (see Figure 38). The share of (EAF) secondary steel in EUTarget scenarios is projected to reach 45% by 2050 compared to 39% in 2015. The EUSupreme scenario builds on this trend and envisions a more pronounced shift. By 2050, secondary steel production reaches 75.5 Mt, representing a 10% increase relative to EUTarget. The share of (EAF) secondary steel increases from 39% to 63% by 2050. This is mainly driven by enhanced recycling capabilities, including the adoption of more advanced sorting techniques, particularly alloy sorting of post-consumer scraps. Material strategies beyond secondary production:

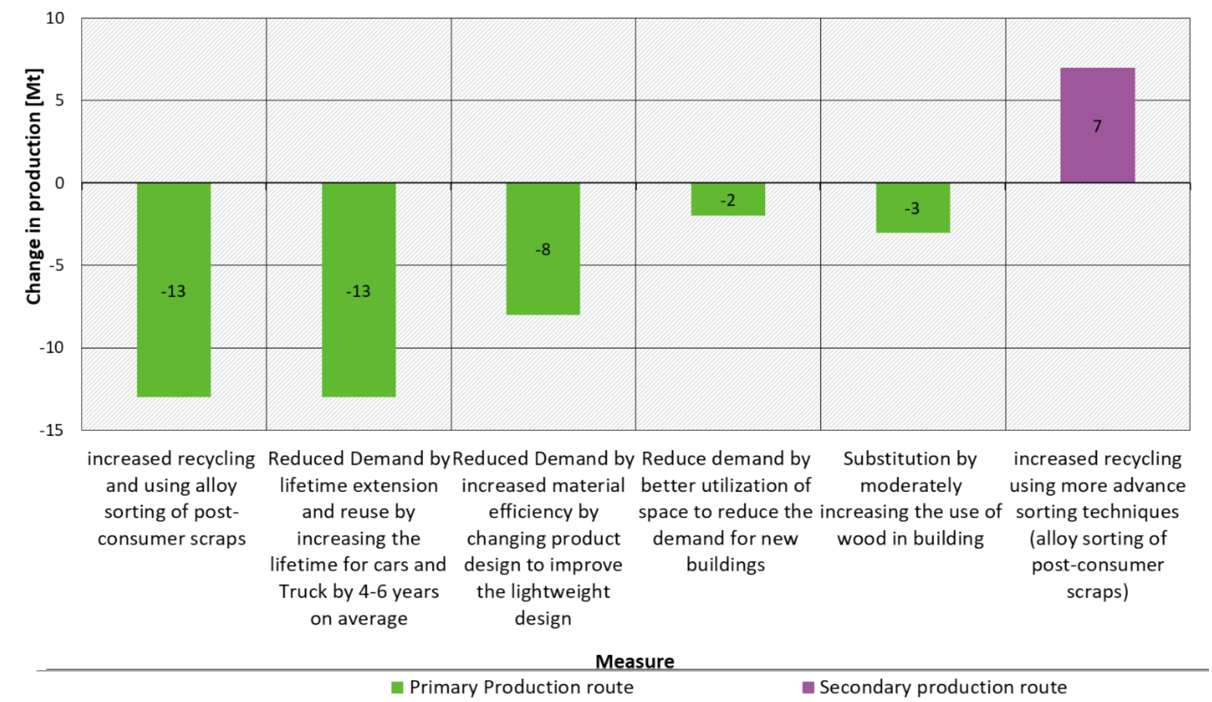
Additional material strategies, i.e. service-oriented models and changes in consumption patterns, are considered in EUSupreme. Lightweight and material-efficient design are expected to decrease steel demand by up to 8 Mt in 2050 based on (Rostek et al. 2022)). Additional measures in the two end-use sectors consuming the majority of steel, automotive and building construction, are assumed to reduce steel production by up to 18 Mt in 2050. In detail, this is achieved by extending the lifetime of cars and trucks, increased the utilization of buildings and timber construction (based on (Xavier Le Den et al. 2020). The impacts of the individual strategies are depicted in Figure 39.

Figure 38: EU 27 crude steel production by production route and scenario (2015-2050)



Source: own calculations by Fraunhofer ISI

Figure 39: Production of crude steel by measure in the EUSupreme scenario compared to EUBase and EUTarget scenarios (in Mt, by 2050)*



* Negative values indicate lower production in EUSupreme while positive values indicate an increase

Source: own calculations by Fraunhofer ISI

Technological and Process Innovations:

In EUTarget and EUSupreme scenarios, H2-DRI will fully replace BF-BOF steel production by 2050. However, due to the reduction in overall crude steel production in the EUSupreme scenario, the H2-DRI capacity is projected to be 45 Mt compared to 84 Mt in EUTarget.

Table 13: Overview of the major assumption for the iron and steel industry

Measure	Scenario assumptions		
	EUBase	EUTarget	EUSupreme
Material efficiency and Circular economy	More efficient steel use and substitution result in decreasing production by about 8% compared to 2015 (13 Mt)		Deeper reduction in total crude steel production compared to EUBase driven by material efficiency comprehensive changes in value chains and consumption patterns (43% reduction in BOF Crude steel production compared to Ref -39 Mt from (83,9 Mt to 45,3 Mt)
Share of secondary route	Increase EAF share from 39% (65 Mt) by 2015 to 45% (67 Mt) by 2050 I		Increase in the EAF from 39% to 62% by
Process switch to H2-DRI route	19.5 Mt by 2030 and 33 Mt by 2050	100% H2-DRI share by 2050 (67 Mt)	Shift toward H2-DRI route around 20 Mt by 2030; 100% H-DRI share by 2050 (~45 Mt)

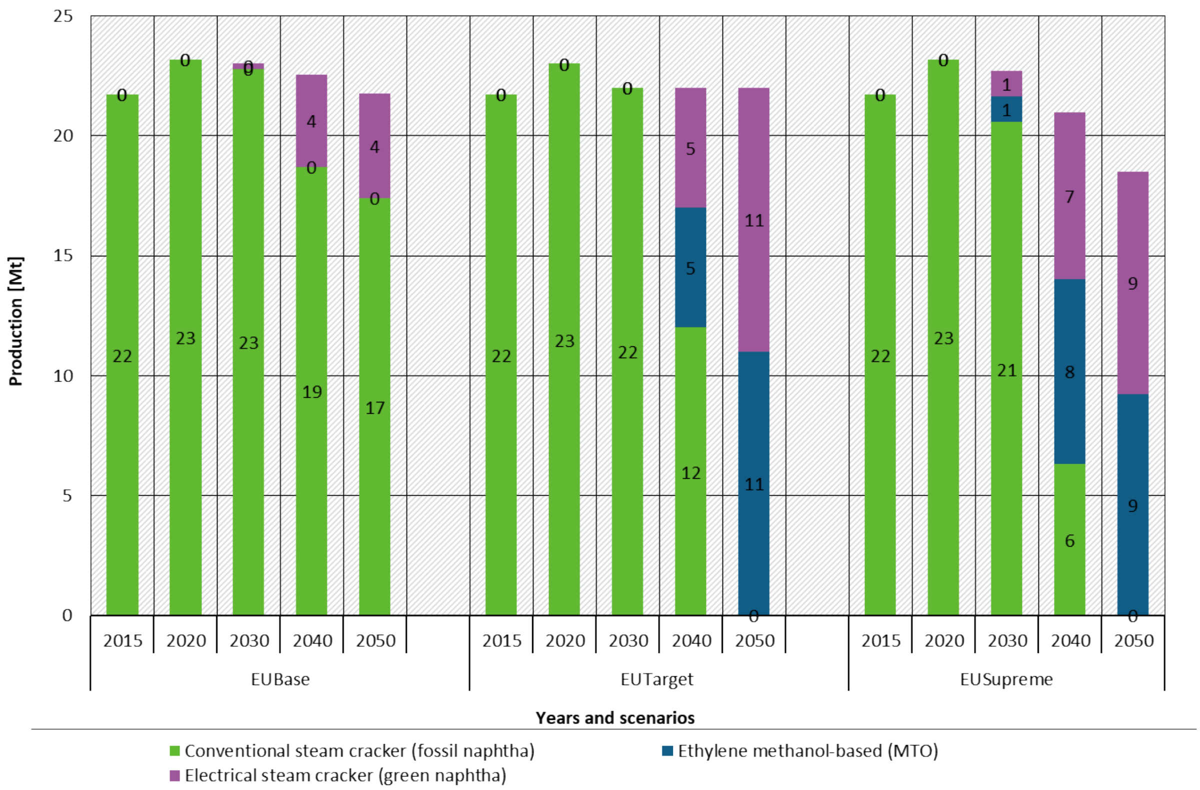
(Petro-) Chemical industry

Production Trends (Material Efficiency and Circular Economy):

In the EUTarget scenario a slight increase in the recycling of High-Value Chemicals (HVCs), leads to a slight decrease of about 5% by 2050 compared to 2015 levels. Whereas ammonia (NH_3) production in the EUTarget increases by around 8% by 2050 compared to 2015. This increase is mainly driven by fertilizer demand and the sub-sector GVA projections.

The **EUSupreme scenario** adopts a more ambitious approach, significantly increasing mechanical and chemical plastics recycling, redesigning packaging, and replacing single-use plastics (SYSTEMIQ 2022). This results in a substantial 17% reduction in HVC production by 2050 compared to the EUTarget scenarios, from 22 Mt to 18 Mt (see Figure 40). Furthermore, the EUSupreme scenario projects a significant reduction in ammonia production due to a lower demand for fertilizers in agriculture, driven by reduced consumption and more sustainable farming. By 2050 ammonia production decreases by 20% compared to 2018 levels, decreasing from 18 Mt to 14 Mt.

Figure 40: EU 27 assumed High-value Chemicals (Ethylene (C_2H_4), Olefine) production by production route and scenario (2015-2050).



Source: own calculations by Fraunhofer ISI

Technological and Process Innovations:

The EUTarget scenario assumes an ambitious technological transition towards the methanol-to-olefins (MtO) route, where methanol derived from hydrogen and captured CO_2 is synthesized into olefins. The HVC production will shift completely to the MtO route by 2050. While, in the EUSupreme scenario, 50% of HVC production will adopt the MtO route, and the remainder will utilize ESC green naphtha. Given the CCS is not used and biomass only for energetic purposes in this scenario, the EUSupreme scenario utilizes biomass through gasification to produce methanol and/or naphtha.

Table 14: Overview of the major assumption for the (petro-) chemical industry by 2050

Measure	Scenario assumptions		
	EUBase	**EUTarget**	**EUSupreme**
Material efficiency and Circular economy	A slow increase in plastic recycling		Ambitious increase in plastics recycling along entire value chain and new consumption models; reduces demand for feedstocks by 15% by 2050 compared to 2015
Process switch Ammonia	33% feedstock H2 for ammonia	100 % Feedstock H2 for ammonia	100 % Feedstock H2 for ammonia
Process switch HVC	20% electrical steam cracker	~50% ESC, ~50% MtO (and Methanol to aromatics (MtA))	

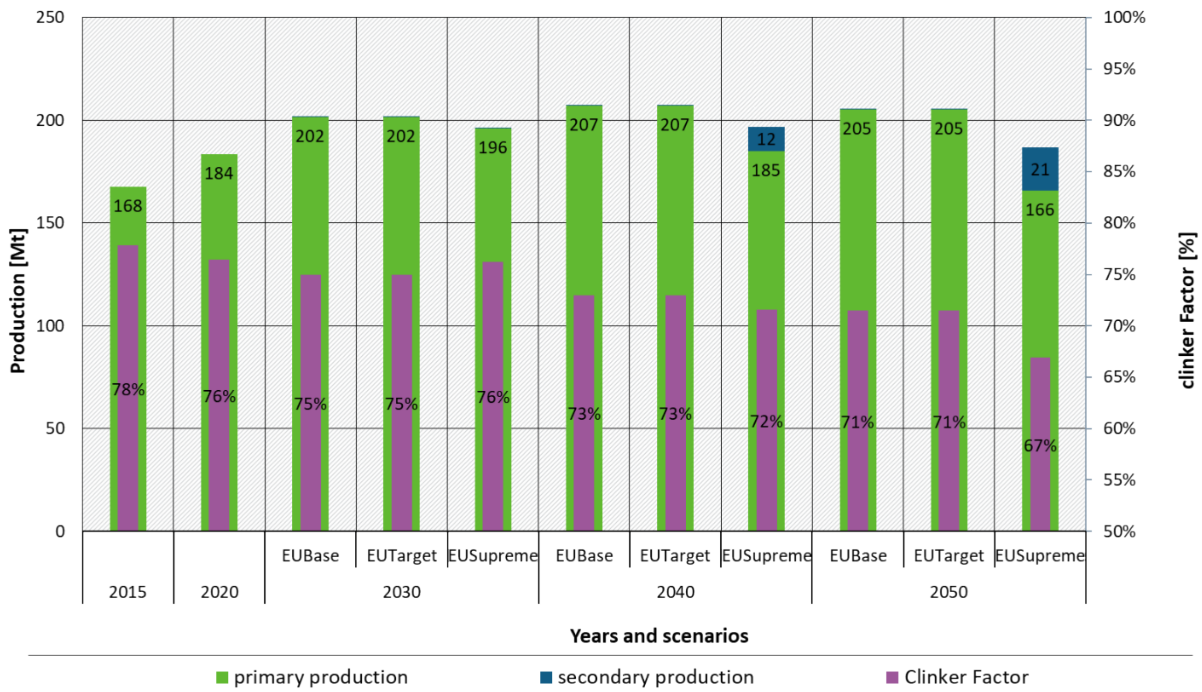
Measure	Scenario assumptions		
	EUBase	**EUTarget**	**EUSupreme**
	(ESC); no switch to MtO		
Primary Feedstock	Fossil-based (Naphtha)	Biomass + H2 + CO_2 (CCS and DACCS)	Biomass (higher share than EUTarget) + H2 + CO_2 + Plastic waste
Feedstock availability	Import	Biomass + import	Leverages EU biomass potential, assuming no energetic use of biomass.

Non-metallic minerals industry (Cement)

Production Trends (Material Efficiency and Circular Economy):

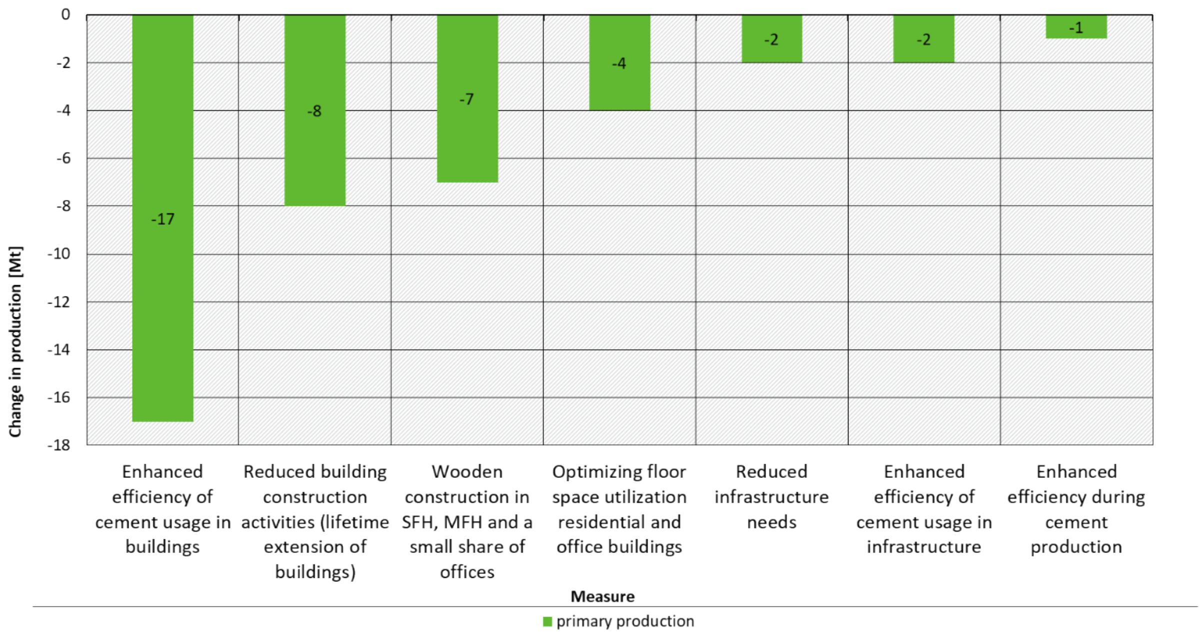
In the EUTarget scenario, the cement production increases significantly (by approximately 30 Mt), leading to a total output of 205 Mt by 2050. This trend aligns with the growing building stock and macroeconomic framework data (GVA) , which assumes a Compound Annual Growth Rate (CAGR) for Non-metallic minerals of 2.4% during this period (Lotz et al. 2024a). The EUSupreme scenario projects a significant reduction of 20% (-39,1 Mt) by 2050, compared to the EUTarget scenario. This decrease is primarily driven by material-efficient design and construction of buildings, the increased utilization of buildings, the switch to timber as construction material and decreases in infrastructure demand due to changes in the transport sector, e.g. increase public transport and less private transport (Lotz et al. 2024b). The assumed production activities across all scenarios are shown in Figure 41, while the significant drivers behind the reduction in EUSupreme are shown in Figure 42 (Lotz et al. 2025).

Figure 41: EU 27 cement production by production route and scenario (2015-2050)



Source: own calculations by Fraunhofer ISI

Figure 42: Assumed change in cement production by 2050 compared to 2015 in EUSupreme detailed by measure



Source: own calculations by Fraunhofer ISI

Technological and Process Innovations:

In the EUTarget scenarios, we assume a minor reduction in the clinker share, from 0.77 in 2015 to 0.71 by 2050 similar to the EUBase scenario. In this scenario, CCS is assumed to be deployed across nearly all cement plants, allowing remaining process-related emissions to be captured directly. This reduces the pressure to pursue further reductions in clinker intensity.

In contrast, the EUSupreme scenario does not assume any CCS deployment. Instead, it focuses on more different emission mitigation measures. Accordingly, the clinker share is reduced more significantly to 0.65 by 2050. Accordingly, the EUSupreme scenario assumes a more significant reduction in clinker share to 0.65. Although technically, it would be possible to lower the clinker share further, the availability of the clinker substitutes as well as the technical applicability restrict more substantial reductions. Additionally, in the EUSupreme scenario, low-carbon types of cement (alternative binder and recycled) are projected to account for around 10% of the production by 2050. This share reflects the potential role that low-carbon cement types can play in further lowering process emissions in the absence of CCS, consistent with the broader transformation pathway assumed in the EUSupreme scenario.

Table 15: Overview of the major assumptions for the cement and lime industry by 2050

Measure	Scenario assumptions		
	EUBase	EUTarget	EUSupreme
Material efficiency and Circular economy	Increase by 22% in total cement production compared to 2015		9 % lower in primary cement production by 2050 compared to EUBase (-19 Mt).
Clinker Factor	Decrease in the clinker share from 0.77 in 2015 to 0.71 by 2050		Decrease in the clinker share from 0.77 by 2015 to 0.67 by 2050.

Measure	Scenario assumptions		
	EUBase	EUTarget	EUSupreme
Process switch	No low-carbon types of cement		low-carbon types of cement enter the market and substitute around 10% by 2050
CCS	CO_2 capture at limited cement sites	CO_2 capture at most cement and lime plants by 2050	No CCS

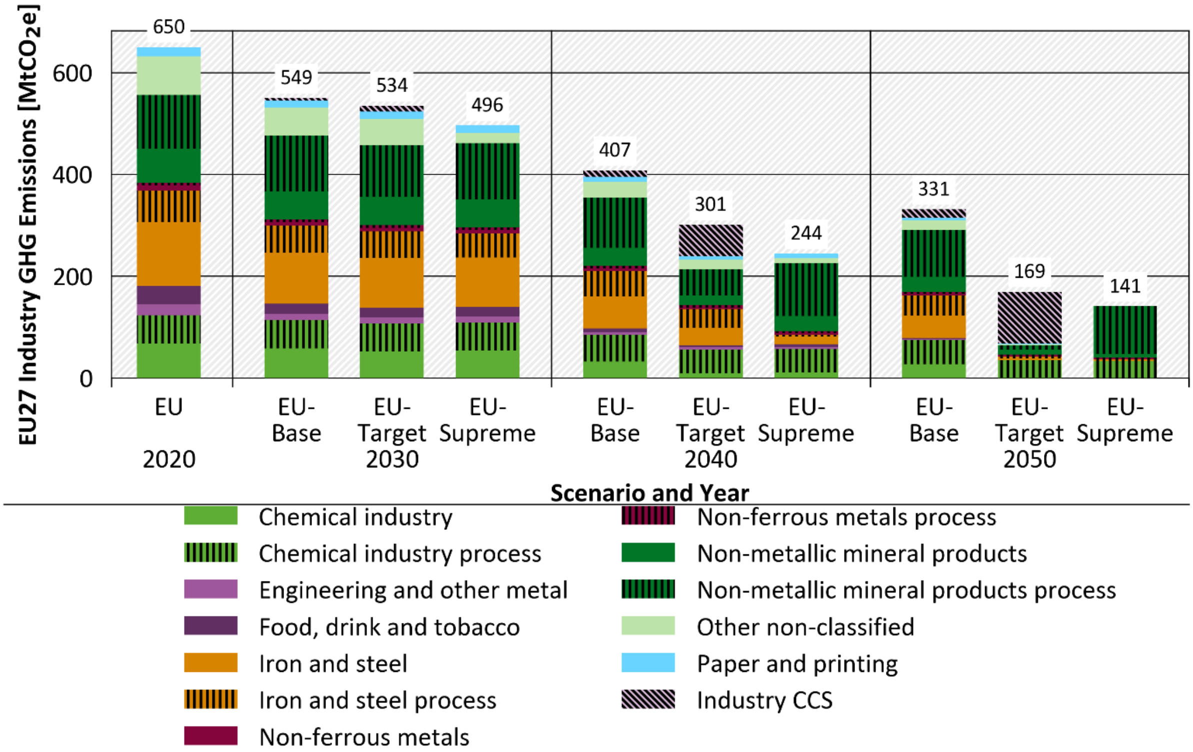
3.2.1.2.4 Results

In the EUTarget scenario, the GHG emissions reduction targets are achieved, with a 55% reduction by 2030 and a 93%[35] reduction by 2050 compared to 1990. This reduction is broadly consistent with commonly accepted definitions of a climate-neutral industry, which account for the fact that certain point-source emissions, particularly from industrial processes, are technically difficult to eliminate and may need to be compensated in other sectors. By 2050, total residual emissions are 179 $MtCO_2eq$, of which 102 $MtCO_2eq$ are captured using CCS technologies. The remaining 77 $MtCO_2eq$, representing the final 7% of 1990 emissions, that would need to be compensated through negative emissions or offsets from other sectors to achieve full climate neutrality. The remaining process-related emissions arise from various smaller sources, including ceramics, glass, and chemical products used in products (solvents, lubricants), as well as product-use electronics. The EUSupreme scenario achieves a 55% GHG emission reduction by 2030 and 86% by 2050. By 2050, process-related emissions dominate the residual GHG emissions, accounting for 91% of the remaining 161 $MtCO_2$ eq. The wide use of CCS in the cement and lime sectors is the notable difference in the EUTarget scenarios compared to others, capturing about 102 $MtCO_2$ eq by 2050, which is partially utilized by the chemical industry to produce HVC.

Cumulative GHG emissions are a key indicator for assessing the long-term effectiveness of sustainable decarbonization strategies. The EUSupreme scenario shows a 7% lower cumulative industrial GHG emission from 2020 until 2050 compared to the EUTarget scenario. Specifically, in the iron and steel sector, the cumulative GHG emissions are reduced by 600 $MtCO_2$ eq, with 65% of these emissions being energy-related.

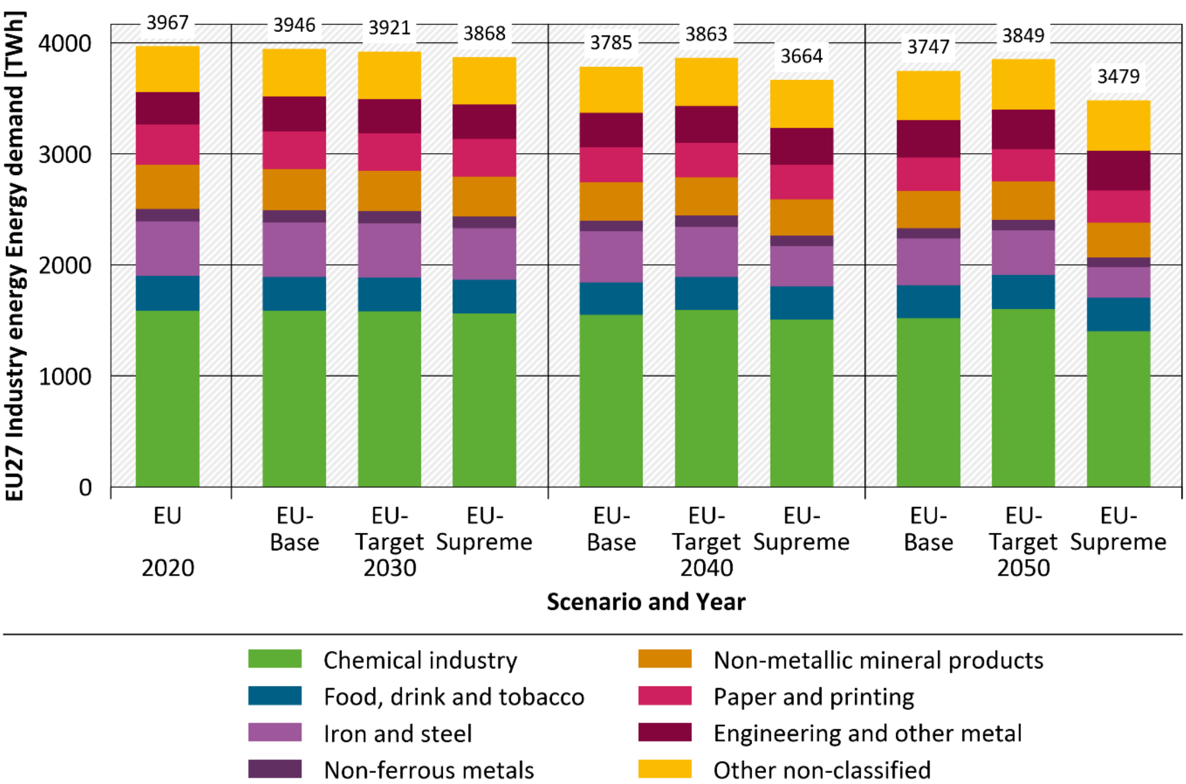
[35] The 93% reduction includes emissions captured through CCS technologies (102 $MtCO_2eq$ by 2050).

Figure 43: Overview of the development of total EU 27 industry GHG emissions by sources in the industry sector (incl. energy-related, process-related emissions and CCS emissions)



Source: own illustration based on Eurostat and own calculations Fraunhofer ISI

Figure 44: Overview of the development of EU 27 total energy demand by sub-sector in the industry sector (including final energy and feedstocks for chemicals)



Source: own illustration based on own calculations Fraunhofer ISI

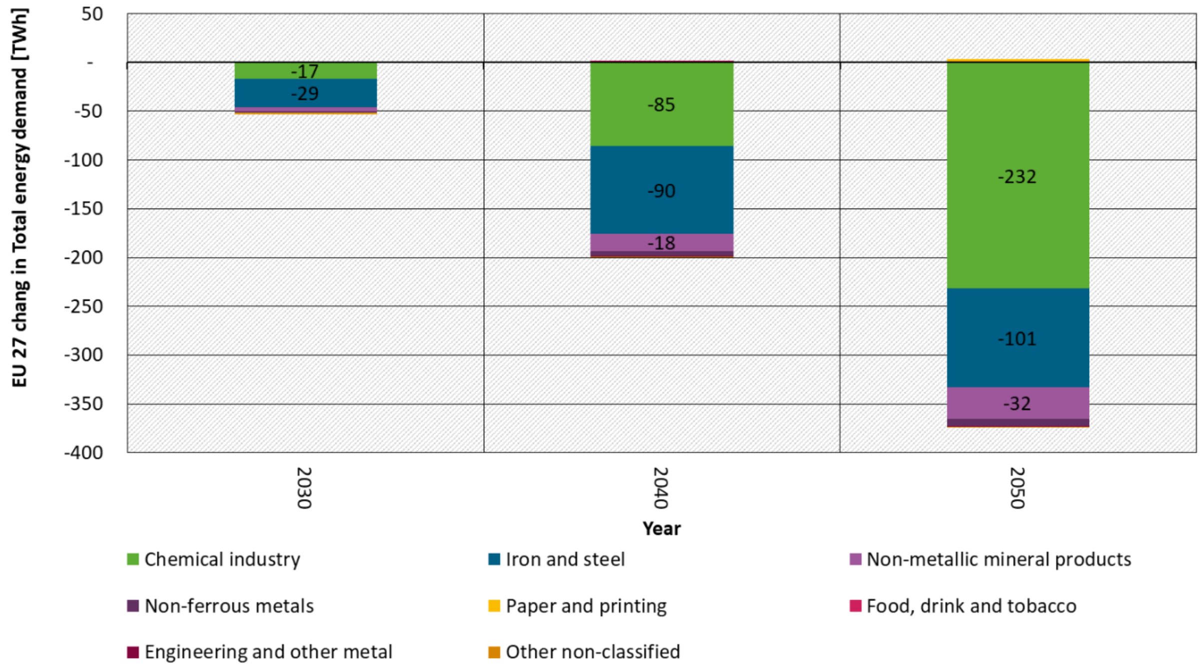
Figure 44 shows the development of the TED for the EU27 industry sub-sectors across different scenarios. Across all scenarios, the TED for the industry sector decreases continuously between 2018 and 2050. This trend holds true for nearly all industrial subsectors. Two notable exceptions exist: First, in the “Engineering and Other Non-Classified” subsector, TED increases by around 16% by 2050 compared to 2020. This is due to higher assumed growth in economic activity. Second, in the EUTarget scenario, the chemical industry shows a slight increase in energy demand of approximately 1% by 2050 compared to 2020. This is primarily driven by the uptake of the MTO route, which is more energy-intensive than conventional fossil-based steam crackers. In contrast, energy-intensive sectors such as cement and steel show a clear decline in TED due to efficiency improvements, process and fuel switch, and structural change.

The EUSupreme scenario achieves greater reductions in TED than the EUTarget scenario, mainly due to material efficiency, circular economy measures, and changes in behavior. More specifically, the TED decreases in the EUTarget scenario from 4,056 TWh in 2018 to 3,849 TWh in 2050, while in the EUSupreme scenario it goes down to 3,479 TWh in 2050.

A comparison between the EUTarget and EUSupreme scenarios further illustrates the added value of more ambitious material strategies: TED is significantly lower in EUSupreme compared to EUTarget, with 1,370 TWh versus 1,603 TWh in 2050. This difference results from structural changes in the scenario narrative, particularly due to circularity and material efficiency measures that reduce production volumes.

Similar trends are observed in the iron and steel sector, TED is also considerably lower in EUSupreme compared to EUTarget, amounting to 304 TWh versus 406 TWh in 2050(~25% difference). This difference is primarily driven by a higher share of secondary steel production and reduced material demand, resulting from increased circularity and more efficient product use. The contrast illustrates the significant energy savings potential associated with material strategies in this sector. As shown in Figure 45, the overall difference between the EUTarget and EUSupreme scenarios for total TED across all sectors is approximately 10%, accounting for around 370 TWh by 2050.

Figure 45: Overview of the Difference in the EU27 Industry Total Energy Demand between the EUTarget and EUSupreme Scenarios by Sub-Sector



Source: own illustration based on own calculations Fraunhofer ISI

Figure 46 presents a breakdown in energy demand for industry by end-use and sub-sector. In 2020 the heating and cooling activities accounted for 54% (2,211 TWh) of TED. This includes high-temperature process heating (HTPH)[36] (>500°C) primarily used in industrial furnaces accounting for 23% (920 TWh) and low and medium-temperature process heating for steam and hot water generation accounted for ~23% (920 TWh). Space heating accounted for a smaller share of around 6% (228 TWh). Feedstock demand, mainly driven by the petrochemical sector, represented 25.5% of TED (1,001 TWh). Mechanical energy and other electrical uses, such as for motors, drives, and lighting accounted for approximately 20% or 822 TWh. The remaining share was associated with cooling activities.

In terms of future trajectories, the energy demand for HTPH is projected to decrease. In the EUTarget scenario by 2050, the energy demand for HTPH decreases by 9% compared to the EUBase scenario. This reduction is primarily achieved through process switching, such as the adoption of H2-DRI in steel production and Electrical steam cracker in the HVC production. More significant reductions are observed in the EUSupreme scenario by 2050, with a decrease of 23%. In the EUSupreme scenario, the transition from primary production in blast furnaces to scrap-based secondary steel production has a particularly significant impact, resulting in a 32% reduction in energy demand for HTPH compared to 2020, reaching approximately 241 TWh.

For steam and hot water generation[37], the energy demand in the EUBase scenario by 2050 remains relatively similar to 2020 levels, reflecting moderate improvements potential in energy efficiency. In both the EUTarget and EUSupreme scenarios, we observe around a 6% reduction in energy demand.

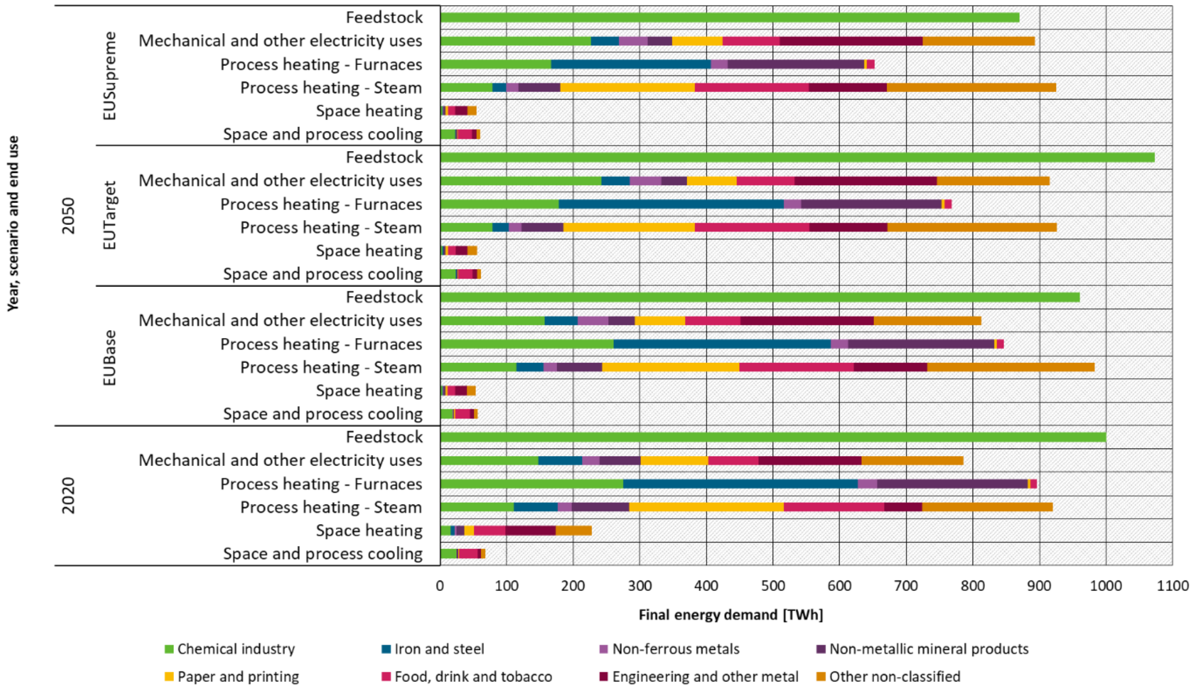
The third main end use is feedstock demand for the petro-chemical sector, exhibits diverging trends. Starting from about 1,005 TWh in 2020, feedstock use increases to around 1,173 TWh in the EUTarget scenario, mainly due to the introduction of MtO route. In contrast, the EUSupreme

[36] In Figure 46 Process heating - Furnaces

[37] In Figure 46 Process heating – steam

scenario shows a significant reduction to approximately 870 TWh. This decline reflects a combination of reduced demand for virgin HVC production, increased circularity, and substitution effects.

Figure 46: Overview of the development of total EU 27 industry energy demand by end-use and sub-sector in the industry sector (EU27, 2020, 2050)

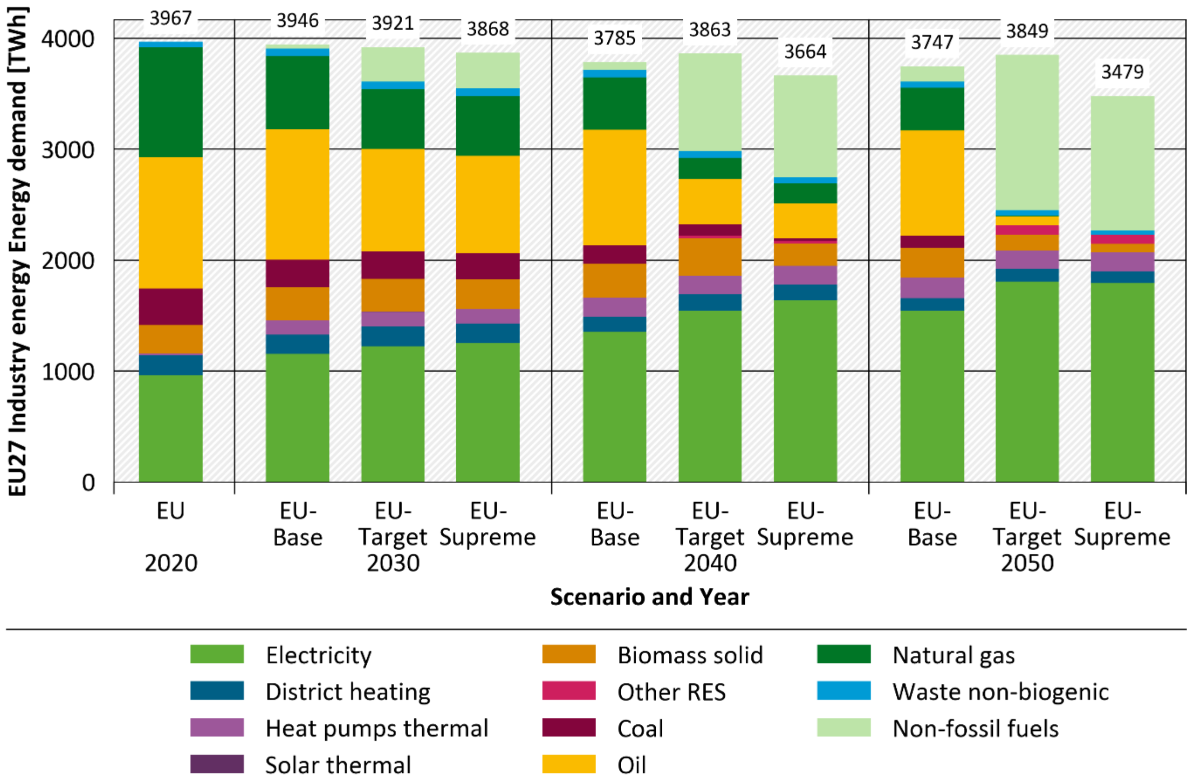


Note: 2018 is calibrated based on Eurostat, subsequent years are model result

Source: own illustration based on Eurostat and own calculations Fraunhofer ISI

Figure 47 shows the development of the TED for the EU 27 industry energy carrier and scenario**.** The transition to a low-carbon industry requires significant changes in the energy mix. The direct and indirect electrification of final energy demand is a persisting trend, with electricity becoming the most important energy carrier in all scenarios by 2050, followed by hydrogen and non-fossil hydrocarbons, with minor contributions from ambient heat, biomass, district heating, solar, and geothermal energy. The following paragraphs explore details of the development of the TED

Figure 47: Overview of the resulting EU27 total energy demand in the industry sector by energy carrier, calibration year 2018 is based on Eurostat, subsequent years are the result of modeling



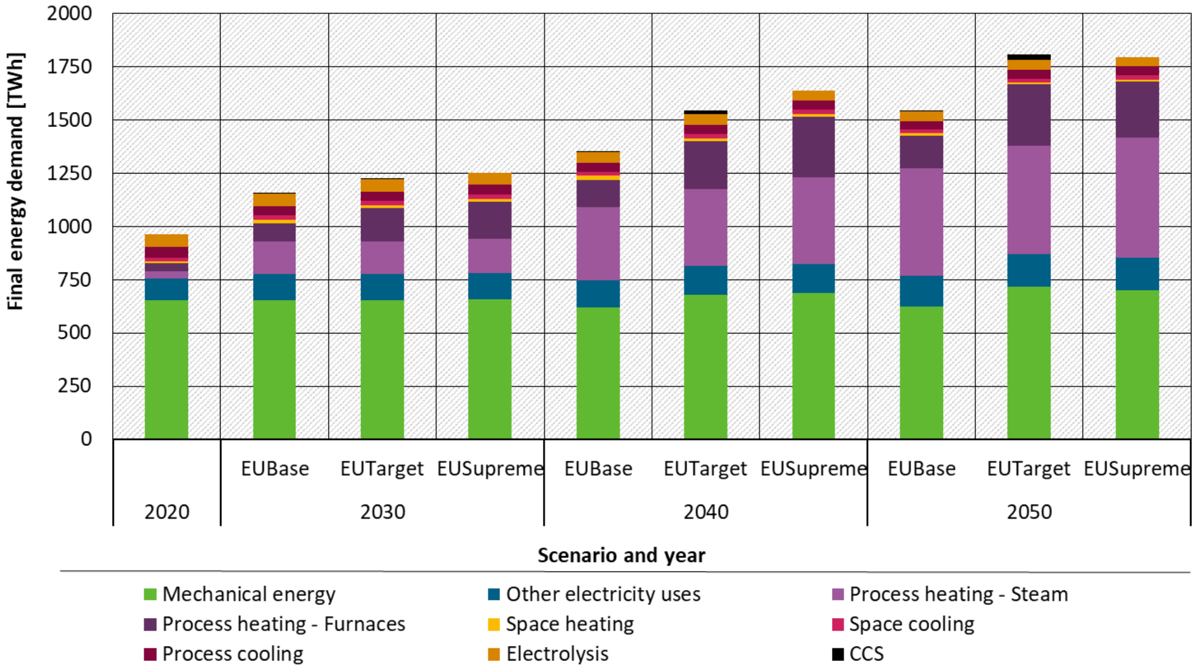
Note: 2018 is calibrated, based on Eurostat, subsequent years are model result

Source: own illustration based on Eurostat and own calculations Fraunhofer ISI

Figure 48 shows the development of direct electricity demand by end-use. In 2020, 69% of electricity demand in the industry was used for mechanical energy, 11% for lighting, and the remainder for processes that are already electrified, such as the electrolysis of aluminium (6%) and electric scrap-based steel production (4%). By 2030, electricity demand in both EUTarget and EUSupreme is projected to increase by approximately 27 - 30% compared to 2020 levels. This increase is mainly driven by the use of electricity to supply low-temperature process heating (below 150-100°C)[38] through industrial heat pumps, which allow efficient electrification within this temperature range. Starting from 2030, the rate of electrification is expected to accelerate, extending to higher temperature processes. The share of direct electricity in TED is projected to increase significantly by 2050, reaching 41% (1,544 TWh) in the EUBase scenario, 47% (1,806 TWh) in the EUTarget scenario, and 51% (1,792 TWh) in the EUSupreme scenario, compared to 24% (958 TWh) in 2020. This growth is facilitated by the adoption of technologies such as electrical boilers and electric furnaces, including increased use of EAF iron and steel as well as the introduction of ESC in the chemical industry. Mechanical energy demand remains relatively constant across scenarios and over time.

[38] Part of the process heating - steam in heat pumps thermal

Figure 48: Overview of the resulting EU27 electricity demand by scenario and end-use in the industry.

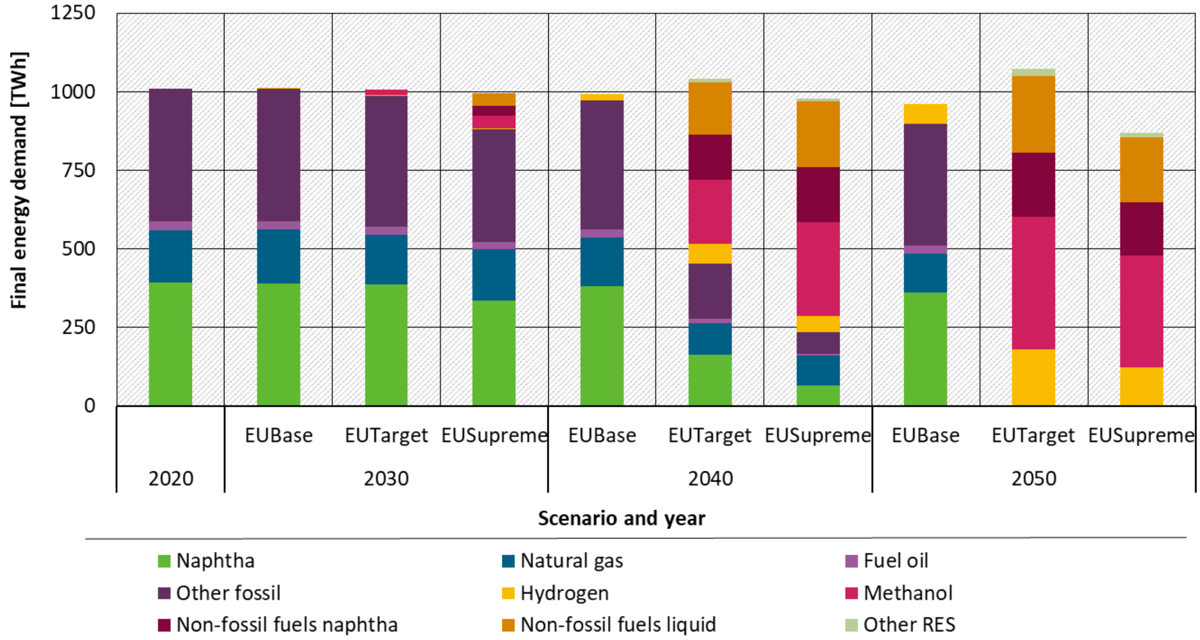


Note: electricity demand is defined as final energy (e.g. electricity demand for electrolysers is not included) 2018 is calibrated based on Eurostat, subsequent years are model result
Source: own illustration based on Eurostat and own calculations Fraunhofer ISI

The demand for hydrogen and non-fossil hydrocarbons is projected to range from 1,209 TWh in the EUSupreme scenario to 1,479 TWh in the EUTarget scenario by 2050. Hydrogen and non-fossil hydrocarbons play an important role in feedstock supply and high-temperature process heating above 500°C. In the latter, electrification still faces significant technical challenges, particularly in the non-metallic sectors. Currently, feedstocks for HVC production are entirely based on fossil fuels, mainly naphtha and natural gas, amounting to about 1,008 TWh in 2020. By 2050, feedstocks use in HVC will account for around 70% of the demand for hydrogen and synthetic fuels in both the EUTarget and EUSupreme scenarios. Figure 49 shows the development of hydrogen and non-fossil synthetic hydrocarbon demand as feedstock for HVC.

The demand for hydrogen and non-fossil synthetic hydrocarbons as feedstock is expected to start increasing significantly from 2030, with demonstration and pilot projects, leading to 20 TWh by 2030 in EUTarget. The scaling up is expected to accelerate between 2030 and 2040, with hydrogen demand for feedstocks reaching 557 TWh in EUTarget and 732 TWh in EUSupreme by 2040. In 2050, the demand for hydrogen and non-fossil synthetic hydrocarbons will reach 1,049 TWh in EUTarget and 869 TWh in EUSupreme. Moreover, about 75% of this projected hydrogen demand is located in northern Europe, reflecting the current spatial concentration of large chemical production clusters. It is important to note that the demand for hydrogen as feedstock is subject to uncertainty. These include uncertainties related to technology choices, feedstock and infrastructure availability, international competitiveness, and the pace and scope of policy support for local low-carbon production routes.

Figure 49: Overview of the resulting EU27 feedstock demand in the (petro-) chemical industry by scenario and energy carrier calibration year 2018 is based on Eurostat, subsequent years are the result of modeling



Note: 2018 is calibrated based on Eurostat, subsequent years are model result

Source: own illustration based on Eurostat and own calculations Fraunhofer ISI

Biomass demand shows varying trends across the scenarios (see Figure 49). In the EUBase and EUTarget scenarios, biomass demand peaks by 2035, increasing by almost 40% compared to 2018, adding around 100 TWh. This increase is driven by CO_2 price levels, which make hydrogen and direct electrification less cost-effective, thereby allowing biomass to gain a significant market share. Importantly, both scenarios do not account for potential limitations in biomass supply, both domestically and internationally. In contrast, the EUSupreme scenario sees biomass demand remaining almost constant until 2030, after which it decreases, reaching 30% of the original 2018 demand by 2050. This decline is mainly concentrated in the paper and printing production sectors and in countries with high biomass availability. Fossil fuels, which accounted for 64% of TED or 2616 TWh in 2018, are completely phased out by 2050 in the target scenarios.

3.2.1.3 Comparison of scenario results (EUBase, EUTarget, and EUSupreme)

The three scenarios (EUBase, EUTarget, and EUSupreme) highlight distinct pathways for industrial decarbonization, offering varying levels of ambition and approaches to achieving emissions reductions. In terms of GHG reduction, the EUBase scenario achieves a 73% reduction by 2050 compared to 1990, leaving 329 Mt CO_2eq of residual emissions. The EUTarget scenario reaches a 93% reduction by 2050, with residual emissions totalling 77 MtCO_2eq. In addition to these residuals, 102 MtCO_2eq are captured through CCS technologies, particularly in the cement and lime sectors. The EUSupreme scenario achieves an 86% reduction by 2050, leaving 161 MtCO_2eq of residual emissions.

The scenarios are further distinguished by energy demand trends. EUBase relies on incremental efficiency improvements and limited process switching, resulting in moderate energy demand reductions while maintaining significant fossil fuel use. EUTarget drives greater reductions with increased electrification and hydrogen adoption, especially in steel and ammonia production. EUSupreme achieves the largest energy demand reductions, with TED projected at 3,479 TWh by 2050, compared to 3,849 TWh in EUTarget and 3,747 TWh in EUBase. This significant reduction is driven by systemic changes to minimize resource and energy use.

By 2050, electricity becomes the dominant energy carrier in all scenarios, growing from 24% of energy demand in 2018 to as much as 51% in EUSupreme. Hydrogen and synthetic hydrocarbons also emerge as key energy carriers, especially in high-temperature processes and as feedstocks. Hydrogen demand in EUBase remains limited, EUTarget and EUSupreme scale its use significantly, with EUTarget reaching 1,479 TWh and EUSupreme 1,209 TWh. The lower hydrogen demand in EUSupreme compared to EUTarget reflects the impact of more ambitious circular economy measures, material efficiency strategies, and reduced reliance on primary production. These measures lead to substantial savings in high-value energy carriers.

Together, these scenarios paint a compelling picture of industrial transformation. Firstly, the EUBase outlines a continuation of current trends and policies, assuming a limited deployment of breakthrough technologies. These include incremental energy efficiency improvements and a partial fuel and technology switch. For example, in the steel sector, H_2-DRI is introduced only at a limited scale and does not fully replace conventional blast furnace production. Similarly, in the chemical industry, electrification progresses slowly, with only pilot-scale deployment of electric steam crackers by 2050. As a result, the scenario falls well short of achieving climate neutrality, highlighting the limitations of the current policy and investment landscape. Secondly, the EUTarget reflects a technology-driven pathway, with significant investments in electrification, hydrogen, CCS and synthetic hydrocarbons It assumes the widespread rollout of low-carbon technologies and needed infrastructure such as full-scale H_2-DRI in steelmaking, electric steam crackers and synthetic hydrocarbons to replace fossil feedstocks (MTO) in the chemical sector and large-scale CCS deployment in cement and lime production. It achieves a net-zero industry in 2050, through technology-driven decarbonization across key sectors.

Finally, the EUSupreme scenario outlines a transformation pathway that goes beyond only technological changes. It emphasizes systemic change in how industrial and societal added value is generated, moving away from volume-driven growth toward resource efficiency, circularity, and new business models. Primary production in energy- and emission-intensive sectors is significantly reduced. For example, in steelmaking, the share of scrap-based production increases markedly, enabled by improved circular business models (e.g., reuse, repair, remanufacturing). Similar trends apply in the chemical and cement sectors, where output levels decline due to material efficiency, substitution, and sufficiency strategies. More specifically, these changes reduce the demand for hydrogen and hydrocarbons by 269 TWh by 2050 compared to the EUTarget scenario. Also 15 TWh less electricity is needed in 2050 than in the EUTarget scenario. The lower demand for climate-neutral secondary energy carriers reduces pressure and costs in the energy system at the supply side. On the other hand, the EUSupreme scenario shows a larger remaining gap towards a climate-neutral industry with remaining 161 $MtCO_2eq$ by 2050 compared to 77 $MtCO_2eq$ in the EUTarget scenario. These need to be compensated by negative emissions from other sectors.

The modeling clearly shows that the current policy and technology framework, as represented in the EUBase, will not be sufficient to achieve climate-neutral industry. However, the modeling also demonstrates that climate-neutral industry in the EU can be achieved through multiple pathways that, despite differences, share a common technological foundation and structural direction. All scenarios assume strong improvements in energy efficiency, electrification of heat, and a shift away from fossil feedstocks. Where they diverge is in the balance between technology-driven transformation focusing on supply-side solutions (e.g., hydrogen, CCS) and structural change focusing on the way materials are produced and used (e.g., circularity, material efficiency). Importantly, the EUTarget and EUSupreme scenarios are not mutually exclusive. Both reflect feasible strategies with overlapping technologies and long-term objectives. Understanding differences and commonalities in pathways helps to identify robust elements of the transition and clarify trade-offs.

While the modeling highlights that climate-neutral industry is technically achievable, it also rests on ambitious assumptions around technology and infrastructure rollout, policy alignment, and behavioral changes. Future work should go beyond technical feasibility and further explore the enabling conditions and consider institutional readiness, actor preferences, societal acceptance, and potential co-benefits of different transition narratives/logic/pathways.

3.2.1.4 Inventory category 2 Product Use D-H

The inventory categories 2. Product Use D-H are dominated by F-gases emissions. No new assessment of the development of F-gases has been done within this project. To complete the GHG balance, modeling results from the Impact Assessment Report for the amendment of the Regulation (EU) No 517/2014 on fluorinated greenhouse gases (Gschrey, Barbara, Behringer, David, Kleinschmidt, Jlia et al. 2022) have been used. The Scenario *Proportionate Action* is considered to be the most likely basis for the revised F-gases regulation and was thus used to model the development in emissions from fluorinated gases within this project. No differentiation between different scenarios is being used which can be seen as a conservative assumption for the two target scenarios.

Table 16: Development of fluorinated gases in Mt CO_2e

	2020	2030	2040	2050
HFCs	77.5	27.8	9.3	6.5
NF_3	0.0	0.0	0.0	0.0
PFCs	2.5	2.3	2.3	2.3
SF_6	7.3	4.4	3.2	4.0
Total	**87.4**	**34.5**	**14.8**	**12.9**

Source: Own calculations, based on Gschrey, Barbara, Behringer, David, Kleinschmidt, Jlia; Jörß, Wolfram; Liste, Victoria; Ludig, Sylvie; Wissner, Nora; Birchby, David et al. (2022). https://climate.ec.europa.eu/system/files/2022-06/f-gases_external_preparatory_study_en.pdf.

For completeness, the non-F-gases within these categories are also included, assumptions for their development following a simple logic. For CO_2, which is mainly coming from category 2.D non-energy products from fuels and solvent use, the development of the N_2O emission follows the change in fossil to green Naphtha within refineries. The underlying assumption there being no change in input of fossil Naphtha in the EUBase and a substitution of fossil Naphtha with green Naphtha of 30% by 2030, 70% by 2040 and 100% by 2050 for the two target scenarios. No change in consumption of N_2Oe products is applied. N_2O emissions are mainly coming from use of the gas for medical applications as anesthetic or for food preparation. Here we assume no change of emissions for any of the scenarios. Likewise, the minor amount of CH_4 emissions is kept constant over all scenarios.

Table 17: Development of CO_2, CH_4 and N_2O from same inventory categories in Mt CO_2e

	2020	2030	2040	2050
CO_2	7.2	7.2/5.0*	7.2/2.1	7.2/0
CH4	0.1	0.1	0.1	0.1
N_2O	2.6	2.6	2.6	2.6
Total	**9.9**	**9.9/7.7**	**9.9/4.8**	**9.9/2.7**

*Where two figures are provided, the first refers to the assumptions for EUBase, the second refers to the assumptions for EUTarget and EUSupreme

3.2.2 Transport

The transport sector is responsible for 29% of the EU's total GHG emissions in 2022. About 75% of these emissions are caused by road transport, followed by navigation (14%) and aviation (12%). Cars are the most important transport mean, causing 59% of road transport emissions, while commercial vehicles (light-duty trucks, heavy-duty trucks and buses) account for 40%. International bunkers, i.e. energy consumption on international connections (intra-EU and extra-EU), dominate the aviation and navigation subsectors. Domestic aviation (i.e., flights within member states) and domestic navigation (covering inland waterways and coastal shipping within member states) combined make up only 3% of transport sector emissions. Other transport means, mainly rail transport (0.3%) and motorcycles (0.9%) are of minor importance in terms of total GHG emissions (European Commission 2024). GHG emissions attributed to the transport sector arise from the combustion of fossil fuels (or fossil components in fuel blends) during vehicle operation. Biogenic emissions are not included and the emissions arising from the production of energy carriers or vehicles are not in the scope of the transport sector.

In the past, the transport sector's final energy consumption has been almost fully covered by fossil energy, in particular oil-based fuels. In 2022, petroleum products covered 93% of its final energy consumptions, mainly diesel, gasoline, and kerosene. Blended bio-diesel and bio-gasoline made up about 6%, whereas electricity (2%) and natural gas (1%) played a minor role. (Eurostat 2024a)

Given the many advantages of electric powertrains compared to conventional powertrains (regarding GHG emissions, energy efficiency, operating costs as well as air and noise pollution), the share of electricity in transport is expected to increase in the future. Plug-in electric vehicles (PEVs), i.e., BEVs and PHEVs, have started to diffuse into the car and van markets, reaching a combined market share of about 20% of all new car registrations in the EU, but already over 40% in Sweden, Finland, Denmark, the Netherlands, and Belgium (ACEA 2024).

Rail transport is the only subsector, in which electricity has already played a major role in the past. Overall, 57% of the railway tracks in the EU have already been electrified until 2022, although this varies greatly from country to country, from 3% in Ireland to 97% in Luxembourg (European Commission 2024). Since the main lines (long-distance services, busy urban and suburban rail transit) are already electrified, electric traction already accounts for 90% of passenger and 80% of freight rail transport performance in the EU (Rozsai et al. 2024). Further electrification of the sector – mainly on low-traffic, secondary routes – can be realized by the continued extension of overhead lines on rail routes or by the introduction of battery electric drivetrains. On rail routes with low transport performance (typically in regional rail transport), where a complete track electrification via overhead lines is not always cost-effective, battery electric multiple units can replace Diesel multiple units in the future, combined with partial track electrification if necessary (Frank et al. 2022).

Besides the ongoing electrification, the second important option for defossilizing the transport sector is to replace today's oil-based fuels in conventional powertrains with non-fossil fuels of biological or non-biological origin. This is particularly promising for the aviation and navigation subsectors, in which viable drivetrain alternatives do not exist or are not market ready in time to fully replace the vehicle fleet before 2050. In aviation, hydrogen propulsion, either based on a hydrogen-fired turbine or on a fuel cell electric drivetrain, might emerge as alternative in the long term. It exhibits greater efficiency in comparison to the conventional kerosene fuel and offers a means to effectively mitigate the remaining global warming potential associated with the combustion of hydrocarbons in the upper atmosphere. However, hydrogen-powered aircraft are still concepts today - Airbus plans to introduce first commercial hydrogen-powered aircraft in 2035 (Airbus 2024). In the short term, a switch from fossil kerosene to bio-kerosene or e-kerosene is likely to be the only realistic option and is therefore driven forward by EU-wide mandates for sustainable aviation fuel (SAF). In maritime transport, several fuels are discussed as substitution for today’s fossil fuel in order to comply with the EU emission mitigation targets. Non-fossil marine fuels could be electricity-based (e.g., green hydrogen, e-methane, e-diesel, e-methanol, e-ammonia) or biogenic (e.g., bio-LNG, biodiesel, or hydrotreated vegetable oil) (NOW 2023). Due to the uncertainty regarding the exact type of fuel replacing today’s fossil fuels, they are grouped as non-fossil fuels for the analysis.

The scenarios presented in the following result from the modeling introduced in section 2.3.2. Road transport is represented by a logistic diffusion model for passenger cars and an agent-based simulation for commercial vehicles (light-duty trucks, medium-duty trucks, heavy-duty vehicles), modeling the diffusion of alternative powertrains into the car and commercial vehicle stocks over time. The energy demand from other road vehicles, notably motorcycles and buses, are included in the calibration of the two models, but as they are not modelled separately, these segments are not further evaluated in the scenarios. The scenarios for the non-road transport subsectors – railway, domestic aviation and navigation (i.e., within individual member states) as well as international aviation and navigation – are developed using a top-down approach.

3.2.2.1 EUBase scenario

3.2.2.1.1 General description

The EUBase scenario models the development of the transport sector, based on measures within the EU's “Fit for 55” package. It is used to analyse the impact of these existing policies on future energy demand and GHG emissions and serves as a reference for the more ambitious EUTarget and EUSupreme scenarios. The framework conditions and the policy measures incorporated into modeling of the different transport modes are detailed in the following, whereas the specific assumptions are given in the subsequent section.

In the passenger car segment, the CO_2 emission performance standards for new vehicles are the EU’s central policy instrument. They prescribe progressive EU-wide emission reduction targets until a 100% reduction is achieved, which effectively bans all cars with an internal combustion engine from being sold in the EU and hence pushes the automotive industry to offer zero-emission vehicles. Given the clarity regarding the transition, EUBase models the transition from today's national vehicle fleets to purely BEV fleets. Unlike the target scenarios (see section 0), it does not enforce the fulfilment of the target by 2035 but allows leeway regarding the year in which 100% market penetration is achieved. Instead, the country-specific diffusion of electric cars is modelled after the historical market development in Norway (see model description in section 2.3.2.1.1), where 90% of new car registrations are already electric. It starts from the recorded market share of electric vehicles, and its trajectory depends on current country-specific monetary incentives, charging infrastructure availability as well as electricity and fossil fuel prices. The development of annual new registrations and stocks until 2050 is taken from the MKS reference scenario for Germany (Krail et al. 2019) and extrapolated to all EU27 countries.

Lowering the emissions of trucking is a vital component of the transition towards defossilization of road transport. The EUBase scenario models this segment using an agent-based bottom-up approach. Unlike passenger cars, which are moving exclusively towards direct electrification, the trucking industry might have multiple feasible options available. Buyers make their purchase decisions based on the total cost of ownership (TCO), selecting the option that offers the lowest cost. Within the EUBase framework, fuel cell, battery electric, and conventional diesel trucks are all viewed as viable alternatives competing in the market. Their competitiveness is influenced by energy carrier prices, technology costs, regulatory conditions (such as toll exemptions for zero-emission trucks), and the ongoing development of hydrogen refuelling and charging infrastructure. Part of the energy carrier prices in the TCO model are CO_2 price assumptions to reflect the implementation of the EU-ETS2.

In rail transport, two drive technologies dominate today: Electric trains are generally used if railway tracks are electrified, otherwise diesel trains are used. EUBase anticipates a continued and reinforced electrification of rail transport.

In aviation and navigation, EUBase is built on two EU regulations, FuelEU Maritime and ReFuelEU Aviation, which were adopted in 2023. The ReFuelEU Aviation Regulation sets binding quotas for SAF from 2025 and for synthetic aviation fuels from 2030 onwards. Eligible SAFs include synthetic aviation fuels, aviation biofuels, and recycled carbon aviation fuels. The FuelEU Maritime Regulation does not set explicit quotas for non-fossil fuels but specifies GHG emission intensity reduction targets. Due to a lack of viable drivetrain alternatives, emission reductions rely on the fuels used. Small reductions to comply with short-term targets might be achieved by using fossil fuels with lower emission intensity, e.g. liquefied natural gas (LNG). In the long term however, maritime transport will rely on the substitution of fossil fuels by non-fossil fuels to fulfil the regulation. Therefore, EUBase models the compliance with the regulation by increasing the use of synthetic and biogenic marine fuels over time.

In all subsectors, the energy efficiency can be further improved, regardless of drive option. In road and rail transport, specific energy consumption can be lowered through improved aerodynamics, lightweight construction or partially automated driving. In navigation, energy efficiency can be improved by operational adjustments, the practice of slow steaming, reductions in port turnaround times, weather routing, optimized autopilot utilization, and additional sails (Timmerberg et al. 2018). As these measures cannot be modelled separately in the models used, flat-rate percentage reductions in energy intensity are assumed.

3.2.2.1.2 Main assumptions

In the passenger car segment, EUBase's basic underlying assumption is a continuous diffusion of PEVs (BEVs and PHEVs) into the vehicle fleet, following a sigmoid curve. The speed of this steady electrification, i.e., the annual market share of PEVs in the new car market, is endogenously determined in a logistic model (see model description in 2.3.2.1.1). The share of PHEVs in all newly registered PEVs is assumed to decrease linearly, reaching zero in 2035. All newly registered vehicles in a year flow into the vehicle stock and leave it after an assumed service life of 12 years. The electric driving performance of a PHEV is assumed 56% of total driving performance (realistic for privately owned PHEVs, cf. Plötz et al. (2022)) to calculate fuel and electricity demands. The average specific energy consumption of the BEV, PHEV, and conventional car stocks is assumed to decrease by 30% each between 2020 and 2050 to account for general energy efficiency improvements.

In the commercial vehicle segment, EUBase considers four to six powertrain options, depending on vehicle size class. For all size classes, conventional vehicles with diesel engines compete with BEV, PHEV and FCEV. For vehicles exceeding 12 t, two types of catenary trucks (full electric with battery as well as diesel hybrid) are additionally available. It is assumed that overhead lines are partly available on 23% of motorways starting in 2030, increasing to 62% by 2050. Given the ongoing discussions regarding catenary trucks, particularly in Germany, and that their use remains very uncertain, the availability of overhead lines as it is realized in the model can also be interpreted as a sufficient coverage of high-power charging infrastructure for commercial vehicles. For the BEV, where range is critical, battery capacities are assumed such that light-duty and medium-duty trucks (gross vehicle weight of less than 12 t) will achieve a range of 200-260 km by 2030 and 300 km by 2050, while heavy-duty vehicles (trucks over 12 t and tractor-trailers) will reach 300 km by 2030 and 500 km by 2050, adequate for typical driving distances between breaks (4.5 hours). Assumptions regarding fuel cell and battery cost trajectories are taken from the long-term scenarios for the transformation of the energy system in Germany (Gnann et al. 2024).The technology costs are declining over time, reaching 70€/kW fuel cell costs and 80€/kWh battery costs in 2050. All vehicles with alternative powertrains (i.e., BEVs, PHEVs, catenary hybrids, and FCEVs) are assumed to be exempt from the toll until 2030. Overall, the efficiency of all drivetrains and weight categories is projected to improve by 35% by 2050. Annual registrations and annual mileages of commercial vehicles grow over time; they are also adopted from the long-term scenarios (Gnann et al. 2024), for which their development was projected in the ASTRA-M model.

In the non-road transport subsector models, key assumptions driving the total energy demand are the future transport activity growth and energy intensity reductions. Assumptions for non-fossil fuel quotas or electrification determine the amount of fossil fuels that are left in the future fuel mix, and thus the CO_2 emissions.

In aviation and navigation, the scenarios are based on exogenous assumptions for transport activity growth and efficiency improvements, which are specified in the following. In aviation, an annual transport performance growth of 0.5% is assumed while energy intensity reduces linearly by 35% between 2020 and 2050. The impact of the COVID-19 pandemic is incorporated into the aviation model by applying factors to scale down total energy demand for 2020, 2021, and 2022. From 2023, it is assumed that aviation has fully recovered. EUBase considers hydrogen propulsion for short-haul flights, using domestic aviation as a proxy. Thus, the share of hydrogen in the domestic aviation fuel mix increases linearly from 1% in 2035 to 100% in 2050. Since domestic air transport only plays a minor role in the energy demand for aviation, this assumption does not lead to high hydrogen demands - it has more of a symbolic relevance to consider a new technology development, which reduces the climate impact of flights more than CO_2 neutral fuels (DENA 2022). If hydrogen aircraft are not technologically or commercially viable in the considered timeframe, the corresponding energy demands must be covered by kerosene. To account for the high uncertainty regarding hydrogen propulsion, hydrogen for use in aviation, as well as e-kerosene and bio-kerosene, are subsumed under “non-fossil fuels”. In international aviation, EUBase assumes a non-fossil fuel share of 70% by 2050, according to the SAF quota of the ReFuelEU Aviation regulation, leaving 30% of fossil kerosene in the fuel mix. In shipping, transport activity is assumed constant while energy intensity reduces linearly by 30% between 2020 and 2050. The share of synthetic fuel increases from 6% in 2030 to 75% in 2050, while the admixture of biofuel increases up to 20% in 2050.

In rail transport, country-specific transport performances are adopted from the EU Reference Scenario (European Commission 2016), in which total EU27 freight rail transport increases by 51% and passenger rail transport by 52% between 2020 and 2050. Linear energy efficiency improvements of 20% between 2020 and 2050 are assumed. EUBase assumes that 80% of the currently non-electrified rail routes in a country will be electrified by 2050, assuming linear progress. The model does not differentiate between electrification via overhead lines and electrification via the introduction of battery electric trains.

An overview of the EUBase's key assumptions is given in Table 18.

Table 18: Overview of key assumptions for the EUBase scenario across all transport modes.

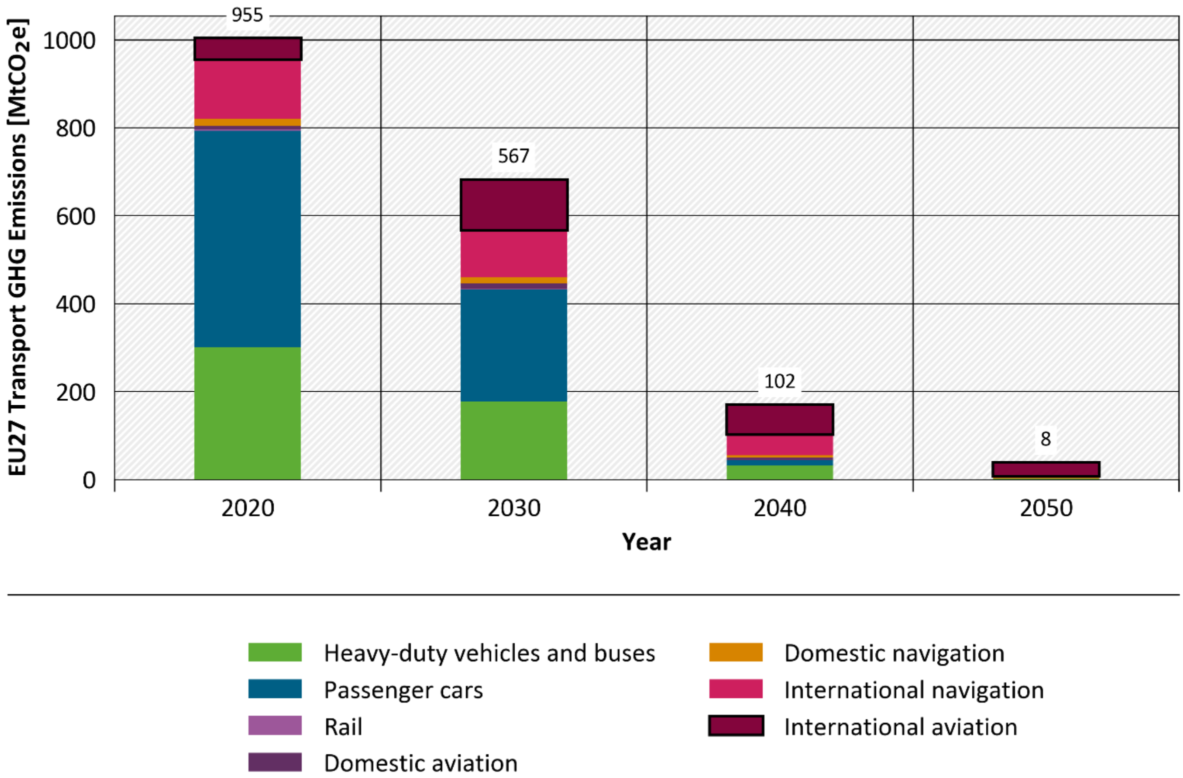
Mode	EUBase Scenario
Cars	Continuous electrification – growth of PEV market shares in car registrations endogenously determined in model
Trucks	Technology costs: 70€/kW fuel cell costs in 2050 80€/kWh battery costs in 2050 Energy carrier prices and EU-ETS2 CO_2 price acc. to Table B.1
Rail	Electrification of 80% of non-electrified routes until 2050 (via track electrification or battery electric trains)
Aviation	Increasing shares of non-fossil jet fuel: Domestic flights: 100% H2 reached in 2050 International flights: 70% non-fossil fuel reached in 2050
Navigation	Increasing shares of non-fossil fuel: 75% e-fuel reached in 2050

3.2.2.1.3 Results

This section presents the transport sector results for the EUBase scenario. It starts by presenting the overall trajectory for the GHG emissions and the final energy demand, before detailing the results on subsector level. The presented energy demands and emissions are the outputs of the transport sector modeling introduced in section 2.3.2., calibrated on GHG emissions of 2019 and parameterized according to the assumptions presented in the previous section 3.2.2.1.2.

As shown in Figure 50, the EUBase scenario demonstrates a significant reduction in fossil GHG emissions in transport, across all subsectors (note that 2020 emissions in aviation are exceptionally low due to the COVID-19 pandemic). The fastest reduction in GHG emissions is projected in road transport, which reduces its GHG emissions by 46% until 2030, 95% until 2040, and 100% until 2050, compared to 2020. Until 2030, the total transport sector emissions are reduced by 32%, driven by the diffusion of electric passenger cars. By 2040, when road vehicle stocks are already largely electrified, total GHG emissions are reduced by 83%. In the later years, GHG emissions are dominated by international aviation and navigation. In 2050, total emissions are reduced to 39 Mt (-96% compared to 2020) - the remaining emissions are primarily from international bunkers and secondarily from the few diesel trucks that are left in the stock (2 Mt). Emissions from rail and domestic navigation are negligibly small while cars and domestic aviation have zero emissions in EUBase.

Figure 50: GHG emissions of the EU27 transport sector under the EUBase scenario



Source: own calculations Fraunhofer ISI

Number relates to total generated GHG emissions excl. int. aviation (visually set apart for this reason)

Figure 51 shows the transport sector's energy demand in EUBase, which in total decreases by 57% between 2020 and 2050. Most of this decrease is already realized by 2040, when the total energy demand will be halved compared to 2020. With the exception of rail transport, energy demand is declining across all subsectors, although to varying degrees. Consequently, the modal split in terms of energy demand changes in the future.

The overall decline in energy demand and emissions is mainly driven by the reductions in road transport, where the future new vehicle market almost fully transitions to electric vehicles (see Table 19). This leads to fully battery electric car and light commercial vehicle stocks by 2050 – BEVs already account for 97% of the stock in these segments by 2040. Note that the service life was not varied within vehicle segments, i.e., all vehicles of the same type are modelled to leave the stock after a deterministic lifetime. This simplifies reality, in which the vehicle lifetimes are stochastically distributed. Thus, in reality, a share of the conventional vehicles will probably remain in service for longer, with their average mileage and thus their fuel consumption decreasing as they age.

The development in medium-duty and heavy-duty vehicles is slower, but their stocks are also nearly completely electrified until 2050. In total, the commercial vehicle stock in 2050 is 96% BEVs and 4% catenary BEVs. FCEVs make up about 0.2% of the commercial vehicle stock in 2050, resulting in a negligibly small hydrogen demand of 1.2 TWh, and showing that FCEVs are not cost-effective for most use cases. 0.4% of the 2050 commercial vehicle stock still have an internal combustion engine (conventional diesel vehicles and diesel hybrids). The large-scale electrification does not only reduce emissions but also reduces the energy demand due to the higher efficiency of electric powertrains compared to conventional internal combustion engine powertrains. In 2050, road transport makes up less than half of the total energy demand of the transport sector.

Table 19: EU27 market shares (in % of new registrations) of plug-in and catenary electric vehicles in road transport for EUBase

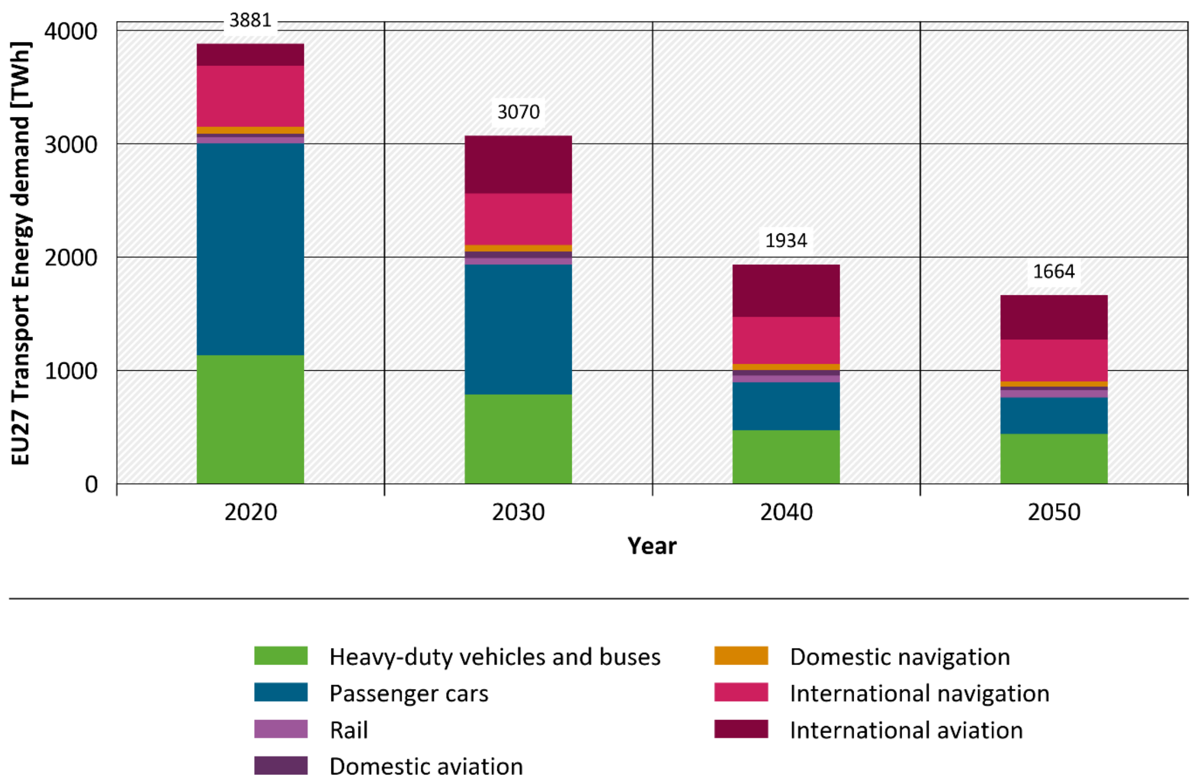
Transport mode	2025	2030	2035	2040	2045	2050
Passenger cars	52%	91%	99%	100%	100%	100%
Light duty trucks (<3.5t)	62%	89%	97%	100%	100%	100%
Medium duty trucks (3.5–12t)	59%	85%	95%	98%	98%	99%
Heavy duty vehicles (>12t)	24%	54%	72%	91%	98%	98%

Source: own calculations Fraunhofer ISI

The energy demand of aviation and shipping decreases as well because annual efficiency improvements are higher than the annual transport activity growth. Please note that the energy demand of aviation in 2020 is exceptionally low due to the COVID-19 pandemic. The modelled climate protection measures in aviation and navigation (i.e., the introduction of non-fossil fuels) only affect the emission intensity, but not the energy demand, unlike electrification in road and rail transport. Consequently, the steady decline in energy demand is slow compared to the observed development in road transport. Combined, aviation and navigation account for half of the transport sector's energy demand in 2050.

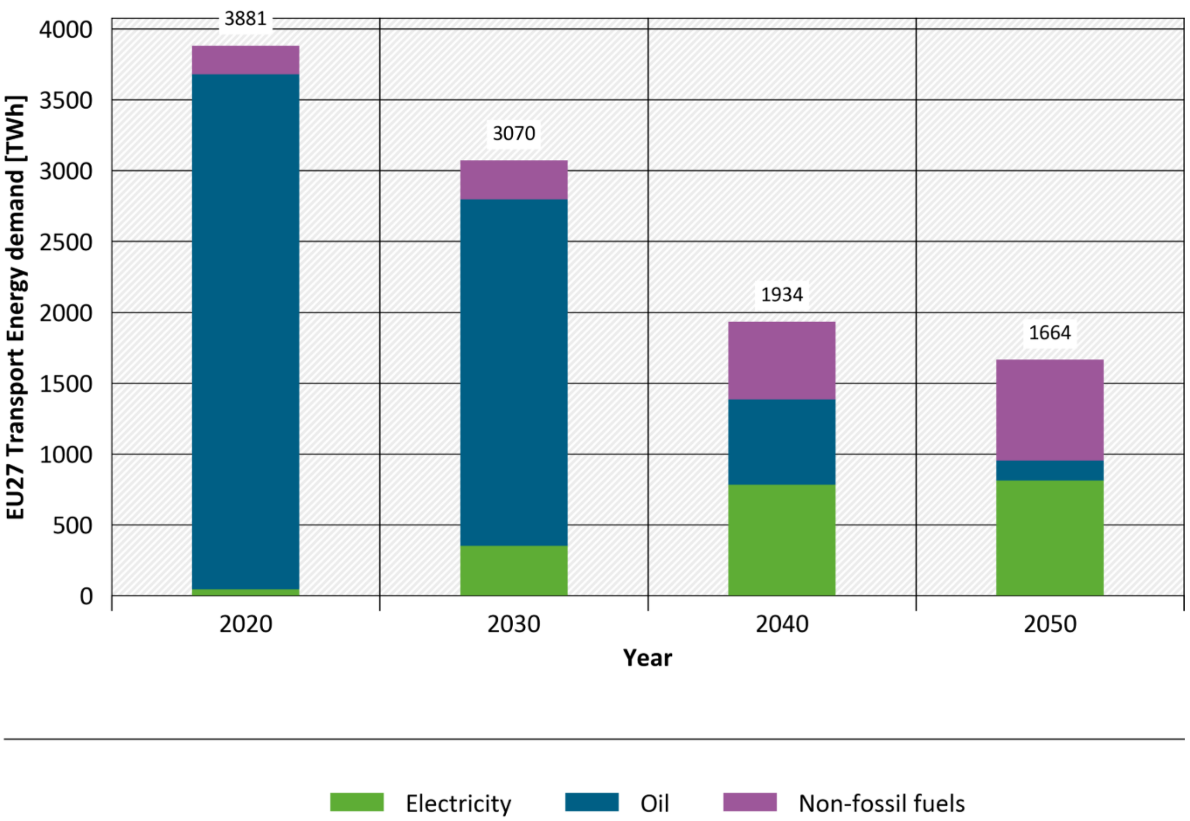
The energy demand in rail transport is increasing due to the rising transport activity. This is partially offset by the efficiency gains due to electrification. In light of the other developments, the share of rail transport in the total energy demand of the sector nevertheless increases from today's 1% to 4% by 2050.

Figure 51: Final energy demand of the EU27 transport sector under the EUBase scenario



Source: own calculations Fraunhofer ISI

Figure 52: Final energy demand in the EU27 transport sector (incl. international bunkers) under the EUBase scenario, by energy carrier.



Source: own calculations Fraunhofer ISI

Figure 52 differentiates the transport sector's energy demand in EUBase by energy carrier, aggregating the developments regarding fuel mix and electrification in the different transport modes. In 2020, the transport sector relies on hydrocarbon fuels, produced mainly from oil (94%) and to a small part from biomass (5%). Electricity, used in rail transport and by PEVs, has a small share (1%). The electricity demand then rises to 812 TWh until 2050, driven by the electrification of commercial vehicles (427 TWh), passenger cars (322 TWh), and to a lesser extent, rail transport (63 TWh). At the same time, the non-fossil fuel demand, driven by aviation and navigation, increases to 709 TWh in 2050. Due to this trend, the demand for oil-based fuels decreases to 603 TWh in 2040, when road transport electrification is already well advanced, and to 142 TWh in 2050, when non-fossil fuel quotas reach a high level.

EUTarget and EUSupreme scenarios

3.2.2.1.4 General description

Both target scenarios show a clear strategy for achieving a transport sector without fossil GHG emissions: Transition to alternative drivetrains on land combined with a complete switch to non-fossil fuels on water and in the air. They are built on the EUBase scenario but model more favourable conditions and more ambitious targets. In the following, the differences to EUBase are presented.

The EUTarget scenario is built on identical EUBase assumptions regarding future transport activity growth but models a higher ambition level targeting net-zero transport by 2050. It is characterized by lower technology costs, higher CO_2 pricing, and a faster electrification as well as a complete phase-out of fossil fuels by 2050, even in the hard-to-abate subsectors. It assumes the realization of the EU-wide 100% CO_2 emission reduction target for passenger cars and vans as of 2035, adopted in March 2023. This effectively bans the sale of all new cars and light commercial vehicles with internal combustion engine, including PHEVs, starting in 2035. This leaves the battery electric drivetrain as only established technology for passenger cars that complies with EU legislation and leads to a homogenous, battery electric car stock as soon as existing conventional and hybrid cars reach the end of their service life. This means that the electrification of the entire car stock will then automatically be complete before 2050, when the EU aims to be GHG neutral. In the truck segment, EUTarget is generally more favourable to the market diffusion of alternative drives than EUBase, as it models a faster cost decline in both batteries and fuel cells combined with higher CO_2 prices. In rail transport, electrification is accelerated. In the hard-to-abate subsectors of aviation and navigation, it models a complete fuel switch to non-fossil fuels, going beyond the implications of the regulations currently in place (ReFuelEU Aviation, FuelEU Maritime).

The EUSupreme scenario shows a pathway to net-zero transport that extends EUTarget by sufficiency measures in both passenger and freight transport. The passenger car stock can be reduced if people are incentivised to give up car ownership and to use public transport, active modes (cycling, walking), or sharing services instead. International and especially domestic flights can be partially replaced by high-speed trains. Freight transport can partially be shifted from trucks to freight trains and inland waterway vessels. Apart from modal shifts, some of the transport might be avoided altogether, for example by returning to local and regional sourcing (hence decreasing the need for long-distance freight transport) or by using digital services (e.g., remote work). The EUSupreme scenario models this more sufficient pathway by assuming different developments of stocks and transport activity in the subsector models, compared to EUTarget and EUBase. Thus, road vehicle stocks, air transport performance and international maritime transport performance are reduced while transport performances in domestic navigation and rail are increased.

3.2.2.1.5 Main assumptions

Table 20 outlines the characteristic assumptions of the two target scenarios EUTarget and EUSupreme by naming the key differences to the EUBase scenario. In the following, the subsector-specific assumptions that apply to both target scenarios, EUTarget and EUSupreme, are detailed, before the additional sufficiency assumptions of EUSupreme are presented. The other assumptions are identical to those in EUBase (see section 3.2.2.1.1).

Table 20: Overview of key assumptions for the EUBase, EUTarget and EUSupreme scenario across all transport modes.

Mode	EUBase Scenario	EUTarget Scenario	EUSupreme Scenario
Cars	Continuous electrification - growth of PEV market shares in car registrations endogenously determined in model	Complete electrification of stock until 2050 via electric vehicle diffusion: Until 2034: PEV market shares endogenously determined in model From 2035: 100% BEV registrations	Electrification as in EUTarget 25% reduction in car stock and thus 25% reduction in total driving performance, compared to EUBase/EUTarget
Trucks	Technology costs: 70€/kW fuel cell costs in 2050 80€/kWh battery costs in 2050	Lower technology costs: 55€/kW fuel cell costs in 2050 70€/kWh battery costs in 2050	Technology costs as in EUTarget Energy carrier prices and EU-ETS2 CO_2 price acc. to Table B.1

Mode	EUBase Scenario	EUTarget Scenario	EUSupreme Scenario
	Energy carrier prices and EU-ETS2 CO_2 price acc. to Table B.1	Energy carrier and EU-ETS2 CO_2 prices acc. to Table B.1 Higher EU-ETS2 CO_2 price than EUBase, reaching 500€ in 2050	Decreased growth in registrations leads to reduced 2050 vehicle stocks, compared to EUBase/EUTarget scenarios: light-duty: -11% medium-duty: as EUBase heavy-duty: -21%
Rail	Electrification of 80% of non-electrified routes until 2050 (via track electrification or battery electric trains)	Full electrification until 2050 (via track electrification or battery electric trains)	Electrification as in EUTarget Additional increase of freight and passenger rail transport performance
Aviation	Increasing shares of non-fossil jet fuel: Domestic flights: 100% H_2 reached in 2050 International flights: 70% non-fossil fuel reached in 2050	Complete phase-out of fossil aviation fuel until 2050: Domestic: 100% H_2 reached in 2050 International: 100% e-kerosene reached in 2050	Complete phase-out of fossil fuel as in EUTarget Decreasing transport performances: Domestic: –50% between 2019 and 2050 International flights: -10% between 2019 and 2050
Navigation	Increasing shares of non-fossil fuel: 75% e-fuel reached in 2050	Complete phase-out of fossil fuel until 2050: Domestic: 70% e-fuel, 30% H_2 reached in 2050 International: 100% e-fuel reached in 2050	Complete phase-out of fossil fuel as in EUTarget Decreasing international transport performance: -10% between 2020 and 2050 Increasing domestic transport performance: +20% between 2020 and 2050.

The target scenarios model a complete electrification of the passenger car stock by mid-century. Until 2035, the annual share of PEVs in new registrations is calculated endogenously by the logistic model, starting with the 2022 market shares of BEVs and PHEVs, as reported by ACEA (2023). From 2035 onwards, new car registrations are exogenously set to be 100% BEV, modeling a strict fulfilment of the 100% emission reduction target within the EU-wide CO_2 emission performance standards by 2035. This, combined with the assumed service life of 12 years (like in EUBase), guarantees that remaining conventional internal combustion engine cars and PHEVs leave the stock in 2046 at the latest.

For commercial vehicles, the target scenarios model techno-economic framework conditions more in favour of alternative powertrains than these of EUBase in order to accelerate the technology diffusion for trucks and to meet the emission reduction targets. Compared to EUBase, a reduction in costs for the key technology components of alternative powertrains, fuel cells and batteries, is assumed, thereby lowering the purchase cost of alternative vehicles. The higher CO_2 prices in these scenarios make fossil fuel vehicles more expensive to operate and further incentivize their phase-out.

In contrast to EUBase, the target scenarios model a full phase-out of fossil fuels in non-road transport until 2050. Rail transport is assumed to be fully electric by 2050, assuming a linearly progressing electrification in all countries. International aviation is modelled to fully switch to e-kerosene, assuming a linear growth in the admixture ratio between 2030 (6%) and 2035 (20%) as well as between 2035 (20%) and 2050 (100%). Likewise, the international maritime transport is modelled to fully switch to synthetic fuels (2030: 6% / 2035: 14.5% / 2050: 100%), assuming that more ambitious policies will tighten the current targets and impose a complete phase-out on fossil marine fuels by 2050. Domestic navigation is modelled to additionally adopt non-fossil hydrogen (alongside synthetic fuels) from 2035 onwards, assuming a linear growth between 2035 (14.5% e-fuel, 0% H2) and 2050 (70% e-fuel, 30% H2). Domestic aviation is assumed to transition to hydrogen propulsion between 2035 and 2050, like in EUBase (see section 3.2.2.1.2)

While EUTarget shares EUBase's assumptions for transport activity, EUSupreme assumes different stock sizes and transport performance developments: For passenger cars, the stock development of the "world of mobility services" scenario from Krail et al. (2019), which models an ambitious decline in individual car ownership in the ASTRA-M model, was adopted for Germany and extrapolated to the other EU27 countries. Here, passenger car stocks in 2050 are reduced by 25%, compared to the reference scenario adopted in EUBase. As EUSupreme assumes unchanged mileages per car, this reduction translates to a 25% reduction in total driving performance of the car stock compared to EUBase and EUTarget. This decrease in total driving performance can be interpreted as a partial shift from car ownership to the use of public transportation (which is represented by the rail subsector in this study as buses are not modelled separately and therefore cannot be evaluated individually, see model description in section 2.3.2.1.2), ridesharing, or active modes. Unlike in EUBase and EUTarget, the annual mileage of commercial vehicles is not increasing over time. Commercial vehicle stocks in 2050 are reduced by 11% for light-duty trucks and 21% for heavy-duty vehicles, compared to EUBase/EUTarget, accounting for a shift in freight transport from road to rail and to inland waterways. Note that this still implies a growth of 23% in commercial vehicle stocks between 2020 and 2050, just not as strong as in EUBase and EUTarget. International maritime transport is reduced by 10% between 2020 and 2050, representing a declining need for container shipping in a more sufficient world. Whereas EUBase and EUTarget model a steady growth of aviation, EUSupreme assumes that air transport performances between 2019 and 2050 are linearly reduced, by 10% in international aviation and by 50% in domestic aviation. This represents that people increasingly avoid flights (or possibly that some flights are not offered anymore due to flight bans) or switch to high-speed rail. In turn, EUSupreme assumes higher transport performances in domestic navigation (+20% in 2050) and both passenger and freight rail transport.

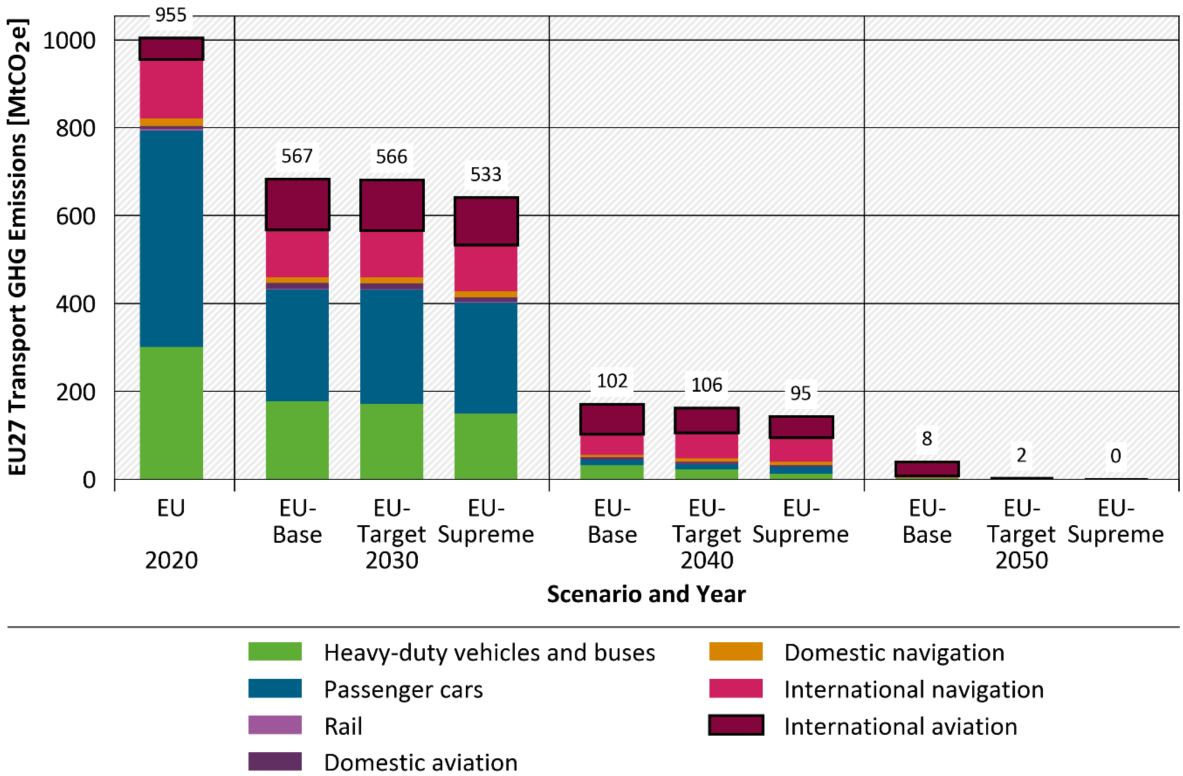
3.2.2.1.6 Results

This section presents the transport sector results for the two target scenarios. For both EUTarget and EUSupreme, it starts by presenting the overall trajectory for the GHG emissions and the final energy demand, before detailing the results on subsector level. The presented energy demands and emissions are the outputs of the transport sector modeling introduced in section 2.3.2., calibrated on GHG emissions of 2019 and parameterized according to the assumptions presented in the previous section 3.2.2.1.5.

Compared to 2020, **EUTarget** shows reductions in fossil GHG emissions of 32% by 2030, 84% by 2040, and 100% by 2050 (see Figure 53). Until 2030, the emission trajectory is almost identical to that of EUBase, due to the similar electrification of passenger cars. In 2040, emissions are further reduced driven by the accelerated diffusion of alternative drivetrains in medium-duty and heavy-duty trucks in the 2030s, compared to EUBase. In 2050, GHG emissions are near zero: Only 2.3 Mt CO_2 are left, caused by very few diesel-fuelled heavy-duty vehicles left in the stock for which the switch to the BEV is not feasible in the agent-based model due to their range requirements. Besides the electrification of road transport, which was already observed in EUBase, this is made possible by the complete substitution of fossil fuels by non-fossil alternatives in aviation and navigation, which drive the emission reduction in the 2040s. Note that, like in EUBase (and EUSupreme), road vehicles are modelled to leave the stock after a deterministic lifetime. In reality, it is expected that a share of the vehicles will remain in service for longer (and some shorter), with their average mileage and thus their fuel consumption decreasing as they age.

Compared to 2020, **EUSupreme** shows GHG reductions of 36% by 2030, 86% by 2040, and 100% by 2050. GHG emissions in 2050 are zero; all remaining fuel volumes are non-fossil. While both EUTarget and EUSupreme achieve a 100% reduction in the long term, EUSupreme differs in that it achieves higher emission reductions along the way. The decline in emissions is accelerated in EUSupreme as the emission and energy intensity reductions (which were already part of EUTarget) are combined with sufficiency measures. These sufficiency measures reduce the energy demand further and hence mitigate the associated emissions. The energy demand pathways of the target scenarios are discussed in more detail in the following.

Figure 53: GHG emissions of the EU27 transport sector under the EUBase, EUTarget and EUSupreme scenarios



Source: own calculations Fraunhofer ISI

number relates to total generated GHG emissions excl. int. aviation, visually set apart for this reason

Figure 53 illustrates the transport sector's final energy demand in the three scenarios.

EUTarget shows total energy demand reductions of 21% by 2030, 51% by 2040, and 57% by 2050, compared to 2020. Developments by subsector are detailed in the following.

The passenger car segment contributes the most to the observed overall decrease in energy demand and emissions. Since the applied logistic diffusion model already reached a 2035 market share of 99% in EUBase, EUTarget - which exogenously sets the 2035 market share in new registrations to 100% - does not show notable differences in the passenger car model output, compared to EUBase.

The agent-based simulation for the commercial vehicle market also arrives at nearly the same 2050 results as EUBase – the stock is practically completely electrified (96% BEV and 4% catenary BEV). The shares of FCEVs (0.2%) as well as diesel-fuelled trucks (0.2%, including hybrids) in the stock are minuscule. However, in EUTarget, which assumed higher EU-ETS2 CO_2 prices than EUBase and thus less favourable conditions for diesel trucks and more favourable techno-economic conditions for zero-emissions drivetrains, the transformation of the commercial vehicle stock is slightly accelerated, compared to EUBase: While the diffusion of BEVs is proceeding at the same speed as in EUBase, FCEVs play a comparatively more important (but still minor) role in EUTarget's simulation, in which they temporarily make up 4% of heavy-duty vehicles (>12 t) and 5% of the medium-duty trucks (3.5-12 t) in the stock during the 2030s, before vanishing again. This results in a peak hydrogen demand of 30 TWh in 2040 and then declines to 1 TWh in 2050. The results suggest that at high CO_2 prices, FCEV can become economically viable compared to diesel trucks and hence could become the cost-effective solution in use cases where BEV is technically not feasible. Thus, in earlier years, when BEVs are assumed to be more restricted in their range, FCEVs are purchased for applications where the range of the modelled BEV is not sufficient. Note that the battery size is not a variable but a fixed parameter in the simulation. In reality, the investment in a BEV with a larger battery might be an available option. Conversely, in use cases with low mileage and low range requirements, a BEV with a smaller battery and hence lower purchase cost might become cost competitive with conventional trucks. Thus, the selection of different battery sizes might enable an even higher market penetration of battery electric commercial vehicles; this possibility is not considered in the present modeling.

Based on the same transport performance growth assumptions as EUBase, rail transport is gaining in importance in EUTarget as well, reaching a share of 4% of overall energy demand in transport. However, its absolute energy demand increases only slightly, from 54 TWh in 2020 to 60 TWh in 2050 (+11%) since the activity growth is largely offset by the energy efficiency gains that result from the additional electrification in EUTarget.

Total energy demands from aviation and navigation, both domestic and international, correspond to EUBase as transport activity and energy efficiency assumptions are the same. However, emissions are linearly decreased, reaching zero in 2050, as defined by the non-fossil fuel quotas assumptions in EUTarget.

The EUSupreme scenario illustrates the impact of the implementation of sufficiency measures aimed at reducing energy consumption in addition to the technology-enabled energy efficiency gains (that were already implemented in EUTarget). The overall energy demand decreases by 66% from 3880 TWh in 2020 to 1330 TWh in 2050. The final energy demand in 2050 is therefore 20% lower than those of EUBase and EUTarget. Developments by subsector are detailed in the following.

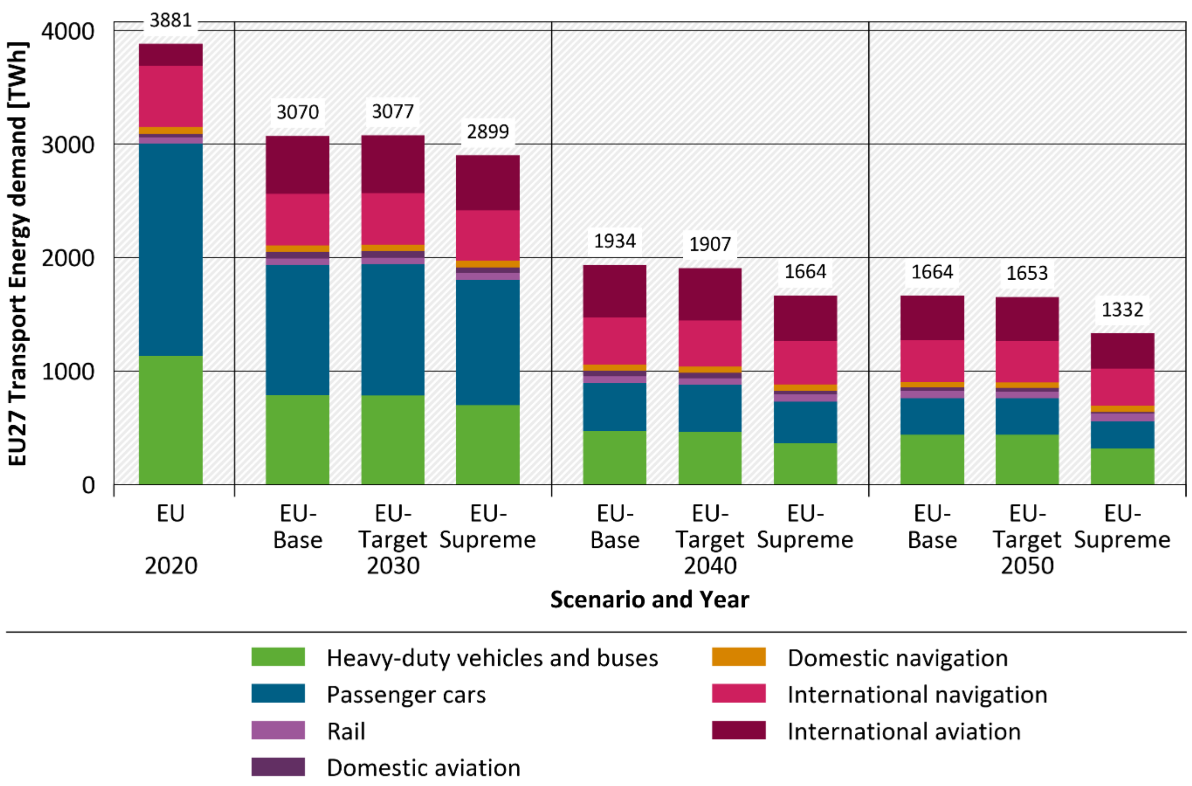
Passenger cars' electrification leads to a total energy demand decrease to 240 TWh until 2050. This is 25% less electricity needed than in EUTarget and results directly from the assumed 25% reduction in car stock.

The energy demand from commercial vehicles is lowered to 310 TWh (-28%, compared to EUTarget) due to the assumption that vehicle stocks and driving performances do not grow like in EUBase and EUTarget. Like in EUBase and EUTarget, battery electric trucks prevail – the commercial vehicle stock in 2050 is made up of 96% BEVs and 4% catenary BEVs. Lower hydrogen price assumptions in EUSupreme (see general modeling assumptions in section 2.4) lead to a temporary share of FCEVs in the medium-duty and heavy-duty segments, in which they make up to 6% of the stock in the mid-2030s, peaking at an annual hydrogen demand of 40 TWh, before vanishing again. Like in EUBase and EUTarget, very few conventional and diesel hybrid trucks remain in operation in 2050 (0.3% of the commercial vehicle stock); their diesel fuel demand of 7 TWh is covered exclusively by non-fossil fuels to comply with a strict ban of fossil fuel in 2050, when net-zero is to be achieved.

In aviation and navigation, the differences in EUSupreme's energy demand (and proportional to that, emissions) compared to EUBase/EUTarget result directly from the modifications in transport activity, with international aviation reduced by about 20%, domestic aviation by 60%, international maritime by 10%, and domestic maritime increased by 20%.

The total energy demand of rail transport grows from a total of 54 TWh of electricity and diesel in 2020 to 69 TWh of electricity in 2050 (+29%). The difference of 9 TWh in the 2050 electricity demand compared to EUTarget results from the higher transport activity growth assumptions. Combined with the reduced transport activity in trucking and aviation, rail transport plays a more important role in EUSupreme than in the other scenarios – in 2050, it is responsible for 5% of the final energy demand and for 11% of the electricity demand in transport.

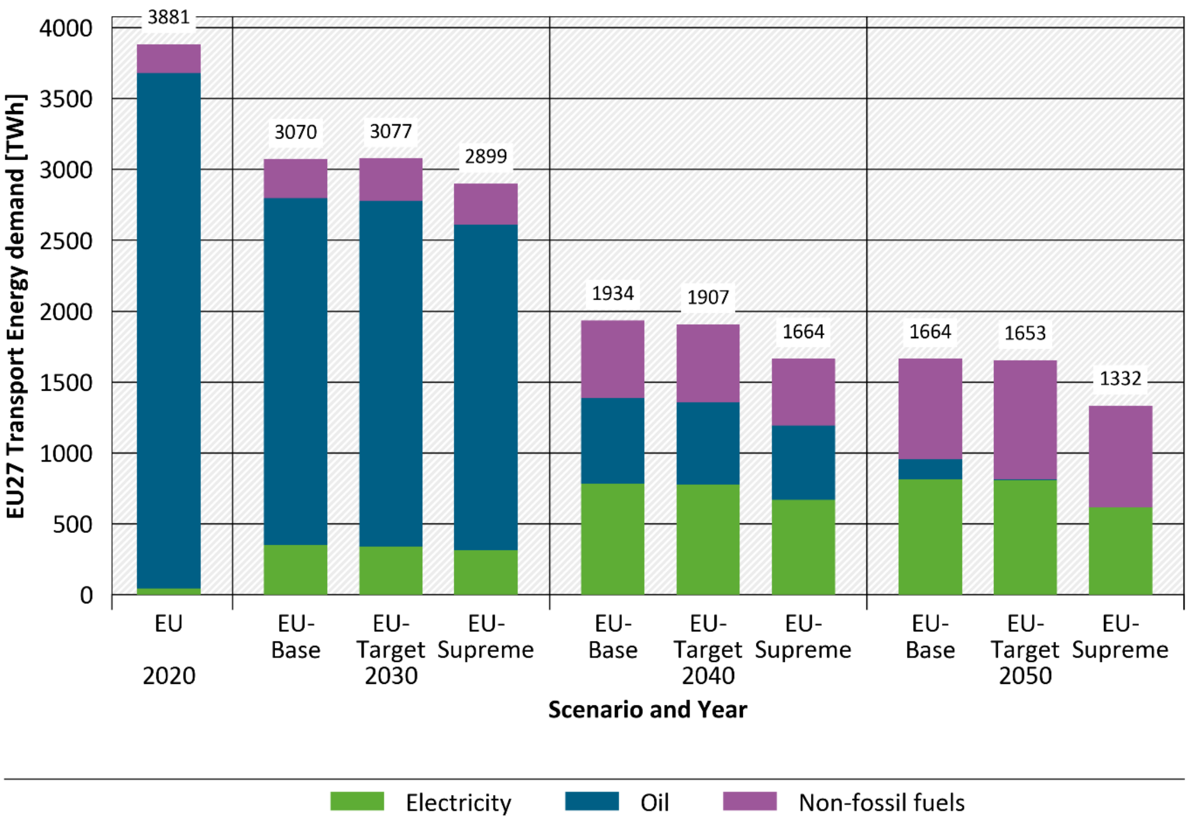
Figure 54: Final energy demand of the EU27 transport sector under the EUBase, EUTarget, and EUSupreme scenario



Source: own calculations Fraunhofer ISI

Figure 55 differentiates the transport sector's energy demand for EUBase, EUTarget, and EUSupreme by energy carrier. 2020 represents the starting point of the transport sector transformation, which relies heavily on hydrocarbon fuels, produced mainly from oil (94%) and to a small part from biomass (5%). Electricity has a small share (1%) - it is used in the rail transport subsector, whose importance in terms of energy demand is minor, and by plug-in electric cars, which only make up a negligible share of the vehicle stock. By 2040, oil-based fuels are only responsible for less than a third, while electricity makes up already 40% of the transport sector's final energy demand. Please note that electric powertrains have a much higher efficiency than the conventional powertrains, meaning that the share of fossil transport activity is even lower. Until 2050, all three scenarios show a near-complete electrification of road transport. Consequently, the electricity demand of EUBase and EUTarget reach the same level of about 800 TWh in 2050. In EUSupreme, which considers a reduction of road transport through modal shifts, the 2050 electricity demand is reduced by 25%, compared to EUBase and EUTarget. The switch to electric powertrains in road and rail transport means that hydrocarbon fuels are exclusively needed in aviation and navigation in the future. In these hard-to-abate subsectors, all three scenarios model the substitution of fossil fuels with non-fossil fuels. Consequently, the reduction in oil-based fuels is accompanied by an increase in non-fossil fuels. The current EU regulations, on which EUBase is built, set an ambitious pathway for the use of sustainable fuels respectively for emission intensity until 2050, but do not yet prescribe complete defossilization. EUTarget models the same energy demand as EUBase in aviation and navigation but also replaces the remaining 130 TWh of fossil fuels from EUBase with non-fossil fuels to achieve zero emissions. EUTarget therefore shows an accordingly increased demand for non-fossil fuels while completely avoiding fossil fuels. EUSupreme on the other hand also achieves zero emissions but, due to its lower overall energy demand in aviation and maritime transport, only consumes about the same amount of non-fossil fuels like EUBase. Thus, even if the effect of EUSupreme's additional sufficiency measures might appear low compared to the impact of road transport electrification, they are valuable as they reduce the demand for potentially scarce and costly non-fossil fuels needed in hard-to-abate areas, e.g., aviation and maritime transport.

Figure 55: Final energy demand in the EU27 transport sector (incl. international bunkers) under the EUBase, EUTarget and EUSupreme scenarios, by energy carrier.



Source: own calculations Fraunhofer ISI

3.2.2.2 Comparison of scenario results (EUBase, EUTarget, and EUSupreme)

This section compares the three scenarios in terms of energy demand and GHG emissions and draws conclusions for the transport modes and the overall picture of the transport sector.

In terms of **energy demand**, all scenarios show a drastic reduction compared to today's energy demand of the transport sector, which heavily relies on oil-based fuels that are burned in inefficient combustion engines. Energy demands of EUBase and EUTarget halve until 2040, primarily driven by the near-complete transition to electric powertrains in road transport, which is responsible for 75% of today's energy demand. After road transport electrification is complete, total energy demand only decreases slowly until 2050 due to general efficiency improvements in all subsectors. EUBase and EUTarget share an almost identical energy demand pathway because the model outputs in road transport are very similar while aviation and navigation only differ in their fuel mix but not in their total energy demand. In addition of the energy efficiency improvements achieved by the large-scale electrification of road transport, the sufficiency assumptions of EUSupreme do further reduce the overall energy demand by 320 TWh in 2050.

In terms of **GHG emissions**, EUBase and EUTarget show similar trajectories until 2040 but differ afterwards because EUTarget models a complete defossilization until 2050, whereas the EUBase scenario definition allows fossil aviation and marine fuels. EUSupreme achieves higher emission reductions in each considered year (apart from 2050 when both EUTarget and EUSupreme reach practically zero emissions), compared to EUBase and EUTarget. This is due to the fact that its overall reduced energy demand (while having the same ambition level as EUTarget in terms of electrification and non-fossil fuel quotas) leads to a lower fossil fuel demand. Please note that only direct GHG emissions from transport are considered and that the reductions in vehicle stock and total energy demand may have a higher overall impact as they reduce indirect GHG emissions (e.g., from battery or fuel production) that are not part of the transport sector's scope. This is particularly relevant in aviation, whose climate impact does not only result from the total amount of CO_2 emissions but also from the combustion of fuels at high altitudes. These non-CO_2 effects of aviation remain even when non-fossil fuels are used and are not taken into account in this study's modeling.

Road transport is the dominating subsector in terms of energy demand and emissions today; therefore, its electrification is the main driver of the energy consumption and emission reductions achieved in all three scenarios. The fact that all three scenarios result in a practically complete road transport electrification highlights that the complete transition to electric vehicles is a robust outcome. This similarity of the scenarios has multiple reasons. In passenger cars, the policy in force is driving the automotive industry to completely abandon combustion-based technology. The absence of viable alternatives makes a complete switch to BEV unavoidable and has led to very similar scenario definitions. In commercial vehicles, where modeling has included several powertrain options, the outcome regarding electrification has shown to be very robust, even if circumstances between the scenarios vary. This demonstrates that the transition to battery electric trucks is possible and economically viable in most use cases. FCEVs as alternative zero-emission technology are shown to be not competitive to BEVs for the large majority of use cases and hence have a long-term market share of less than 1% in the three scenarios, which questions if the necessary hydrogen refuelling infrastructure will be build up and if hydrogen-fuelled trucks will become a mass market product at all.

Rail transport is also further electrified but this ongoing process is of comparatively little relevance for emission reduction due to the minor importance of rail transport in terms of total energy demand and the fact that most rail transport activity in the EU is already performed by electric trains today. However, this does not mean that rail transport itself is irrelevant – the subsector's low energy demand is also a result of its superior energy efficiency and shifts from road to rail transport are generally associated with additional energy savings. Therefore, rail transport has a higher energy demand in the EUSupreme scenario than in the EUBase and EUTarget scenarios.

In the hard-to-abate subsectors of **aviation** and **navigation**, the scenarios reflect that, from today's knowledge, sustainable drop-in fuels are the only viable way to fully eliminate fossil emissions in time. Here, the main difference between the EUBase and the two target scenarios is observed: As the non-fossil fuel quota pathway derived from existing EU policies does not reach 100%, there is a fossil fuel demand left in the EUBase scenario, leading to fossil emissions. This gap is filled in the target scenarios, where the more ambitious non-fossil fuel quotas reach 100% in 2050. Both target scenarios achieve zero emissions in the long term, but the lower energy demand achieved through reduced transport performances in EUSupreme requires smaller non-fossil fuel volumes to achieve this goal and leads to lower emissions in the years before 2050.

Overall, the scenarios show fundamentally similar and clear pathways for future transport: electrification on land combined with a fuel switch on the water and in the air. On land, the transition to electric powertrains, which are associated with zero GHG emissions in operation and are more energy efficient than conventional powertrains, provides a no-regret option: Not only do electric vehicles enable a zero-emission road transport, they also reduce the total energy demand that has to be supplied in the energy system and free up non-fossil fuel volumes that would otherwise be bound by road vehicles, for use in aviation, navigation, or other hard-to-abate demand sectors outside of the transport sector. While electrification and the uptake of non-fossil fuels are a necessity to achieve net-zero in transport, sufficiency measures can support this transformation by reducing the overall energy demand, thereby accelerating absolute emissions reductions, lowering the demand for non-fossil fuels, and mitigating indirect emissions.

3.2.3 Buildings

The building sector in the European Union is a key pillar of energy and climate policy. It covers final energy use in households as well as in commercial and public services, including residential, tertiary, and public buildings. This definition captures the energy needed for space heating and cooling, domestic hot water, lighting, appliances, and other building-related services. It explicitly excludes the industrial sector.

Collectively, the EU's building stock accounts for approximately 40% of final energy consumption and over one third of energy-related greenhouse gas emissions (Directive (EU) 2024/1275). Space heating dominates the energy use, especially in residential buildings, while cooling demand is growing steadily in response to climate change. In both residential and non-residential buildings, lighting, appliances, and information and communication technologies (ICT) represent a significant share of electricity consumption. In households, these include refrigeration, cooking, entertainment, and smart home systems, while in non-residential buildings – such as offices, schools, and hospitals – large loads stem from lighting, ventilation, computing, and specialised equipment.

In terms of heating and cooling energy use, a large share of the EU building stock is outdated and inefficient. Roughly 75% of buildings are considered energy-inefficient, yet 80–90% of today's buildings will still be in use in 2050. With current renovation rates standing at around 1% per year, deep renovation and electrification are central to the EU's decarbonization pathway (Energy Performance of Buildings Directive (EU) 2024/1275). The integration of renewable technologies, such as heat pumps, solar thermal, and photovoltaic systems, is increasing but remains uneven across Member States.

To address these challenges, the EU has put in place a robust policy framework. The recast Energy Efficiency Directive (Directive (EU) 2023/1791) and the recast Energy Performance of Buildings Directive (Directive (EU) 2024/1275) form the backbone of the EU's efforts to improve building performance. They include targets for energy savings, Minimum Energy Performance Standards (MEPS) for non-residential buildings, trajectories for renovation of the residential building stock, requirements for smart readiness, and the phase-out of fossil fuel-based heating. In parallel, the EU Emissions Trading System 2 (Directive (EU) 2023/959) introduces carbon pricing for fuels used in buildings and transport from 2027 onward, sending a price signal to encourage decarbonization. At the product level, the EU Ecodesign (Directive 2009/125/EC) and Energy Labelling frameworks (Regulation (EU) 2017/1369) set minimum efficiency requirements and provide transparency for appliances, lighting, and heating systems. These measures have been instrumental in reducing electricity demand from household and office equipment and are evolving to address lifecycle impacts and repairability under the Ecodesign for Sustainable Products Regulation (ESPR) (Regulation (EU) 2024/1781).

The three scenarios explored in the following analysis illustrate a spectrum of possible futures for the EU building sector. They reflect varying degrees of reliance on technological innovation, energy efficiency measures, and changes in behaviour and lifestyles (energy sufficiency). While EUBase represents a continuation of current trends and policies (business-as-usual), EUTarget aligns with existing EU climate and energy goals. The most ambitious of the three, EUSupreme, outlines a pathway that maximises all available levers for decarbonization. Together, these scenarios highlight the critical choices and trade-offs ahead and provide insights into how different policy approaches can shape the building sector's contribution to the EU's climate neutrality target.

3.2.3.1 EUBase scenario

3.2.3.1.1 General description

The EUBase scenario for the buildings sector serves as a reference scenario for the two target scenarios (EUTarget and EUSupreme). The EUBase scenario is based on current policies: This means that CO_2 prices, as they are foreseen in the EU-ETS 2, are implicitly taken into account in the modeling of EUBase (see data inputs in appendix B). Another crucial driver in the modeling is the renovation rate, which is based on the renovation rates from the PRIMES modeling for the Fit-for-55 MIX scenario (up until 2030)[39], which in turn reflects the current policies at the time of calculation of EUBase (2022). Minimum energy performance standards (MEPS) for non-residential buildings, however, have not been taken into account in the EUBase scenario, since they have only recently been adopted in the revised EPBD in 2024 (after the EUBase scenario was calculated). The adoption of appliances and processes in the household and tertiary sectors likewise follows business-as-usual trends, with the MEPS prescribed by the EU Ecodesign implementing regulations in particular driving effective reductions in energy demand over time.

3.2.3.1.2 Main assumptions

3.2.3.1.2.1 Space heating and cooling

The modeling assumptions for space heating and cooling in the EUBase scenario is by and large based on the continuation of already implemented policies in the buildings sector (as of mid-2022). Energy standards for new and refurbished buildings are not increasing in ambition over time. Minimum energy performance standards (MEPS) as are being discussed for the EPBD recast are not considered, neither are national legislations such as, e.g., the current German

[39] The PRIMES Fir-for-55 MIX scenario assumes, amongst other things, the introduction of buildings emissions in the EU ETS 2 from 2027, a medium level of energy efficiency efforts, and building retrofits based on cost-efficiency

Building Energy Law, which was amended as recently as autumn 2023 (i.e. after modeling the scenario). The renovation rates are based on the Fit-for-55 MIX scenario with rates staying at the 2030 levels until 2050. Since CO_2 prices are not directly integrated into the buildings model, the scenarios are modelled by making and parameterising assumptions regarding the implementation of policies such as the introduction of the EU ETS 2. These are translated into changes in uptake rates of certain heating technologies. For the EUBase scenario, recent trends reflecting the increasing uptake of renewable energy heating systems, such as heat pumps, are implemented. Traditional if modernised fossil fuel boilers for gas (and oil where applicable) are still being installed, but in reduced numbers as we approach 2050. Coal usage is steadily reduced over time and completely phased out by 2050.

Demolition rate: the demolition rate is based on historical data from Germany[40]. The rate is increasing over time – for residential buildings it starts at 0.15 % per year in 2015 and reaches 0.50 % per year by 2050, for non-residential buildings it starts at 0.30 % per year in 2015 and reaches 1.00 % per year by 2050 (see Table 21). Due to increased migration away from countries of the North-eastern and Eastern clusters (cf. Table 2), the demolition rates for residential buildings for these two clusters were specifically controlled and increase slightly more in comparison to the other clusters.

Table 21: Demolition rates (EUBase)

	2015	2020	2025	2030	2035	2040	2045	2050
Residential	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Residential (Cluster Northeast + East)	0.20	0.30	0.35	0.40	0.45	0.50	0.55	0.60
Non-residential	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00

Source: PRIMES Fit for 55 MIX (until 2030), assumptions Oeko-Institut (from 2035 onwards)

Rate of newly built buildings: the rate of newly built buildings is based on a regression analysis for the entire EU (historical data from 2000 to 2014), both for residential and non-residential buildings. For residential buildings, the rate of newly built buildings in each country is calculated according to $y = 0.81\,x + 1.0$ where y is the rate of newly built buildings and x is the change in population growth two years previously (i.e. the rate in e.g. 2020 is based on the population change in 2018). For non-residential buildings, the rate is based on $y = 0.62\,x + 1.1$ where y is the rate of newly built buildings and x is the change in GDP with respect to the previous year.

Renovation rate: the renovation rate is taken from the Fit-for-55 MIX scenario up until 2030 and, over time, increases in slightly different ways depending on the cluster considered – see Table 22. For the EUBase scenario the post-2030 rates are kept constant at 2030 levels.

Table 22: Assumptions on renovation rates for each cluster (residential buildings, EUBase)

As % of total floor area	2020	2025	2030	2035	2040	2045	2050
North	0.83	1.49	1.20	1.20	1.20	1.20	1.20
Northeast	0.91	1.42	1.84	1.80	1.80	1.80	1.80
East	1.03	1.52	2.04	2.00	2.00	2.00	2.00

[40] At the time of calculating the scenarios demolition rates were only known for Germany.

As % of total floor area	2020	2025	2030	2035	2040	2045	2050
South	0.84	1.44	2.34	2.30	2.30	2.30	2.30
West	1.10	1.77	2.22	2.20	2.20	2.20	2.20
Central	0.91	1.78	1.78	1.80	1.80	1.80	1.80

Source: PRIMES Fit-for-55 MIX (until 2030), assumptions Oeko-Institut (from 2035 onwards)

Energy standard of new buildings: All clusters start with a space heating FED for new buildings of 60 kWh/(m^2a) in 2017. The only exception is the cluster "South", where the existing building stock space heating FED partly lies below 60 kWh/(m^2a): here new buildings are being built with a FED of 48 kWh/(m^2a), which is a reduction by 20 % compared to the other clusters. The values were chosen after assessing the current (i.e. 2017) values for space heating demand of the existing building stock in each cluster. The energy standards for new buildings are kept constant in the EUBase scenario.

Energy standard of renovated buildings: Renovated buildings follow a similar pattern. Here the renovation standard for newly renovated buildings starts at 80 kWh/(m^2a) in 2017 and is kept constant in the case of the reference scenario for all years up to 2050. Clusters with existing building stock space heating FED below 80 kWh/(m^2a) keep their 2017 energy standards for all years up to 2050.

Energy carrier distributions: Based on the status-quo energy carrier distributions in the different country clusters (starting year 2017), we defined energy carrier distributions for each cluster for 2050, based on the assumptions that limitations for new fossil boilers will be implemented over time. In the EUBase scenario heating oil usage is cut by about half in each cluster. Gas usage is also substantially reduced in each cluster. Coal is entirely phased out by 2050. We differentiate between the different fossil fuel types based on their emission factors – the higher the emission factor, the faster the phase-out. This tries to reflect the effects of the ETS 2 regime. Heat pumps compensate for most of the reductions in fossil fuels. The main differences between country clusters relate to the use of biomass and district heating. The Nordic, eastern and many southern countries historically have a high share of district heating, which we tried to emulate in the EUBase Scenario. Biomass being a much sought-after energy carrier with limited availability is reduced substantially in its use in buildings – nonetheless it is still in use in 2050, especially in country clusters that show a strong historical reliance on biomass (i.e., clusters North, Northeast, East and South).

Floor area per person: The development of the floor area per person in residential buildings rises by approx. 10 m^2 from 39 m^2 per person in 2020 to 49 m^2 per person by 2050. This is not a direct assumption but follows from the fact that the rate of newly built buildings exceeds the buildings' demolition rate. The resulting per person floor area is a good indicator for an efficient (and sufficient) use of the available floor area and allows for a good comparison between the different scenarios.

3.2.3.1.2.2 Appliances and processes

Buildings, whether residential or non-residential, use a wide range of appliances and processes beyond just space heating and cooling (see section above). These appliances and processes include electrical equipment (computers, televisions, etc.), kitchen appliances (ovens, dishwashers, etc.), laundry equipment (washing machines, dryers), lighting systems (LED lights, CFLs, etc.), refrigeration systems (refrigerators, freezers), process heating systems (dryers, furnaces, etc.) and others. All these appliances and processes contribute significantly to the energy consumption of buildings.

In the EUBase scenario, the diffusion and use of appliances and building-related processes in both residential and non-residential buildings largely follow business-as-usual trends, with no additional policy ambition beyond what is already implemented. Energy efficiency improvements continue incrementally, driven primarily by ongoing updates under the EU Ecodesign and Energy Labelling frameworks, but no major expansions or tightening of standards are assumed. Market uptake of highly efficient or smart appliances remains moderate, as purchase decisions are often guided by upfront cost rather than lifecycle efficiency. Behavioural patterns and usage intensity show little change, without explicit adoption of sufficiency-oriented practices such as reduced standby consumption or smaller/fewer appliances.

Prices: Cross-sectoral CO_2 pricing is directly taken into account via the consumer energy prices for electricity and fuels. Through the ETS II, applications that can run on fossil fuels (natural gas, LPG, diesel, etc.) rather than electricity are also addressed, including ovens, steam boilers, and forklifts. In principle, higher prices provide greater incentives for households and firms to adopt energy-efficient equipment.

Ecodesign and energy labelling: The EU's energy labelling and ecodesign legislation aims to enhance the energy efficiency of appliances and processes available in the EU market. The Ecodesign directive establishes universal minimum standards across the EU to eliminate the least energy-efficient products from the market. Energy labels, on the other hand, offer an easy-to-understand indication of the energy efficiency and other essential features of products at the point of sale. As summarized in Table 23, existing provisions reported in (European Commission 2022) are taken into account in the bottom-up technology stock models Forecast-Appliances (section 2.3.3.2 and Forecast-Tertiary (section 2.3.3.3).

Table 23: EU Ecodesign and labelling requirements by product group considered in the EURef scenario

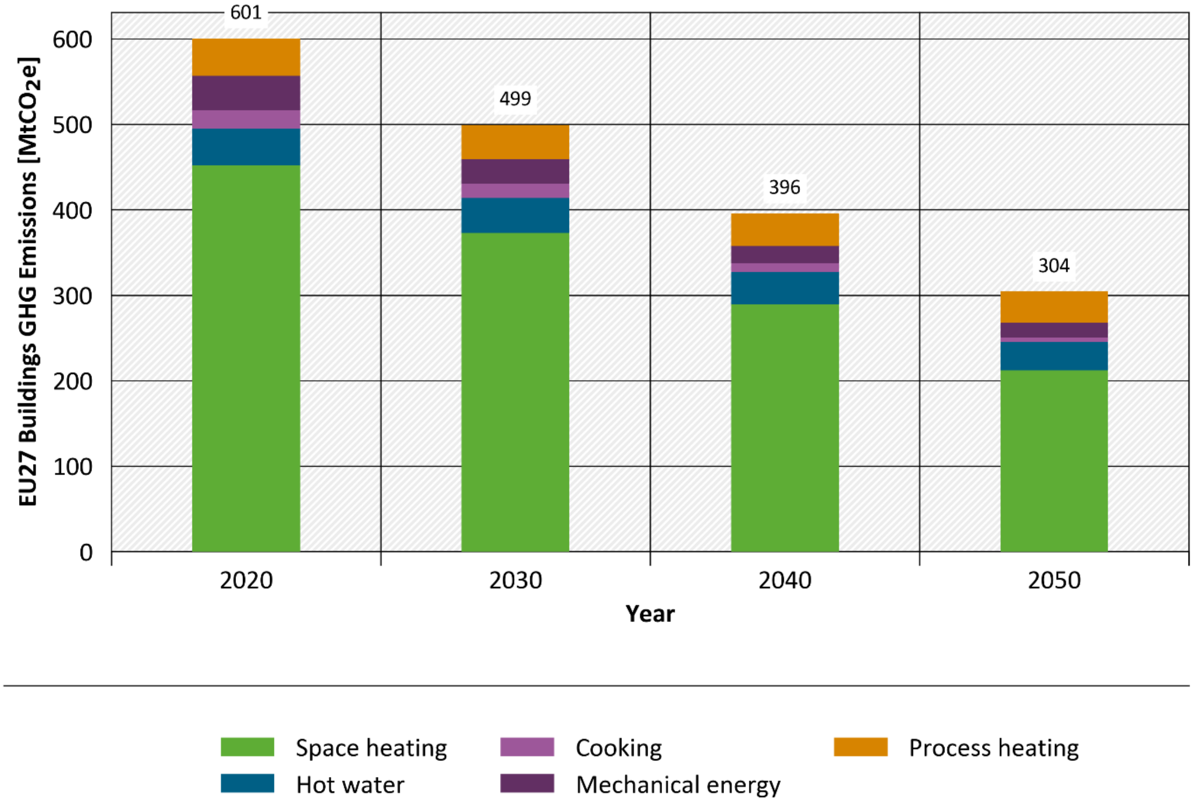
Product group	Ecodesign	Labelling
Computers	Regulation (EU) 617/2013	no legal requirements
Dishwashers	Regulation (EU) 2019/2022	Regulation (EU) 2019/2017
Domestic cooking appliances: ovens, range hoods, hubs	Regulation (EU) 66/2014	Regulation (EU) 65/2014
Household fridges and freezers	Regulation (EU) 2019/2019	Regulation (EU) 2019/2016
Light sources and control gears	Regulation (EU) 2019/2020	Regulation (EU) 2019/2015
Professional refrigeration equipment	Regulation (EU) 2015/1095	no legal requirements
Refrigerating appliances with sales function	Regulation (EU) 2019/2024	Regulation (EU) 2019/2018
Servers and data storage products	Regulation (EU) 2019/424	no legal requirements
Simple set-top boxes	Regulation (EU) 107/2009	no legal requirements
TVs/Electronic displays	Regulation (EU) 2019/2021	Regulation (EU) 2019/2013
Washing machines + washer-dryers	Regulation (EU) 2019/2023	Regulation (EU) 2019/2014

3.2.3.1.3 Results

Figure 56 shows the GHG emissions for the EUBase scenario split by end use. Since only direct emissions are included, space heating clearly dominates the overall emissions contributing 452 to the total of 601 Mt CO_2e in 2020 (a share of 75%) and 212 of 304 Mt CO_2e in 2050 (approx.

70%). The reduction in GHG emissions for space heating derives from a combination of gains in energy efficiency through renovation of existing buildings, and a shift away from fossil energy sources to higher shares of renewable energy sources, mainly to heat pumps. Because of the GHG balancing logic, replacing an old fossil-fuel boiler by a heat pump shifts the carbon accounting from the buildings sector to the supply sector, which is another reason for the drop in GHG emission in Figure 56. Since hot water is also increasingly generated from heat pumps, there is a similar, but less pronounced drop in GHG emissions for hot water. Mechanical energy comes from the tertiary sector and includes, for example, motors, pumps, compressors, elevators and escalators, and conveying systems. Process heat is comprised of generic ovens and drying processes in the services sector, whereas cooking encompasses food-related fuel usage for stoves and ovens in households, canteens, bakeries and other segments.

Figure 56: Direct GHG emissions for the entire buildings sector (residential and non-residential) split by end use in the EUBase scenario

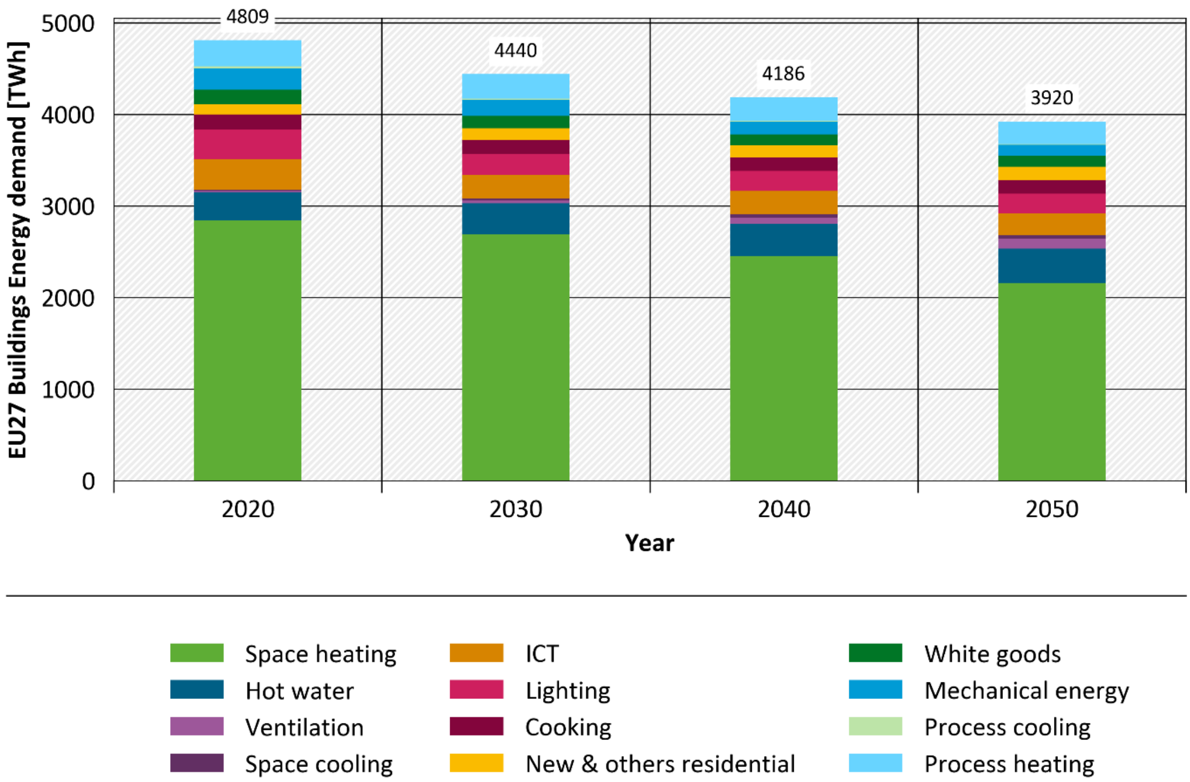


Source: own calculation Oeko-Institut & Fraunhofer ISI

Note: In line with emission balance principles, indirect emissions (Scope 2) from electricity and heat production are not included in the building sector, but under Supply (Chapter 2.3.4). Consequently, electricity-run heat pumps, appliances, lighting, ventilation and cooling equipment are not included in the building sector emissions balance.

Figure 57 shows the final energy demand of the total buildings sector split by end-use over time in the EUBase scenario. There is an overall reduction from 4,809 TWh in 2020 to 3,920 TWh in 2050 (reduction by 18.5%) with space heating clearly dominating the end-uses. Renovating existing buildings is the main driver in reducing the final energy demand for space heating. Compared to the GHG reductions, which are also reduced by electrifying via heat pumps and thereby shifting emissions to the supply sector (as can be seen in Figure 57), the reduction in final energy is only moderate.

Figure 57: Final energy demand for the entire buildings sector split by end use in the EUBase scenario

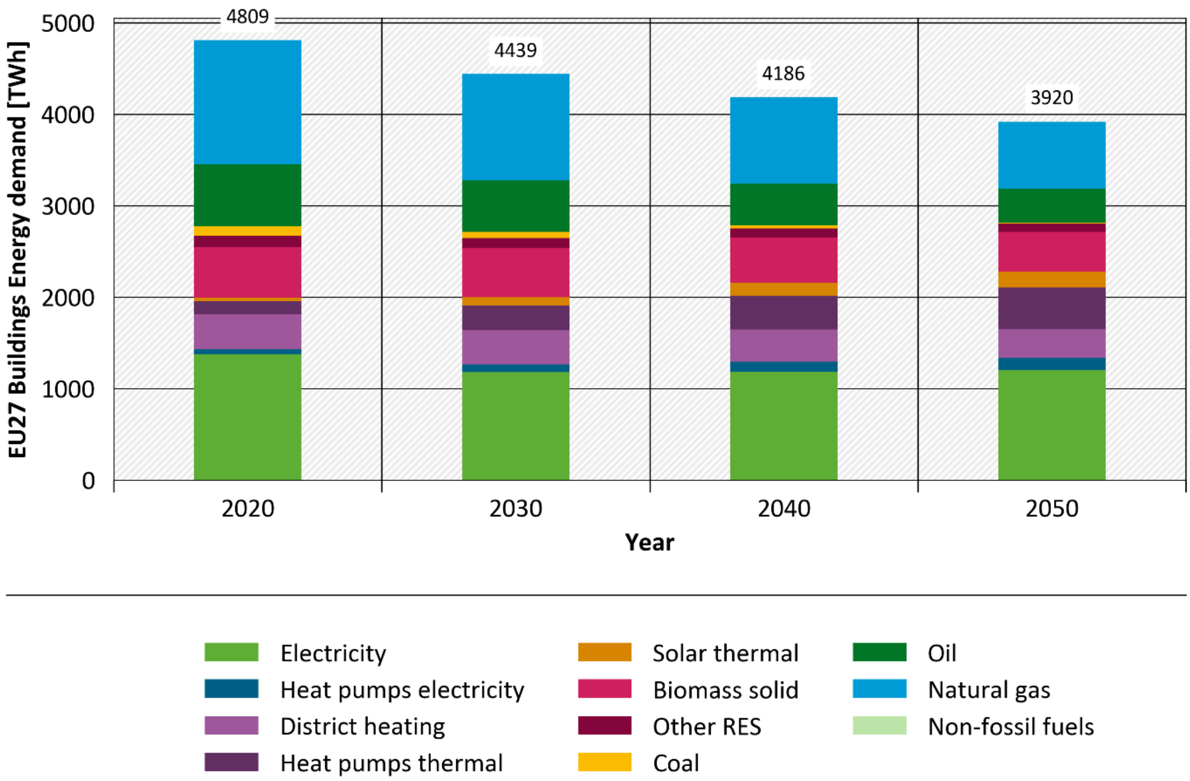


Source: own calculation Oeko-Institut & Fraunhofer ISI

"New & others residential" includes generated technologies not yet on the market (e.g. smart home innovations) and residual categories with limited data (e.g. niche or multifunctional appliances).

Figure 58 shows the final energy demand of the entire buildings sector, this time split by energy carriers. Whilst direct burning of fossil fuels decreases from a combined total of 2,136 TWh in 2020 to 1,111 TWh in 2050 (reduction by 48.0%), overall electricity demand stays nearly flat (1,431 TWh in 2020 and 1,334 TWh in 2050). The overall demand for electricity is the result of two opposing effects: firstly, there is a decrease in specific electricity demand due to gains made in energy efficiency in appliances, as well as less direct electrical heating (for space heating and hot water); secondly, affluence is associated with larger and often more appliances per household (e.g. televisions). Renewable energy sources such as ambient heat and solar thermal heat increase substantially, while biomass usage is reduced by around 20% (from 554 TWh in 2020 to 438 TWh in 2050). The change in energy carrier distribution over time closely follows the input parameters: fossil fuel usage is reduced substantially, district heating and renewable energy sources (ambient heat, solar thermal) increase, whereas biomass usage is decreased. With regard to appliances, it is evident that these are already predominantly electricity-driven in the base year 2020, and it is projected that there will be a modest reduction in final energy demand by 2050, largely driven by MEPS under the EU Ecodesign and autonomous efficiency progress.

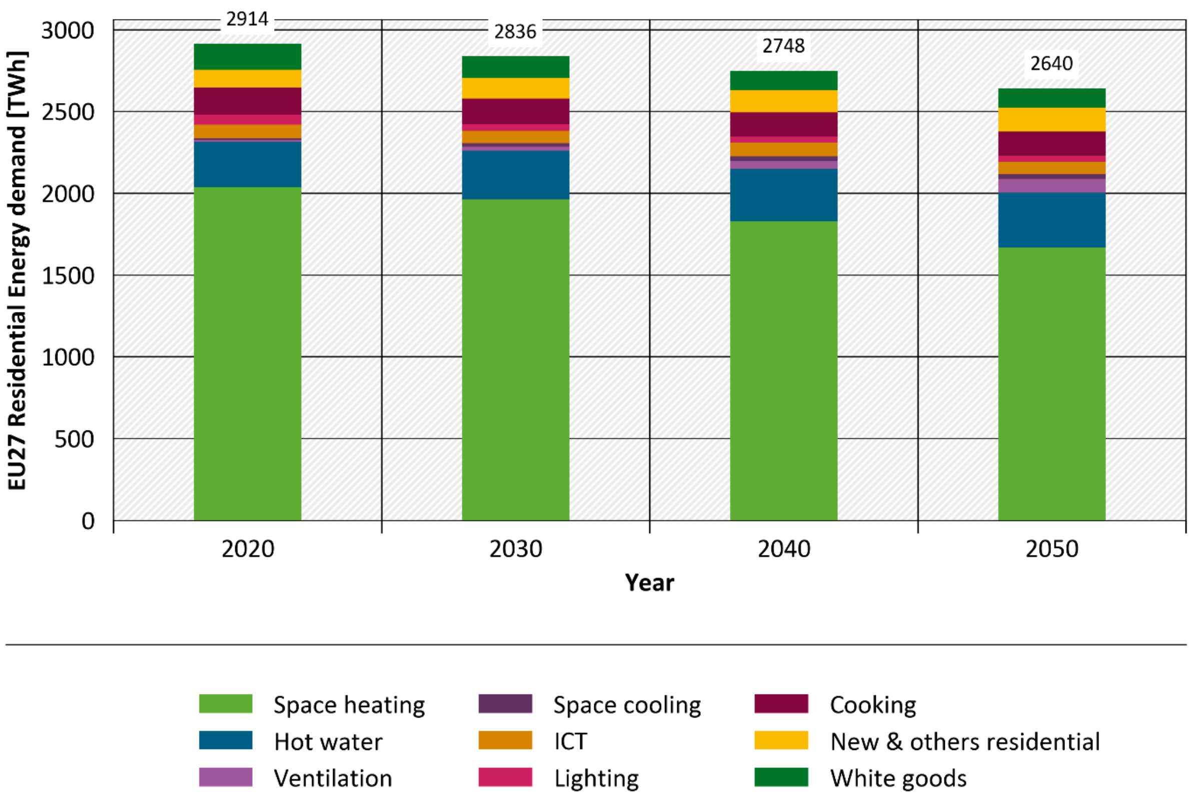
Figure 58: Final energy demand for the entire buildings sector split by energy carrier in the EUBase scenario



Source: own calculation Oeko-Institut & Fraunhofer ISI

Figure 59 below shows the final energy demand in residential buildings for different end uses. Whereas space heating decreases over time carrying the bulk of the overall reduction in final energy demand, hot water, cooling and ventilation all increase slightly over time. Overall final energy demand in residential buildings is reduced by 9.4% (from 2,914 TWh in 2020 to 2,640 TWh in 2050). The main driver behind reducing energy demand for space heating is the renovation rate for already existing buildings. To a lesser degree the combination of demolishing old (and energy-intensive) buildings and replacing them with new buildings with high energy efficiency standards also plays a role in the energy demand reduction.

Figure 59: Final energy demand by end-use in residential buildings

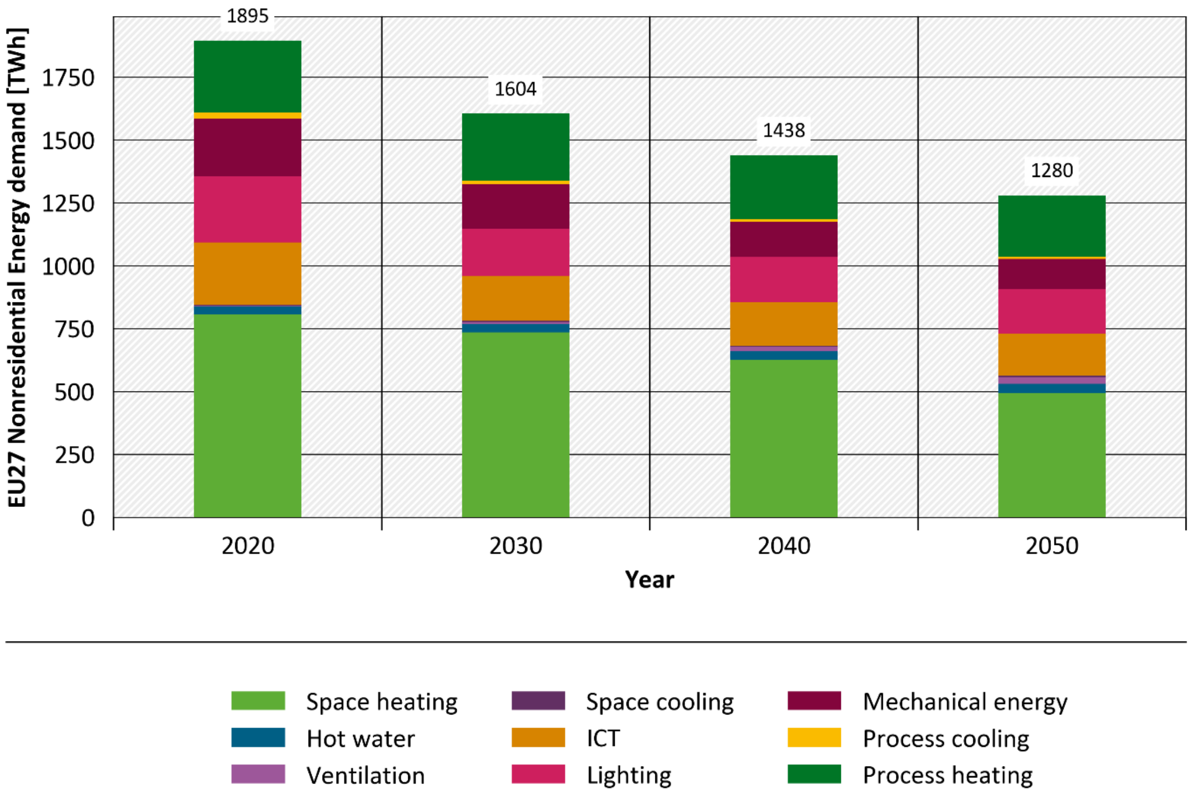


Source: own calculation Oeko-Institut & Fraunhofer ISI

The category of "New & others residential" encompasses technologies in the household sector that have not yet been commercialised, including smart home innovations, as well as residual categories for which data is limited, such as coffee machines, hairdryers and small kitchen appliances.

Figure 60 shows the final energy demand split by end-use for non-residential buildings. Reflecting residential buildings, non-residential buildings are also dominated by space heating, but to a much lesser degree with energy demand for space heating staying below 50% of the total energy demand in non-residential buildings. Again – similarly to residential buildings – all end-uses bar hot water, ventilation, and space cooling decrease markedly over time. Overall final energy demand in non-residential buildings is reduced by 32.5% (from 1,895 TWh in 2020 to 1,280 TWh in 2050). As for residential buildings, the main driver behind reducing energy demand for space heating is the renovation rate for already existing buildings. To a lesser degree the combination of demolishing old (and energy-intensive) buildings and replacing them with new buildings with high energy efficiency standards also plays a role in the energy demand reduction. Aside from space and water heating, the remaining categories experience a modest decline in final energy demand due to existing legal provisions as part of EU ecodesign (MEPS) and labelling (information), as well as energy price taxation and CO_2 pricing, which incentivize a shift from relatively inefficient fossil technologies (ovens, motors and steam boilers) towards more efficient electrified counterparts.

Figure 60: Final energy demand by end-use in non-residential buildings



Source: own calculation Oeko-Institut & Fraunhofer ISI

3.2.3.2 Target scenarios

3.2.3.2.1 General description and differences to EUBase scenario

The EUTarget and EUSupreme scenarios represent increasingly ambitious pathways for transforming the EU building sector beyond the baseline. In contrast to EUBase, which assumes a continuation of current trends, both EUTarget and EUSupreme have the goal, and are explicitly designed to achieve zero direct greenhouse gas emissions in the building sector by 2050, i.e. there are no remaining fossil emissions from the buildings sector in 2050. In EUTarget, stronger policy action drives a significant boost in energy renovations, tighter performance standards, and a rapid shift away from fossil fuels toward renewable heating solutions. The scenario also assumes higher efficiency in appliances and building systems, supported by enhanced Ecodesign performance standards, digitalisation, and moderate behavioural changes. EUSupreme goes a step further: renovation rates and depths are even higher, and biomass is used more selectively. Even more importantly, EUSupreme embraces energy sufficiency – encouraging more compact living, lower energy use through behavioural shifts (e.g. usage duration), and fewer, smaller electrical appliances.

3.2.3.2.2 Main assumptions

3.2.3.2.2.1 Space heating and cooling

The main assumptions and drivers for the two target scenarios EUTarget and EUSupreme are presented in Table 24.

In terms of demolition rates, all scenarios assume an increasing trend, starting at 0.2–0.4% per year in the 2020s and rising to 0.5–1.0% by 2050 in the EUBase scenario. The EUTarget scenario anticipates a slightly steeper increase, reaching 0.6–1.3% by 2050. This assumption follows the logic that the demolition of worst-performing buildings happens more often in EUTarget compared to the continuation of the historical trends seen in EUBase, as building owners opt for replacement buildings rather than realizing costly building renovations. The EUSupreme scenario follows the same pattern as EUTarget.

The rate of new construction is tied to population changes (for residential buildings) and GDP growth (for non-residential buildings) in both EUBase and EUTarget. However, the EUSupreme scenario assumes a 25% reduction in new construction to reflect increased sufficiency efforts and reduce the added floor area. The energy efficiency standard of new buildings remains constant at 60 kWh/(m^2a) in EUBase, but improves in the EUTarget and EUSupreme scenarios, decreasing linearly to 15 kWh/(m^2a) by 2040.

Renovation rates also vary, starting at 0.8–1.1% annually and reaching up to 2.3% by 2050 in EUBase. The EUTarget scenario accelerates this pace, reaching 2.75%, while the EUSupreme scenario is the most ambitious, with a renovation rate of up to 3.0% by 2050. Likewise, the renovation standard improves only in the EUTarget and EUSupreme scenarios, dropping from 80 kWh/(m^2a) in the 2020s to 30 kWh/(m^2a) by 2050.

Regarding energy carriers, the EUBase scenario – starting from historical country-specific energy carrier distributions – assumes a gradual shift to cluster averages by 2050. EUTarget envisions a faster transition away from gas and oil, with heat pumps becoming dominant and fossil fuels being completely phased out by 2050. The EUSupreme scenario accelerates this transition even further, with a stricter phase-out of fossil fuels and a more restrictive use of biomass, reducing it to zero by 2050.

Lastly, the EUBase and EUTarget scenarios make no explicit assumptions about sufficiency. The EUSupreme scenario, however, includes a reduction in per capita floor area, decreasing by 2 m^2 per person per decade starting in 2030, which leads to an EU-average per person floor area in 2050 of 43 m^2 (compared to 49 m^2 for EUBase).

Table 24: Buildings: Differences in assumptions in the EUBase, EUTarget and EUSupreme scenarios for space heating and hot water

Category	Description of variable	Assumption in EUBase Scenario	Assumption in EUTarget Scenario	Assumption in EUSupreme Scenario
Demolition rate	Rate describes the share of existing buildings that are demolished per year	Increasing demolition rates starting with 0.2-0.4% per year in the 2020s and rising linearly to 0.5-1.0% per year by 2050 (lower values are for residential buildings, higher values for non-residential buildings)	Slightly steeper rise in demolition rates reaching 0.6-1.3% per year by 2050	Same as EUTarget scenario
New construction rate	Rate at which new buildings are constructed	Linear regression depending on change in population (RES) or GDP (NRES)	same as EUBase scenario	New construction rate reduced by 25%

Category	**Description of variable**	**Assumption in EUBase Scenario**	**Assumption in EUTarget Scenario**	**Assumption in EUSupreme Scenario**
New construction standard	Average energy standard of new buildings	Constant at 60 kWh/(m²a)	Starting with an average of 60 kWh/(m²a) in the 2020s, linearly decreasing to 15 kWh/(m²a) by 2040	Same as EUTarget scenario
Renovation rate		Starting with 0.8-1.1% per year in the 2020s, reaching 1.2-2.3% per year by 2050	Starting with 1.0-1.4% per year in the 2020s, reaching 2.75% per year by 2050	Starting with 1.2-1.7% per year in the 2020s, reaching 3.0% per year by 2050
Renovation standard		Constant at 80 kWh/(m²a)	Starting with an average of 80 kWh/(m²a) in the 2020s, linearly decreasing to 30 kWh/(m²a) by 2050	Same as EUTarget scenario
Energy carriers		Distribution per country for latest available year (2017) and linear change to country cluster averages by 2050	Faster shift away from gas and oil in particular compared to EUBase; heat pumps as main beneficiary; fossil fuels completely phased out by 2050	Same as EUTarget, but even faster shift away from fossil energy carriers and more restrictive use of biomass: linear reduction to zero in 2050
Floor area per person		No assumptions regarding sufficiency	Same as EUBase	Lower per capita floor area: minus 2 m² per person per decade starting in 2030

3.2.3.2.2.2 Appliances and processes

Table 25 shows the relevant assumptions in the EUBase, EUTarget and EUSupreme scenarios for appliances and processes in households, commercial and public buildings. In line with the scenario storylines, EUTarget is characterized by strengthened MEPS which are further tightened in EUSupreme, leading to significant final energy savings compared to EUBase. Driven by both rising CO_2 prices (national carbon pricing, ETS 2) and MEPS in the model, fuel-based equipment and processes (e.g. motors, ovens and drying processes in the tertiary sector) are gradually electrified – faster so in the EUSupreme scenario from 2040 onwards than in the EUTarget scenario.

In addition to the EUTarget assumptions, the EUSupreme scenario goes further and includes non-technical and behavioral sustainability measures. It is assumed that the use intensity (hours per year) of non-essential large appliances (e.g. dryers) is reduced by 20% between 2025 and 2050. Driven by the emergence of ESPR standards on the repairability of consumer goods, EUSupreme assumes an average increase in technology lifetime of 20% from 2030 onwards.

Additionally, the EUSupreme scenario assumes that ownership rates (number of appliances per household) do not increase over time. For example, the observed trend towards additional tumble dryers or towards more than one refrigerator per household would come to a halt in the EUSupreme compared to both EUTarget and EUBase, reflecting sufficiency in appliance ownership.

Table 25: Buildings: Differences in assumptions in the EUBase, EUTarget and EUSupreme scenarios for appliances and processes

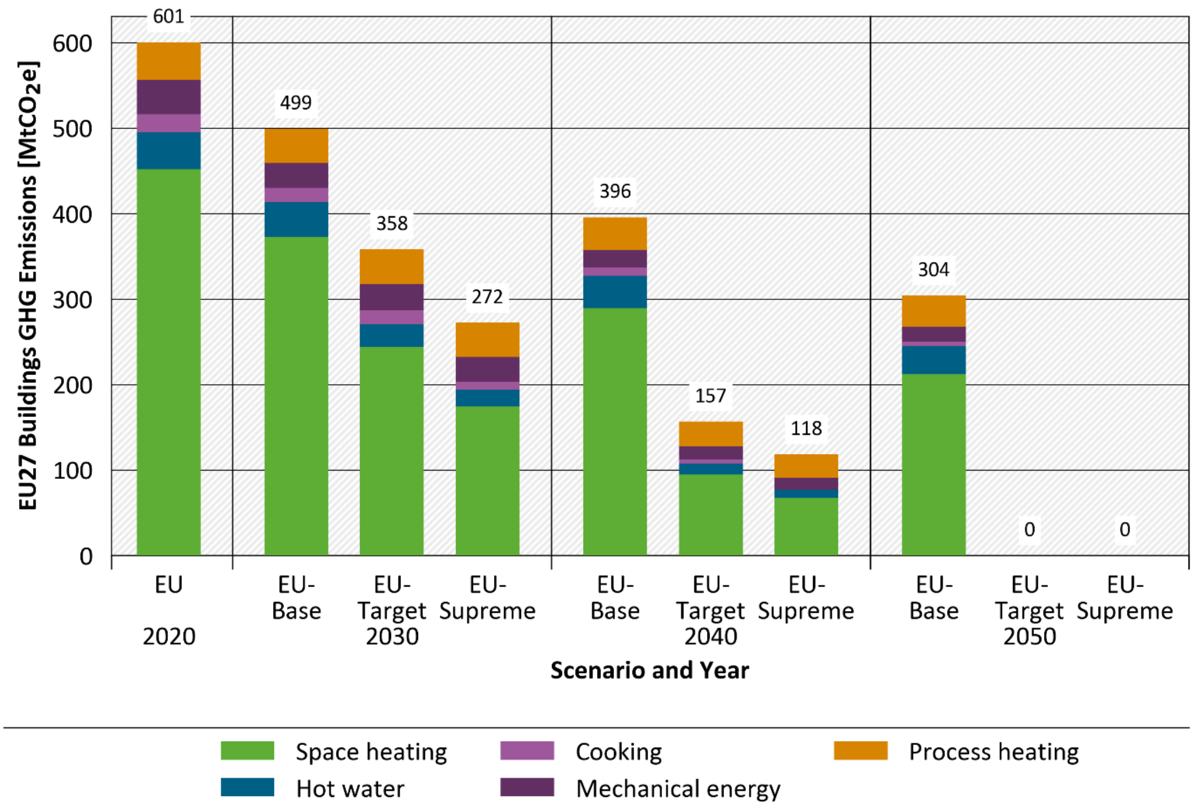
Category	Description of variable	Assumption in EUBase Scenario	Assumption in EUTarget Scenario	Assumption in EUSupreme Scenario
Energy efficiency of appliances and processes	Minimum energy performance standards for difference labelling classes	Business-as-usual improvements following existing EU Ecodesign and Energy Labelling revisions. (see Table 23)	2020: Default 2030: Remove +1 worst performing efficiency class vs. EUBase 2040: No further tightening vs. EUBase	2020: Default 2030: Remove +1 worst performing efficiency class vs. EUBase 2040: Remove +2 worst performing efficiency classes vs. EUBase
Electrification	Degree of electrification for fuel-based appliances and processes	Continued electrification in line with historical trends and price signals; fossil-fueled processes remain available, especially in commercial sector.	From 2040: All new processes/appliances are electricity-based	From 2030: All new processes/appliances are electricity-based
Usage intensity	Usage intensity in hours per year per process	Stable usage patterns across most appliance categories, including ICT and comfort-related appliances; no behavioral or regulatory intervention.	Same as EUBase	From 2025 to 2050: Gradual reduction of 10% for ICT (e.g. TVs); 20% for non-essential large appliances (e.g. dryers)
Product lifetime	Trends in product lifetime, influenced by regulatory requirements for product repairability	No systematic increase in product lifetimes; current patterns of premature replacement and limited repairability persist.	Same as EUBase	Increase in average product lifetime by 20% from 2030 to 2050
Ownership rate	Average numbers of appliances per household	Gradual increase in appliance ownership per household, driven by rising income and consumer trends. Includes uptake of new ICT devices and secondary appliances.	Same as EUBase	No increase in the rate of ownership, e.g. households continue to have an average of 1.1 washing machines per household, but no more.

3.2.3.2.3 Results

Figure 61 shows the projected direct GHG emissions in the buildings sector under the EUBase, EUTarget and EUSupreme scenarios. EUTarget already achieves a substantial reduction in GHG emissions compared to EUBase with the EUSupreme scenario achieving additional GHG emissions reductions through even higher energy efficiency efforts and additional sufficiency measures. To get a better understanding of how the different scenarios for the buildings sector perform over time and not just for 2050, we consider the following theoretical approach. When the relative GHG reduction targets for the entire EU are transferred onto the buildings sector, EUSupreme is the only scenario close to achieving both the Fit-for-55 2030 reduction target (–55%) as well as the recommended target for 2040 (–88-93%). The 2050 target for GHG-neutrality is achieved by both EUTarget and EUSupreme. EUTarget GHG emission reductions do not meet the hypothetical –55% target by 2030. Rather, the buildings sector in EUTarget achieves a –32% reduction by 2030 (358 Mt CO_2e) with respect to 2020 and a –51% reduction with respect to 1990. Considering the ESR framework, which foresees an overall 40% reduction in 2030 with respect to 2005 levels, however, EUTarget overachieves the ESR 2030 target of 409 Mt CO_2e by around 50 Mt CO_2e. In the decade to 2040 GHG emissions are more than halved to 157 Mt CO_2e. Depending on the framework considered, EUTarget achieves either the 2050 target and the ESR framework for 2030 target or only achieves the 2050 target. In EUSupreme, the GHG reduction in 2030 with respect to 2020 levels amounts to 54.8% (272 Mt CO_2e). By 2040, GHG emission levels are down to 118 Mt CO_2e, which represents a reduction by 83,9% with respect to 1990 levels, close to the GHG emissions target proposed by the EU Commission of a reduction of 90% with respect to 1990 levels[41]. Finally, GHG emissions are down to zero by 2050 in EUSupreme.

[41] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en

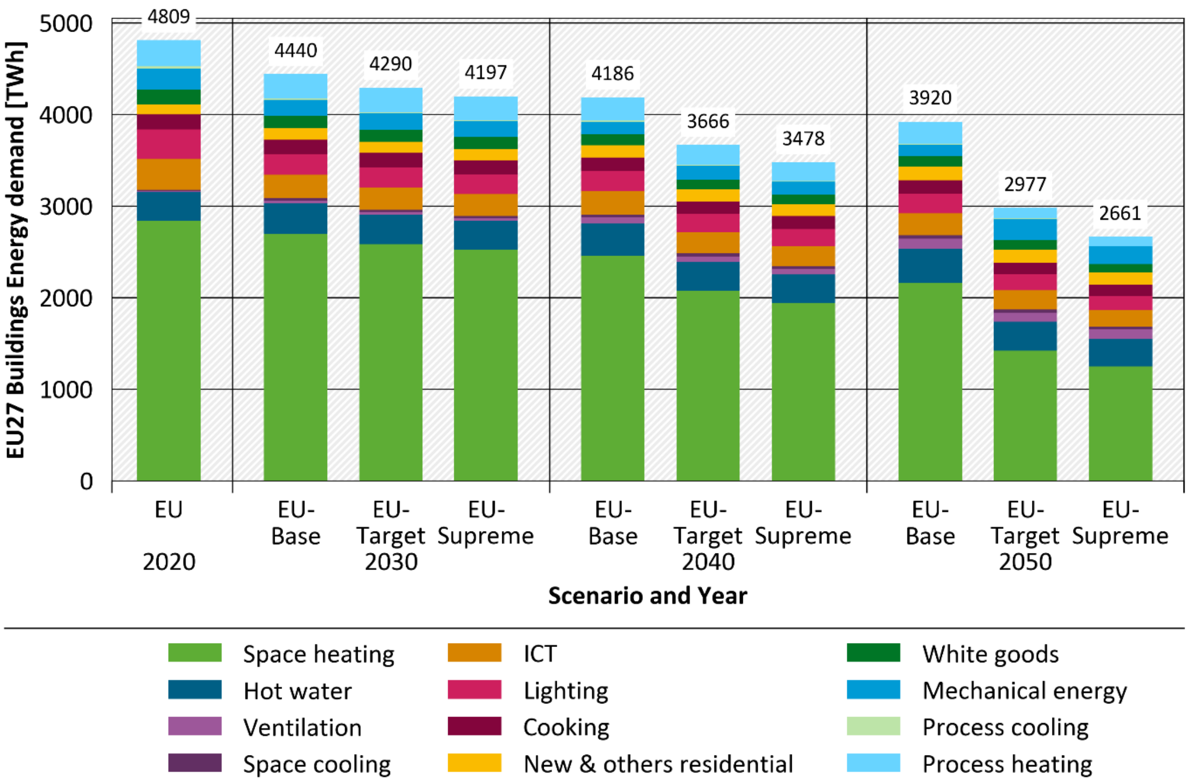
Figure 61: Projected direct GHG emissions for the buildings sector (residential and non-residential) across the EUBase, EUTarget and EUSupreme scenarios



Source: own calculations Oeko-Institut & Fraunhofer ISI

Figure 62 presents the total final energy demand split by end-use within the buildings sector across the EUBase, EUTarget, and EUSupreme scenarios. Whereas the EUBase scenario achieves only modest reductions, the graph shows that the final energy demand is relatively similar between the two target scenarios, with the EUSupreme scenario achieving progressively lower energy demands compared to the EUTarget scenario. Within the set of end-uses results are driven by space heating which shows the highest final energy demand reductions. Again, as for GHG emissions, this is due to increased renovation rates, more ambitious renovation standards, less new construction and the introduction of sufficiency efforts in the EUSupreme scenario. By 2050 final energy demand is reduced to 2.661 TWh from 4.804 TWh in 2020 (reduction by 44,6%). Most of the reduction is achieved by lower demands in space heating. Electrical appliances in total also contribute to the reduction, whereas demand for hot water, space cooling and ventilation increase slightly.

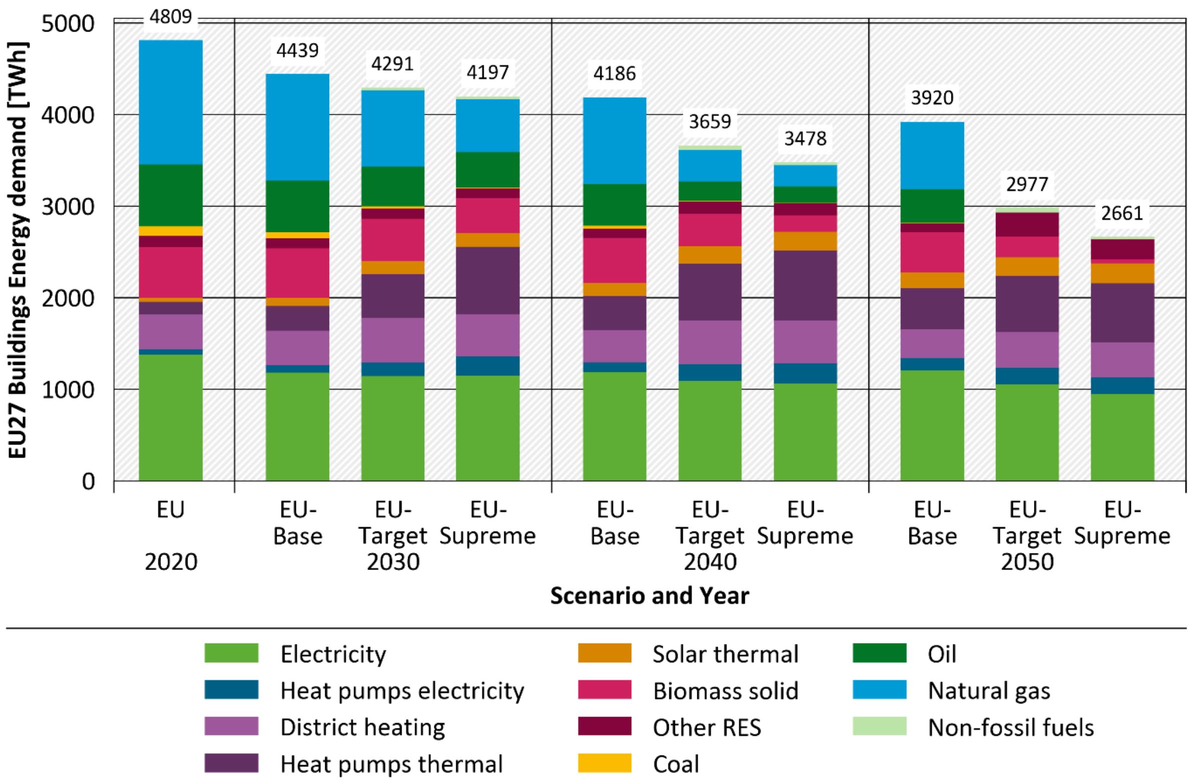
Figure 62: Final energy demand split by end use across the EUBase, EUTarget and EUSupreme scenarios in buildings (residential and non-residential)



Source: own calculations Oeko-Institut & Fraunhofer ISI

Figure 63 shows the demand for all different energy carriers within the buildings sector for the three scenarios. This graph illustrates that the EUSupreme scenario leads to a more significant reduction both in the use of fossil fuels as well as the use of biomass at all time steps. Conversely, ambient heat and solar thermal energy have their highest shares in the EUSupreme scenario. Fossil fuel usage is almost completely absent in 2040 in both target scenarios, due to the faster phase-out of fossil fuels. The absolute amount of district heating is more or less the same between the two target scenarios, while the total electricity used is slightly lower in the EUSupreme scenario compared with the EUTarget scenario, causing less pressure on the energy supply sector. This is mainly achieved by higher renovation rates and lower per person floor areas in EUSupreme, and, in turn, lower energy demand in buildings. Zooming in on the EUSupreme scenario we can see that fossil fuels are already halved in 2030 compared to 2020 levels and further reduced to 418 TWh in 2040 (starting with 1.876 TWh in 2020). There are no fossil fuels left in the energy carrier mix by 2050 in EUSupreme. Biomass follows a similar path with a continuous reduction over time starting at 511 TWh in 2020 and ending at 42 TWh in 2050. The remaining biomass is predominantly used for space heating within the northeastern, eastern and southern country clusters. The reduction in biomass is far less pronounced in EUTarget, which nonetheless uses only half the amount of biomass in 2050 compared to EUBase. Ambient heat in the EUSupreme scenario shows a steep increase in the decade leading to 2030 and stays at this level until 2040 before being reduced again in absolute terms by 2050. This is due to increased efforts in energy efficiency. Overall electricity usage in EUSupreme decreases slightly with electricity for heat pumps showing a steep rise from 2020 to 2030 before levelling off. District heating increases slightly along the trajectory until 2040 before falling again slightly due to, again, increasing energy efficiency efforts.

Figure 63: Final energy demand split by energy carrier across the EUBase, EUTarget and EUSupreme scenarios in buildings (residential and non-residential)



Source: own calculations Oeko-Institut & Fraunhofer ISI

3.2.3.3 Comparison

In summary, the following picture emerges from looking at the three different scenarios in the buildings sector: EUBase presents a reference scenario, which – following a business-as-usual approach – manages a reduction in GHG emissions in buildings by 50% in 2050 compared to the base year 2020. In contrast, EUTarget and EUSupreme both achieve zero emissions in 2050. The two target scenarios present two slightly different pathways to get to zero emissions in 2050: EUTarget follows a technological approach, focusing on higher renovation rates in combination with higher energy efficiency standards as well as a faster phase-out of fossil fuels. This makes it already much more ambitious compared to EUBase. EUSupreme adds even more ambition by introducing sufficiency measures in addition to yet higher renovation rates and an even faster shift away from fossil fuels compared to EUTarget. All these measures lead to even higher energy efficiency gains in EUSupreme compared to EUTarget, which shows that even moderate sufficiency approaches like lowering the per person floor area can have a significant impact in reducing energy demand and, in turn, GHG emissions. Furthermore, EUSupreme is the only scenario that actually achieves the overall 2030 GHG emissions target set by the EU and applied to buildings: a 55% reduction compared to 1990 levels.

In terms of overall energy efficiency, EUSupreme shows the greatest reduction in final energy use. (reduction by 45% in 2050), reflecting the high renovation rates, ambitious energetic standards (building envelopes and appliances) and sufficiency improvements. EUTarget and EUBase reduce their final energy demand by 38% and 18%, respectively. Looking at the different end-uses, it is obvious that the highest efficiency gains stem from space heating, which is also by far the most dominant energy end-use in buildings. It accounts for nearly 60% of all final energy used in 2020. Whilst EUBase arrives at a reduction by 24% in 2050, EUTarget reduces its final energy demand for space heating by 50% being further surpassed by EUSupreme with a reduction of 56%.

Looking at the energy carrier distributions, the picture emerges that a fast phase-out of fossil fuels combined with a consistent push towards electrification (by installing heat pumps and replacing fossil-driven process heating technologies) are the two pillars of reaching GHG targets in 2050. District heating as well as other renewable energy carriers such as solar thermal further assist in achieving the GHG reduction targets.

Compared to EUTarget, EUSupreme achieves its very ambitious path to 2050 by a combination of high energy efficiency gains (helped, e.g., by introducing sufficiency measures that lead to lower per-person floor areas and fewer appliances, and high renovation rates) and strict and fast phasing out of fossil fuels. The high gains in energy efficiency allow for less pressure on the remaining renewable energy sources – both for those used in buildings directly and those needed in the supply sector for generating electricity/district heat. The scenarios in the buildings sector show that a technological approach can already achieve the 2050 target (EUTarget). Adding sufficiency measures, however, achieves not only the EU 2050 target, but also reduces the pressure of adding more generating capacity in the supply sector (EUSupreme).

3.2.4 Supply

The energy supply sector of the European Union plays an important role in the fight against climate change. In 2023, the electricity sector remains a significant source of greenhouse gas (GHG) emissions, contributing 657 Mt of CO_2. To reduce GHG emissions and decrease dependence on Russian fossil fuels, the European Commission has developed strategies aimed at transforming the energy supply sector. Key strategies include binding targets for the share of renewable energy in final energy consumption (42.5% by 2030) and expedited permitting for wind and solar projects (Renewable Energy Directive 2023/2413). Previous policies have already led to significant progress; in 2023, renewable energy accounted for 24.5% of final energy consumption in the EU, while 45.3% of electricity generation was derived from renewable sources.

The energy sector plays a different role compared to the final consumption sectors. In the final consumption sectors of industry, transport, and buildings, the development of demand for primary and secondary energy carriers is examined, and the drivers for various developments are discussed. The supply sector provides secondary energy carriers such as electricity, district heating, hydrogen, and synthetic fuels. This chapter, therefore, investigates how and why the provision of electricity, district heating, and hydrogen is evolving. Today, the energy sector has a higher share of renewable energy (RE) compared to these final consumption sectors. The decarbonization of electricity generation relies on increasing use of weather-dependent sources such as wind and solar, which are expected to dominate the energy supply by 2050, complemented by highly flexible low-carbon power plants, energy storages, optimized grid infrastructure, and flexibility. Therefore, the transformation of the energy supply sector is essential for the decarbonization of other energy demand sectors through sector coupling: the direct electrification of heating, transport, and industrial processes, as well as indirect electrification through hydrogen in hard-to-abate areas.

3.2.4.1 EUBase scenario

3.2.4.1.1 General description

The EUBase scenario reflects the current regulatory and legislative framework at the EU and national level in force as of mid-2024. It serves as a reference framework for assessing the existing political landscape in Europe, capturing the measures already implemented at both the

EU and member state levels. It forms the basis for the two target scenarios (EUTarget and EUSupreme), which consider additional measures to achieve the EU's climate targets for 2030 and climate neutrality by 2050.

The EUBase scenario is based on the actual European policy landscape and the most recent National Energy and Climate Plans (NECPs, 2023/24), combined with major EU-wide regulations such as the European Green Deal, the “Fit-for-55” legislative package, and the EU Emissions Trading System (EU ETS).

Developments in the end-use sectors significantly influence the supply tasks of the energy sector. Its trajectory is shaped by moderately increasing electrification of end-use sectors, steady improvements in energy efficiency, and sector coupling, but without the full mobilization of efficiency and sufficiency strategies or the highest levels of renewable deployment (discussed in depth in the end-use sector results in 3.2.1 Industry, 3.2.2 Transport, and 3.2.3 Buildings).

In the following section, in addition to electricity and hydrogen demand, further assumptions related to the EUBase scenario that specifically pertain to the energy sector will be presented.

3.2.4.1.2 Main assumptions

The EUBase scenario considers existing policies. In recent years, the electricity sector has already made substantial progress in terms of decarbonization compared to other sectors. Current policies that will further drive decarbonization include:

- Renewable Energy Directive - RED II: At least 65% of electricity generation from renewable sources by 2030.
- REPowerEU Plan: Enhancing grid stability and flexibility through investments in energy storage solutions and demand response technologies, setting minimum wind (450 GW) and solar (600 GW) installed capacity by 2030.
- European Green Deal: Promoting cross-border electricity trade to ensure a more integrated and resilient energy market.
- EU-ETS: drives fossil fuel phase-out through a rising carbon price, affecting dispatch order and economics of fossil fuels.

Additionally, the electricity sector is significantly influenced by national policies. Therefore, European policies are complemented and differentiated by national energy policies and updates to National Energy and Climate Plans (NECPs 2023/24) to account for country-specific commitments to renewable expansion and fossil fuel phase-outs.

Key parameters such as installed capacities for 2020 and 2030—e.g., wind and solar capacities derived from the latest NECPs and REPowerEU targets—are treated as exogenous constraints. Likewise, fossil fuel phase-out schedules and nuclear power lifetime extensions are imposed strictly in accordance with national plans and EU policies. CO_2 prices and fuel costs (see 2.4 and Annex A.1.1) are fixed inputs influencing dispatch decisions.

A summary of major assumptions, with the focus on electricity, is provided in Table 26.

Table 26: Main Supply-Side Assumptions in the EUBase Scenario

Technology / Category	Year	EUBase Scenario Assumptions
Wind Onshore / Offshore	2030	270 GW onshore, 71 GW offshore (aligned with NECPs and REPowerEU minimum trajectories)

Technology / Category	Year	EUBase Scenario Assumptions
	2050	~950 GW total wind capacity (endogenously optimized within resource and policy constraints)
Solar Photovoltaics (PV)	2030	335 GW (aggregate from NECPs; below REPowerEU targets)
	2050	≤1,200 GW (cap based on land availability and techno-economic limits; capacity expansion optimized endogenously)
Fossil Fuel Phase-Out	—	No new coal plants after 2025; coal/gas phase-out follows NECP and updated national targets; progressive retirement; CO_2 price drives economics
Nuclear Power	2030–2050	Existing reactors' life extensions plus selective new builds in France, Czechia, Poland; capacity and retirements strictly follow national plans
Hydrogen (Renewable Electrolysis)	2030	Electrolyser capacity scaled to meet endogenous hydrogen demand; up to 30 GW installed in North Sea cluster countries (Esbjerg Declaration)
Novel Synthetic Fuels (e-fuels / CH_x)	2030–2050	No domestic production modeled in EUBase; aviation and maritime fuels assumed imported
Biomass	2030–2050	Use decreases by ~35% relative to 2020; limited to sustainable domestic residues; imports decline accordingly
Waste (Fossil Content)	2050	Reduced fossil content of waste incineration
Grid and Infrastructure	2030	80 GW new electricity interconnectors; ~5000 km hydrogen pipeline infrastructure expansion per TYNDP and PCI lists

For wind power by 2030, the assumption of 270 GW onshore and 71 GW offshore aligns with the aggregated National Energy and Climate Plans (NECPs) updated through 2023/24 and the binding targets under RED III. This trajectory also reflects the minimum REPowerEU ambition of reaching at least 450 GW total wind capacity (combined onshore and offshore), although EUBase assumes a more conservative split given permitting and grid integration constraints. The offshore component sees more moderate growth (71 GW vs. 150+ GW ambitious targets) due to spatial planning challenges and slower infrastructure roll-out. By 2050 wind power capacity is optimized within the model without a minimum capacity limit. The presented ~950 GW total wind capacity results from the Enertile model's endogenous optimization, bounded by country-specific wind resource potentials derived from multi-year weather datasets. This level balances maximum technical potential with realistic limits on delivery, and grid integration capability under current policy frameworks.

For photovoltaic, the expansion to 335 GW by 2030 is derived from NECP aggregates and represents moderate growth relative to REPowerEU's 600 GW solar target. The slow growth in EUBase reflects regulatory bottlenecks, land-use limitations, and grid congestion issues. For 2050 a capacity ceiling of up to 1,200 GW by 2050 is imposed mainly based on land availability.

The scenario restricts biomass use to the sustainable domestic resource base, resulting in a reduction of biomass consumption in the supply sector to approximately 30% of the 2020 values (for more detail see 3.1.2.5 Non-fossil fuels balance). Biomass imports decrease to zero by 2050.

The fossil fuel phase-out follows a policy-driven trajectory. The scenario strictly prohibits the commissioning of new coal power plants after 2025, in accordance with the NECPs and national legislation such as Germany's law on the termination of coal-fired generation (Kohleverstromungsbeendigungsgesetz). Existing coal capacity is expected to retire progressively by 2030–2040, and gas-fired power plants gradually phase out by 2050 (European Commission, 2024). This path is supported by the rising EU ETS carbon price.

Nuclear capacity dynamics are heterogeneous due to divergent national policies. Belgium commits to a full phase-out by 2035, while countries like France, the Czech Republic, Poland, and Hungary plan selective life extensions and new builds in line with their NECPs. For example, France's capacity is projected to decline from 61.4 GW in 2030 to 45.1 GW in 2040, followed by an assumed increase to 70.1 GW by 2050 driven by planned new nuclear plants – albeit with significant uncertainties linked to reactor construction, regulatory approval, and public acceptance. The scenario incorporates these capacity extensions by adopting official capacity plans. Nevertheless, the risks of delays and cost overruns are higher than for renewable energies.

The EUBase scenario assumes hydrogen production capacity expands to accommodate actual modeled demand rather than fixed ambitious targets. This includes up to 30 GW of electrolyser capacity in Denmark, the Netherlands, Belgium, and Germany as articulated in the Esbjerg Declaration (Esbjerg Declaration, 2022). Larger goals such as the EU Hydrogen Strategy's target of 10 million tons of domestic renewable production by 2030 are deferred beyond this timeframe in EUBase to avoid overbuilding infrastructure in the absence of matching demand growth.

While achieving the full 10 million tons target could theoretically generate excess hydrogen production capacity available for domestic synthetic fuel manufacturing, this approach faces significant long-term sustainability challenges. As hydrogen demand continues to grow toward 2050, a progressively larger share of European hydrogen production will be needed for direct industrial and transport applications rather than for synthetic fuel synthesis. Maintaining synthetic fuel production at scale would thus require substantial additional hydrogen imports. Alternatively, synthetic fuel production in Europe would need to be scaled down to prioritize direct hydrogen usage, potentially resulting in stranded investments. Given that meeting meaningful minimum synthetic fuel production targets in Europe will very likely depend on imported hydrogen in the long term, the EUBase scenario does not model domestic synthetic fuel production. Instead, it assumes that decarbonization demands in aviation and maritime sectors will primarily be satisfied through imports.

An expansion of electricity interconnectors and hydrogen pipelines by 2030 is assumed to enable integration of variable renewables, support sector coupling. While enforcements until 2030 are set as an input, further investment needs are modelled endogenously.

The Enertile model applies these input assumptions as fixed constraints or initial conditions up to 2030, reflecting binding political commitments and observed deployment data. Beyond 2030, the model has certain freedoms within specified bounds — expanding wind, solar, hydrogen electrolysis, storage, and grid infrastructure capacities endogenously to minimize system costs while respecting policy-driven ceilings, resource potentials, technical limits, and grid feasibility.

For instance, wind and solar capacities beyond 2030 are determined by the interplay of resource potential (derived from multi-year weather datasets), system flexibility options, grid constraints, and cost minimization objectives. Fossil and nuclear retirements occur according to exogenous schedules; the model cannot accelerate them but can reduce utilization as variable costs and renewables penetration increase. This hybrid approach — complementing exogenous policy targets with endogenous techno-economic optimization — ensures that the scenario accurately reflects policy and remains technically and economically plausible.

3.2.4.1.3 Results

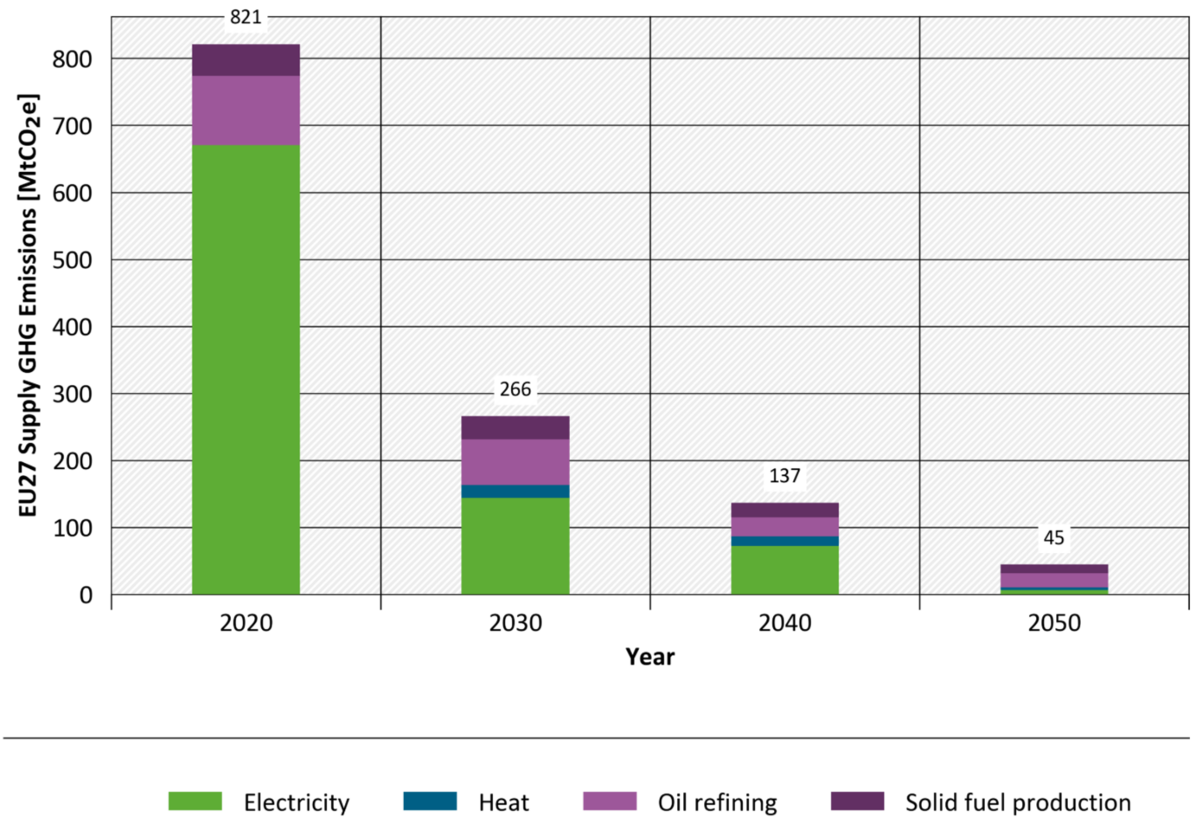
The evolution of the European power system under the EUBase scenario reveals a rapid transformation in electricity and district heat generation, particularly by 2030. This substantial transformation in energy generation within the EUBase is driven by combined effects of primarily exogenous policy assumptions, market signals such as rising CO_2 prices, and technological progress, alongside endogenous system responses driven by the optimization model. The development outlined is based on the supply task of electricity, hydrogen, and district heating in the EUBase scenario, and is therefore heavily dependent on the evolution of final energy demand.

Figure 64 shows the modelled GHG emissions from electricity and district heat generation as well as fossil fuel supply. Notably, refinery emissions supplying fossil solid and liquid fuels make up over half of the supply sector emissions by 2030, and this share slowly rises up to 2050, due to fossil fuel demands in the end-use sectors.

In 2020, total emissions from both electricity and heat production were 670 $MtCO_2e$. By 2030, emissions fall sharply to around 144 $MtCO_{2e}$ for electricity generation and 19 $MtCO_{2e}$ for district heat generation. Emissions from heat generation remain comparatively low, as the expansion of heat networks is not very ambitious in the EUBase scenario.

A decade later, in 2040, continued transformation of the energy supply leads to further reductions, with electricity generation emissions dropping to 73 $MtCO_2e$ and heat emissions falling to 14 $MtCO_2e$. Looking ahead to 2050, emissions from electricity generation are projected to decline to 6 $MtCO_2e$, with heat emissions reaching 4 $MtCO_2e$. These relatively low figures are a result of renewable energy sources dominating the energy mix.

Figure 64: GHG Emissions from heat and electricity generation



Source: own calculation Fraunhofer ISI

Wind energy generation increases sharply from about 398 TWh in 2020 to approximately 1,294 TWh by 2030, reflecting substantial investments primarily driven by binding policy targets. By 2030, onshore and offshore wind capacities are exogenously set to roughly 270 GW onshore and 71 GW offshore, based on aggregated commitments in the National Energy and Climate Plans (NECPs) and REPowerEU minimum trajectories. From 2030 onward, capacity expansion is determined endogenously by the model, balancing resource availability, grid integration limits, and economic costs. This results in wind capacity reaching approximately 736 GW by 2050, with offshore expansion accelerating to about 300 GW, while onshore capacity adjusts to roughly 437 GW due to spatial and integration constraints. Consequently, wind generation grows further to about 2,518 TWh by 2050,

Solar energy follows a similar trajectory, starting at 140 TWh in 2020 and increasing to 552 TWh by 2030. The installed PV capacity is exogenously fixed to about 335 GW in 2030, again reflecting NECP and REPowerEU targets. Beyond 2030, endogenous capacity expansion and dispatch optimization lead to about 610 GW by 2050. Generation closely mirrors these capacity changes, stabilizing close to 950 TWh by 2050. The solar mix includes growing shares of concentrated solar power (CSP), which increases to approximately 68 GW by 2050, contributing to system flexibility through thermal storage. These endogenous adjustments reflect technical feasibility, land availability, grid congestion, and cost considerations integrated into the model.

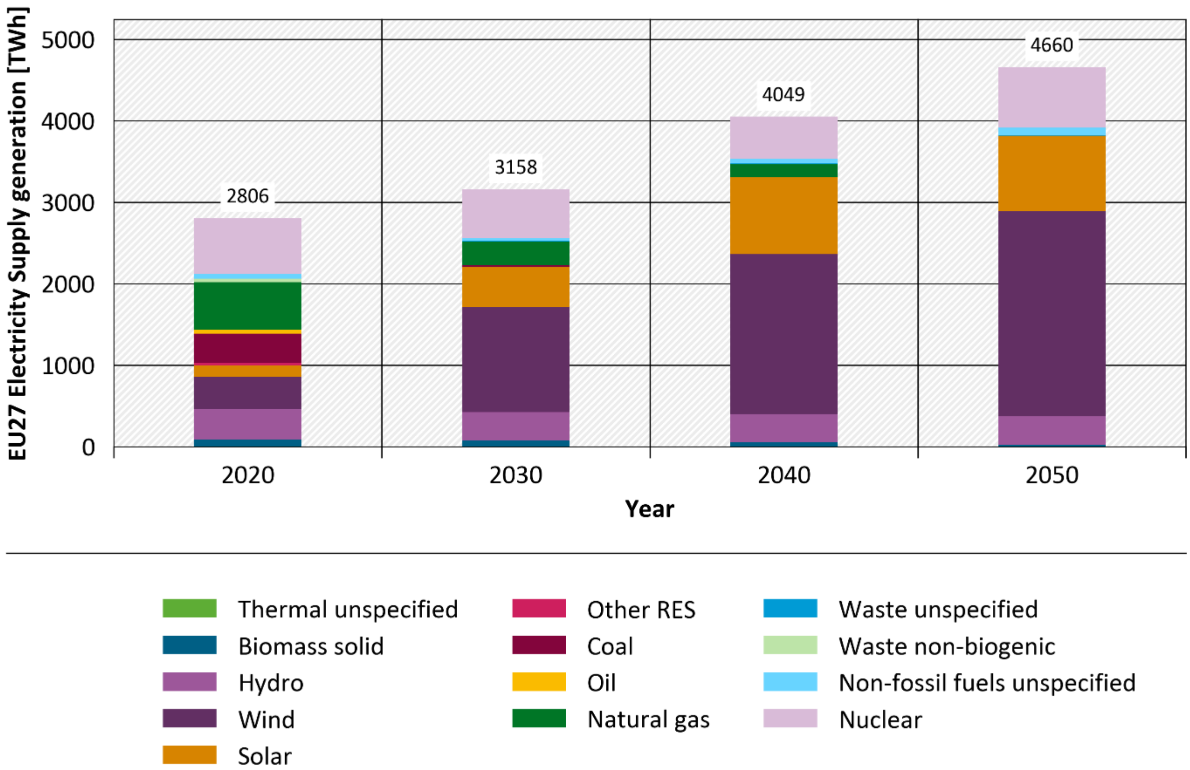
Hydropower remains stable around 348 TWh, reflecting its limited expansion potential in Europe.

In 2020, coal-fired power plants generated 358 TWh of electricity. However, by 2030, coal's contribution diminishes significantly, amounting to merely 18 TWh, driven both by policy-driven coal phase-outs and the increasing economic non-competitiveness of coal due to higher CO_2 prices and falling renewable costs. The developments in countries that either have a coal phase-out or plan a phase-out after 2030 illustrate that coal-based electricity generation is not solely influenced by political measures. Rather, it is also a consequence of declining generation costs for renewable energy and increasing generation costs for fossil-based electricity, driven by rising CO_2 prices. These trends reduce the competitiveness of coal-based electricity generation not only across Europe as a whole but also in countries that continue to rely on coal-based electricity generation. Consequently, the existing coal power plants are projected to result in far below 1000 full load hours by 2030 and a total generation of only 18 TWh.

Natural gas, which contributed 586 TWh in 2020, is projected to decrease to 294 TWh by 2030 and 163 TWh by 2040, with complete phase-out anticipated by 2050. This declining trend reflects both exogenous fossil gas phase-out pathways established by European climate objectives and NECPs, and endogenous system optimization favoring renewables, storage, and sector coupling technologies. A complete cessation of fossil gas generation is anticipated by 2050. Until then, gas-fired plants function primarily as flexible balancing and peak-load units.

Nuclear power, which generated 684 TWh in 2020, maintains a substantial part of the generation mix until 2050. Model results show a slight decline to 519 TWh in 2040, followed by a rebound to 747 TWh by 2050, reflecting assumed lifetime extensions and selective new reactor builds according to national plans (e.g., France, the Czech Republic). However, to effectively integrate nuclear generation into a system with high shares of fluctuating renewable energy sources (RES), additional flexibility measures, including electrolyzers and hydrogen storage systems as well as an enhanced electricity grid infrastructure are required. Nevertheless, nuclear plants maintain a high utilization, while flexibility is provided mainly by hydrogen production as a flexible load, expansion of grid interconnections, and deployment of energy storage and demand side management strategies.

Figure 65: Electricity supplied by utilized energy carrier EUBase[42]



Source: own calculation Fraunhofer ISI

Electricity-based hydrogen becomes an important energy vector in the modeled system with strong interactions with the energy supply sector. Figure 65 shows the electricity supplied for all scenario years. Electricity generation in hydrogen power plants increases to 15 TWh by 2030, to 46 TWh in 2040, and ultimately reaches 89 TWh in 2050. The member states of the EU27 produce all hydrogen domestically using electrolysis (see Figure 18).

3.2.4.2 Target scenarios

The target scenarios, EUTarget and EUSupreme, outline two pathways for the European Union to achieve its climate goals of net-zero greenhouse gas emissions by 2050. These scenarios build upon the foundations established by the EUBase scenario but incorporate more ambitious measures aimed at significantly reducing emissions across all sectors.

3.2.4.2.1 General description

The EUTarget scenario adopts a technology-oriented approach and is based on the assumptions of the EUBase scenario. It remains technology-open, allowing for various mitigation strategies including nuclear and CCS based on the specific circumstances of each Member State. In this scenario, the demand for electricity and hydrogen increases significantly. The rising demand for electricity is driven by the electrification of the industry, transport, and building sectors. At the same time, the final energy demand for hydrogen grows considerably to support decarbonization in hard-to-abate areas. The highest level of final energy demand for electricity and hydrogen occurs in the EUTarget scenario.

In contrast, the EUSupreme scenario takes a more comprehensive approach with greater emphasis on efficiency and sufficiency strategies, sustainability criteria and circular economy principles (discussed in depth in the end-use sector results in 3.2.1 Industry, 3.2.2 Transport,

[42] Figures represent gross electricity generation

and 3.2.3 Buildings). It aims for a significant reduction in overall energy demand. The scenario focuses on non-technical and behavioral solutions and limits the dependency on nuclear fuels. Nevertheless, the demand for electricity and hydrogen in this scenario also rises, although the hydrogen demand is lower due to increased efficiency and reductions in overall energy consumption. However, hydrogen remains important as energy carrier for industry and transport and as energy storage and flexibility option in energy supply.

Both target scenarios require additional measures to achieve climate goals, including accelerating the deployment of renewable energy sources, expanding hydrogen production capacities, and phasing out fossil fuels. Building on this overview, the following section details the key assumptions and drivers that distinguish the EUTarget and EUSupreme scenarios from the EUBase, highlighting their specific technology targets, policy measures, and system dynamics.

3.2.4.2.2 Main assumptions and drivers

The main assumptions and drivers for the two target scenarios, EUTarget and EUSupreme in contrast to EUBase, are outlined in Table 27. Key differences include higher capacity targets for renewable energy sources. The EUSupreme scenario additionally aims at a reduced reliance on nuclear energy.

Table 27: Scenario assumptions in supply

Technology	Year	EUBase Scenario	EUTarget Scenarios	EUSupreme Scenario
Wind	2030	270 GW onshore and 71 GW offshore	450 total (aligned with REPowerEU)	
	2050	No minimum target	> 1200 GW	
PV	2030	335 GW	600 GW (aligned with REPowerEU)	
	2050	<= 1200 GW	<= 1200 GW	
Fossil fuel phase out	2030-2050	No new coal plants after 2025; coal/gas phase-out follows NECP and updated national targets; progressive retirement; CO_2 price drives economics	As EUBase, endogenous modeling, reinforced by high RES	
Nuclear	2030-2050	Life extension + selective new builds (France, Czechia, Poland); per national plans	As EUBase	Constrained, no new sites, earlier retirements
Hydrogen	Hydrogen	As required to meet hydrogen demand, up to 30 GW in North Sea cluster (Esbjerg Declaration)	As EUBase, but higher hydrogen demand	
Novel fuels (CHx)	2030-50	No domestic production; imports as needed	As EUBase	
Biomass	2030-50	Biomass usage decreases to available domestic potential	Biomass imports decrease, biomass consumption increases by 20% until 2050 but is restricted to domestic biomass	
Waste	2050	Reduced fossil share	As EUBase, increasing share of CCS	Higher reduction of fossil share, no CCS

In 2020, the installed capacity of onshore wind power was 162.5 GW, while the offshore capacity stood at 14.5 GW. In the target scenarios, the EU's expansion goals from the RePowerEU plan are set to be achieved. For wind power by 2030, both the EUTarget and EUSupreme scenarios build on the ambitious REPowerEU targets of reaching at least 450 GW total wind capacity (combined onshore and offshore). This represents a substantial increase compared to the EUBase assumption of 270 GW onshore and 71 GW offshore, which aligns with aggregated National Energy and Climate Plans (NECPs) updated through 2023/24. By 2050, both scenarios allow wind power capacity expansion well beyond 1,200 GW, driven by endogenous optimization within the modeling framework. This optimization balances technical wind resource potential—derived from multi-year meteorological datasets—with realistic delivery capabilities and grid integration limits. These expansion targets are considered feasible and achievable if permitting processes are streamlined and grid infrastructure is significantly expanded, which are priorities under current EU policies (WindEurope 2025).

Regarding photovoltaic (PV) capacity, both EUTarget and EUSupreme aim to meet or exceed the REPowerEU 2030 target of 600 GW installed solar capacity, which is nearly double the 335 GW assumed in EUBase derived from NECP aggregates. For both EUTarget and EUSupreme, a capacity ceiling of around 1,200 GW by 2050 is assumed for PV, reflecting limitations mainly driven by land availability.

Similar to the EUBase scenario, biomass imports are reduced to zero by 2050 in both the EUTarget and EUSupreme scenarios. While in the EUBase scenario about 166 TWh of sustainable domestic biomass is available for the supply sector in 2050, this figure increases significantly in the target scenarios, exceeding 650 TWh in EUTarget and 950 TWh in EUSupreme (for more detail see 3.1.2.5 Non-fossil fuels balance). This higher availability of sustainable domestic biomass enables an overall increase in biomass consumption despite the reduced imports.

All scenarios assume a politically mandated coal and gas phase-out for countries where such decisions have been made, based on the NECPs. By 2050 at the latest, none of the NECPs foresee the use of fossil gas or coal in any country. Unlike in the EUBase scenario, the very high share of renewable energy in the EUTarget and EUSupreme scenarios leads to a situation where there is only little room for fossil fuels within the energy supply system and thus to an accelerated decline of fossil fuel-based electricity generation, even in countries that do not have explicit coal phase-out plans. However, this decline emerges endogenously from the modeling and is not driven by direct maximum capacity constraints. In the EUSupreme scenario, additional sufficiency measures further reinforce this trend. In both target scenarios, a full phase-out of coal and gas in power generation by 2050 is imposed as a boundary condition through their specific National Energy and Climate Plans (NECPs).

For nuclear energy, the EUTarget scenario assumes the same approach as EUBase, with life extensions and new builds strictly following the targets set in the national NECPs. In contrast, the EUSupreme scenario assumes fewer lifetime extensions and limits nuclear development to replacement of existing plants only, explicitly excluding the commissioning of new reactor sites. This means that while some countries continue to operate existing reactors longer or replace aging capacity, no new nuclear power plant locations are developed under EUSupreme.

In the EUBase scenario, hydrogen production grows in line with modeled demand rather than fixed ambitious targets. The EU goal of producing 10 million tons of domestic renewable hydrogen by 2030 is deferred to avoid overcapacity risks. In contrast, the EUTarget and EUSupreme scenarios project significantly higher hydrogen demand due to faster energy system transformation and accelerated expansion of renewables, which provide abundant low-cost, variable electricity for electrolysis. By 2030, hydrogen demand in EUTarget is roughly twice that of EUBase and remains elevated thereafter. In EUSupreme, total hydrogen demand across end-use sectors is lower than in EUTarget over the long term, reflecting additional sufficiency and efficiency measures. Hydrogen also plays a vital role within the supply sector as a flexibility option for system balancing, including reconversion to electricity (power-to-power) and district heating. Neither scenario imposes fixed minimum hydrogen production targets; instead, meeting end-use sector demand, either through domestic production or imports, is endogenously optimized, including the share of imports and hydrogen used in the supply sector.

All three scenarios—EUBase, EUTarget, and EUSupreme—employ a consistent modeling framework and methodological approach. Key input parameters such as minimum or maximum restrictions for installed renewable capacities, fossil fuel phase-out schedules, and nuclear lifetime extensions are treated as fixed policy constraints reflecting binding national and EU-level commitments (e.g., NECPs, REPowerEU, EU ETS). Beyond that, the Enertile model allows endogenous optimization within defined policy-driven limits, resource potentials, and technical constraints. This hybrid approach ensures that capacity expansions for wind, solar, hydrogen electrolysis, storage, and grid infrastructure are selected to minimize system costs while respecting GHG emissions reduction, grid feasibility, and policy targets.

While all three scenarios apply the same modeling framework and policy-based constraints, differences in assumptions—such as renewable capacity targets, nuclear deployment, and sufficiency measures—drive distinct system outcomes. For example, the full coal and gas phase-out mandated by NECPs occurs in all scenarios, but the renewable-dominated energy mix in EUTarget and EUSupreme accelerates fossil fuel reductions via endogenous market dynamics beyond explicit capacity limits.

3.2.4.2.3 Results

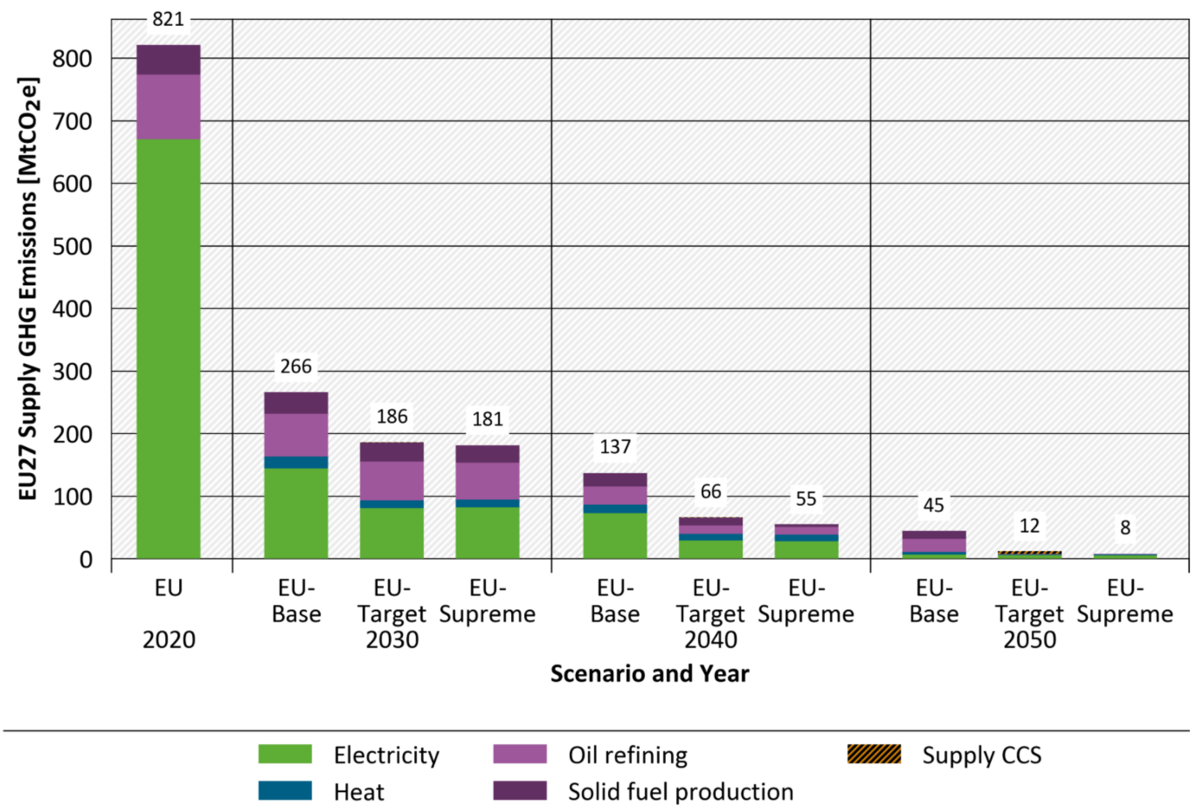
The transformation of the European power system under the target scenarios, EUTarget and EUSupreme illustrates a significant shift in electricity and hydrogen generation by 2030 and beyond (Figure 68). The substantial changes in energy production are driven by ambitious decarbonization targets that considerably increase final energy demand, particularly for clean electricity and hydrogen. The growth of hydrogen production not only supports decarbonization of hard-to-electrify sectors but also plays a crucial role as a flexibility resource, enabling the balancing of variable renewable energy through power-to-power reconversion and district heating. These scenario outcomes are shaped by specific policy objectives set in the modeling assumptions, including accelerated renewable energy deployment, a nearly complete fossil fuel phase-out by 2050, and differentiated nuclear capacity pathways as detailed in the main assumptions (see Table 27).

All scenarios show a clear downward trend in total greenhouse gas (GHG) emissions from electricity and heat production between 2020 and 2050 (see Figure 66). Starting from historic emissions of approximately 821 Mt CO_2e in 2020, emissions decline to 266 Mt CO_2e by 2030 and 45 Mt CO_2e by 2050 in the EUBase scenario. The target scenarios show faster reductions, with emissions falling to 186 Mt CO_2e (EUTarget) and 181 Mt CO_2e (EUSupreme) by 2030 and further declining to about 12 Mt and 8 Mt CO_2e by 2050, respectively.

When examining emissions from fossil fuel production, the differences between the scenarios become more pronounced. In the EUBase scenario, emissions from liquid fossil fuels start at 104 Mt CO_2e in 2020 and decrease to 69 Mt CO_2e by 2030, with a gradual decline to 21 Mt CO_2e by 2050. In contrast, the EUTarget scenario shows a more drastic reduction, with liquid fossil fuel emissions dropping to 62 Mt CO_2e by 2030 and nearly disappearing by 2050 at 0.4 Mt CO_2e. The EUSupreme scenario follows a similar trend, with emissions from liquid fossil fuels decreasing to 59 Mt CO_2e by 2030 and also approaching zero by 2050. Solid fossil fuel emissions also reflect this trend. The EUBase scenario projects emissions of 47 Mt CO_2e in 2020, decreasing to 34 Mt

CO_2e by 2030 and 13 Mt CO_2e by 2050. In contrast, the EUTarget scenario anticipates a sharper decline, with emissions dropping to 31 Mt CO_2e by 2030 and virtually disappearing by 2050 at 0.02 Mt CO_2e. In the EUSupreme scenario, emissions from fossil fuel production, particularly liquid and solid fuels, are expected to decline sharply as a result of reduced demand from industry, the energy sector and especially the transport sector. The model results show solid fossil fuel emissions decreasing to 28 Mt CO_2e by 2030 and to 0.03 Mt CO_2e by 2050. It is important to note that these remaining emissions in 2050 are attributed to waste incineration, while waste in 2050 still contains non-renewable components.

Figure 66: GHG Emissions from heat and electricity generation in the three scenarios



Source: own calculation Fraunhofer ISI

The transformation of the European energy supply system in the target scenarios is characterized by a shift toward a climate-neutral electricity supply—driven by ambitious decarbonization targets and a strong increase in final demand for both electricity and hydrogen. This increase occurs not only from electrification of the industry, transport, and building sectors, but also from the growing role of hydrogen as a flexibility option to shift renewable electricity production from summer to winter and to balance short-term fluctuations.

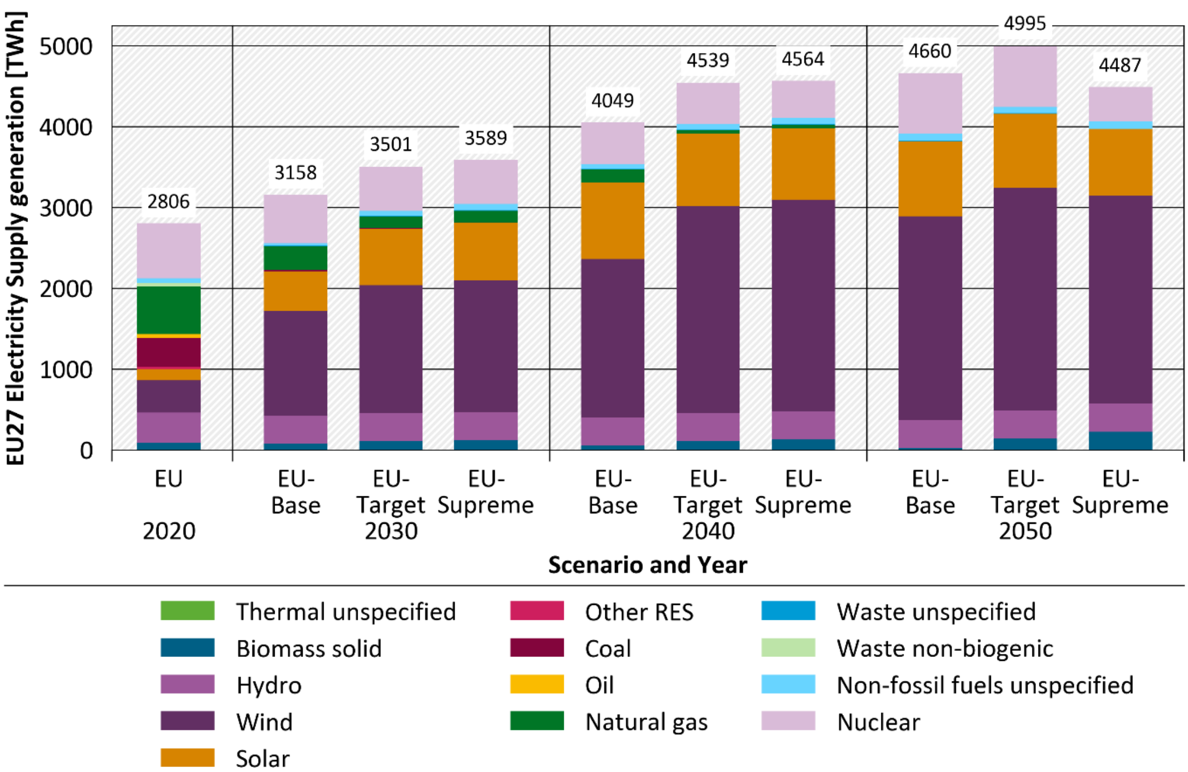
Besides the transformation of the electricity system to a GHG-neutral supply, the increase in electricity demand is a key challenge in the electricity sector. Total electricity demand across all energy demand sectors is projected to grow significantly from 2020 to 2050. In the EUBase scenario, electricity demand is expected to reach 3,561 TWh by 2050. In the EUTarget scenario, the increase in electricity demand from the industry sector is substantial enough that, despite reductions in electricity demand from the buildings and transport sectors, overall electricity demand peaks at 3,668 TWh by 2050. Conversely, efforts toward efficiency and sufficiency in the EUSupreme scenario lead to a reduction in demand to 3,355 TWh by 2050.

The increasing demand for electricity and hydrogen – i.e. indirect electricity demand - presents distinct challenges for energy supply. The rapid growth in electricity demand, particularly in the industry and transport sectors, necessitates a significant expansion of renewable energy sources, especially wind and solar. By 2030, wind energy generation in the EUBase scenario is projected to reach 1,294 TWh, while solar energy is expected to increase to 489 TWh. However, the expansion of renewable energies is significantly more ambitious in the target scenarios. In the EUTarget scenario, wind energy generation is expected to rise to 1,580 TWh by 2030, while solar energy is projected to increase to 701 TWh. Similarly, the EUSupreme scenario shows comparable growth patterns, with wind energy reaching 1,633 TWh and solar energy at 706 TWh by 2030. Together, wind and solar supply around 2,280 TWh in EUTarget and about 2,330 TWh in EUSupreme by 2030. This corresponds to renewables making up approximately 77% of gross electricity generation in EUTarget and 79% in EUSupreme, with wind and solar alone contributing about 61% and 62–65%, respectively.

Looking ahead to 2050, the expansion continues, with wind power generating over 2,750 TWh (EUTarget) and 2,570 TWh (EUSupreme) and solar reaching about 910 TWh (EUTarget) and 830 TWh (EUSupreme). Consequently, renewables account for roughly 85% of gross electricity generation in EUTarget and 87–88% in EUSupreme, with wind and solar together delivering more than 70% (EUTarget) and 74–77% (EUSupreme).

Parallel to this, electrolytic hydrogen production grows strongly in Europe, reflecting the rising role of hydrogen both as an energy carrier and as a flexibility option for the power system. By 2050, electrolysis-based hydrogen production reaches approximately 557 TWh in EUTarget and about 406 TWh in EUSupreme, due to lower overall electricity and hydrogen demand in EUSupreme. Hydrogen trade volumes increase by 2050, simultaneously, hydrogen storage capacities rise.

Figure 67: Electricity supplied by utilised energy carrier in the three scenarios



Source: own calculation Fraunhofer ISI

To effectively integrate high shares of fluctuating renewable energy sources, significant flexibility measures are required. Technologies such as electrolyzers and storage solutions are crucial for balancing variable loads. However, it is important to note that complete avoidance of curtailments will not be feasible in practice. During periods of excessive renewable generation, particularly in peak hours, the costs of additional electricity storage or electrolyzers cannot be amortized, as these systems would operate only for a limited number of hours each year. Therefore, accepting curtailments as part of the system will be necessary to limit the overall costs of energy supply.

While flexibility measures are essential for integrating fluctuating renewable energy sources, they are also relevant for integrating technologies that rely on a base load operation mode, such as nuclear power. Nuclear power, which generated 684 TWh in 2020, is projected to increase its contribution to 747 TWh in the EUBase and 756 TWh in the EUTarget scenario by 2050. In the EUSupreme scenario, however, its role is gradually reduced to 426 TWh by 2050.

The decline of coal and gas is a crucial component of the transformation across all scenarios. Coal-based electricity generation drops from 358 TWh in 2020 to 18 TWh in the EUBase scenario and to just around 6 TWh in the target scenarios by 2030. This consistent reduction reflects a strong commitment to phasing out coal as a primary energy source. Natural gas generation also shows similar reductions across the scenarios, decreasing from 586 TWh in 2020 to 294 TWh in the EUBase scenario and 140 TWh in both target scenarios by 2030. This trend continues, with both coal and gas expected to be phased out entirely by 2050.

Hydrogen power plants play an essential role as a backup in the electricity system in all scenarios. In 2030, they generate between 15 TWh (EUBase) and 60 TWh (EUSupreme) of electricity, depending on the scenario. In 2050, electricity generation using hydrogen increases to between 57 TWh (EUTarget), 59 TWh (EUSupreme) and 89 TWh (EUBase). It can be argued that in the EUSupreme scenario, the lower electricity and hydrogen demand should result in a diminished role for hydrogen in flexible electricity generation compared to the other scenarios. Nevertheless, this reflects the impact of reduced nuclear output, which is projected to decline to 426 TWh by 2050, in contrast to an increase to 756 TWh in the EUTarget scenario. The discrepancy is addressed through improvements in energy efficiency, enhanced biomass utilization attributed to greater availability of domestic biomass (see main assumptions), and an additional contribution of 2 TWh from increased hydrogen back conversion. Hydrogen back conversion itself does not rely on hydrogen imports but is supplied by domestic hydrogen in EUTarget and EUSupreme.

In the EUBase scenario, hydrogen supply is solely based on domestic production. However, this outcome does not align with the RePowerEU plan, which aims for significant import volumes of hydrogen, and several contracts for hydrogen supply have already been signed between EU member states and other countries. Nevertheless, the hydrogen demands projected in the EUBase scenario are lower than both hydrogen production and the hydrogen import goals until 2040. By 2050, hydrogen demand can be fully met by domestic production alone (see Figure 31).

3.2.4.3 Comparison

The comparison of the three scenarios—EUBase, EUTarget, and EUSupreme—highlights significant trends in the transformation of the European energy supply sector, particularly regarding emissions reductions and energy demand dynamics.

Overall, all scenarios illustrate a clear downward trend in emissions from electricity and heat production, as well as from fossil fuels, from 2020 to 2050, resulting from a combination of policy and regulatory actions—such as expansion goals for renewables, the phase-out of fossil power plants and CO_2 pricing. The EUTarget and EUSupreme scenarios achieve faster emission reductions, especially in fossil fuel usage, compared to the EUBase scenario. By 2050, emissions from electricity generation are projected to be minimal across all scenarios, with the EUSupreme scenario achieving the lowest levels.

The demand for electricity and hydrogen, the key secondary energy carriers in the system, increases across all scenarios. This growth is driven by the expanding use of electricity in industry, transport, and buildings, alongside the rising role of hydrogen both as an energy carrier and as a flexibility option within the power system. However, the EUTarget scenario exhibits the highest levels of electricity and hydrogen demand. This increase is largely driven by the electrification of the industry, transport, and building sectors (discussed in depth in the end-use sector results in 3.2.1 Industry, 3.2.2 Transport, and 3.2.3 Buildings and used as input for supply sector modeling). To cover these high demands, a significant expansion of renewable energy sources, particularly wind and solar proves cost-efficient in the modeling. This expansion is driven endogenously by declining costs for photovoltaic and wind technologies, as well as, even more importantly, by improved system integration capabilities that enable substantially increased renewable generation.

In terms of hydrogen, demand is expected to rise significantly in all scenarios, with the EUTarget scenario projecting the highest levels of hydrogen production. The role of hydrogen as a key energy carrier and an essential element for sector coupling underscores its importance in decarbonizing hard-to-abate sectors, such as heavy industry and long-haul transport. The comparison of hydrogen-related results across the scenarios reveals a clear link between decarbonization ambition and hydrogen infrastructure development. While the EUBase scenario exhibits modest hydrogen trade and storage expansion, the EUTarget and EUSupreme scenarios demonstrate significantly higher volumes of hydrogen exports, imports, and storage capacity by 2050. The growth of a pan-European hydrogen trade network, coupled with substantial storage infrastructure, emerges as a key enabler for integrating high shares of renewable energy and ensuring supply security.

The decline in coal and gas generation is a critical element in order to reduce GHG emissions in the supply sector across all scenarios. The EUBase scenario reflects a gradual reduction in coal and gas, while the target scenarios demonstrate a more aggressive phase-out. This transition is influenced not only by political measures but also by decreasing costs of renewable energy and rising CO_2 prices, which render fossil fuel generation less economically viable. By 2050, both coal and gas are expected to be phased out entirely, supporting the EU's climate objectives.

In summary, the comparison of scenario results emphasizes the necessity for a comprehensive and coordinated approach to energy supply, highlighting the essential role and dynamics of renewable energy sources, hydrogen, and energy efficiency measures.

3.2.5 District heating

District heating networks can act as a bridge between the building sector and the broader energy supply sector. Their development, in coordination with building retrofits and the decarbonization of energy supply, can support the EU’s climate targets. A systems-level approach that aligns building renovations, heat demand planning, and the integration of low-carbon energy sources is necessary to fully realize the benefits of district heating in a sustainable energy future.

The interdependency between the building sector and the energy supply sector is central to the decarbonization potential of district heating networks. Buildings represent the primary heat demand, and their characteristics—such as insulation level, density, and efficiency—directly affect both the technical and economic feasibility of district heating. While upgrading buildings can enable lower supply temperatures and improve system efficiency, it may also reduce heat demand to a level where district heating becomes less economically viable, particularly in low-density or highly efficient neighborhoods.

On the supply side, as the EU transitions towards a cleaner energy mix, district heating can serve as a balancing mechanism, particularly in integrating variable renewable energy sources like wind and solar. By utilizing excess electricity through power-to-heat technologies (e.g., large-scale heat pumps and electric boilers), district heating systems can convert surplus renewable electricity into thermal energy, helping to stabilize the power grid. Furthermore, the potential role of green hydrogen in the future energy mix may supplement district heating by providing seasonal storage and backup generation, ensuring resilience and flexibility.

Policies targeting the building and energy supply sector have a direct and often compounding impact on the district heating sector. Building regulations that drive energy efficiency improvements, renovation rates, and heat demand profiles influence the technical and economic viability of district heating. Simultaneously, energy sector policies—such as those promoting renewable electricity, phasing out fossil fuels, or supporting the development of hydrogen and waste heat recovery—shape the availability and cost of heat supply options. As a result, coherent and aligned policymaking across these sectors is essential to support the sustainable growth and decarbonization of district heating systems.

3.2.5.1 EUBase Scenario

3.2.5.1.1 General description

As the interdependencies between buildings and the energy supply sector are crucial for the development and decarbonization potential of district heating networks, the EUBase scenario for the district heating sector aligns with the developments of the EUBase scenario of the buildings and the energy supply sector. The developments in the buildings sector have a significant impact on the trajectory of the district heating networks in the EU. The share of district heating from the total space heating and hot water demand follows the development of the EUBase scenario in the buildings sector. The EUBase energy supply scenario provides a comprehensive overview of the district heating heat supply mix and decarbonization potential. Hence, the EUBase scenario for the district heating sector serves as a reference case built on the same policy and regulatory foundations as the buildings and supply sector, reflecting the European policy landscape in force as of mid-2024. In this scenario, the district heating sector evolves under current policies, including the CO_2 price signals from the EU ETS, which shape cost structures and competitiveness of district heating relative to alternative heating options. Demand for district heating is closely linked to the trajectory of the buildings sector, where renovation rates, energy efficiency improvements, and business-as-usual adoption of appliances influence overall heat demand. At the same time, the supply side is driven by moderate increases in renewable and low-carbon energy integration, but without the accelerated measures foreseen in the more ambitious target scenarios. As such, the EUBase scenario depicts a path of gradual decarbonization in the district heating sector, guided by existing legislative frameworks and national plans, but falling short of mobilizing the full potential of renewable deployment, sector coupling, and sufficiency strategies required for climate neutrality.

3.2.5.1.2 Main assumptions

The district heating network development follows the share of district heating from the total space heating and hot water demand in residential and non-residential buildings presented in Section 3.2.3. In Table 28, the development of the district heating share is presented. The analysis focuses on the EU25 excluding the countries of Malta and Cyprus. Since in these two countries there is no existing district heating networks and due to their size and climate conditions it is assumed that district heating will have no role in their future heat supply.

The development of the district heating network is based on the proportion of district heating to the total space heating and hot water demand in residential and non-residential buildings, as illustrated in section 3.2.3. A link to the results of the building model is provided, indicating that the assumptions made in the building model are transferred to the district heating model without modification. The main reason for a reduction in the district heating share is the fact that individual countries are grouped together in clusters for modeling the scenarios in the buildings sector (cf. section 3.2.3) Therefore, the status-quo value in 2020 suggests a higher level of resolution compared to the scenario years thereafter. Austria, for instance, is grouped together with Germany and Luxembourg. Due to its size Germany dominates the energy carrier mix of that "central" cluster (cf. Table 2). Even though the share of district heating in the "central" cluster increases overall, the "Austrian share" decreases.

Table 28: District heating share from space heating and hot water demand in residential and non-residential buildings in the EUBase scenario

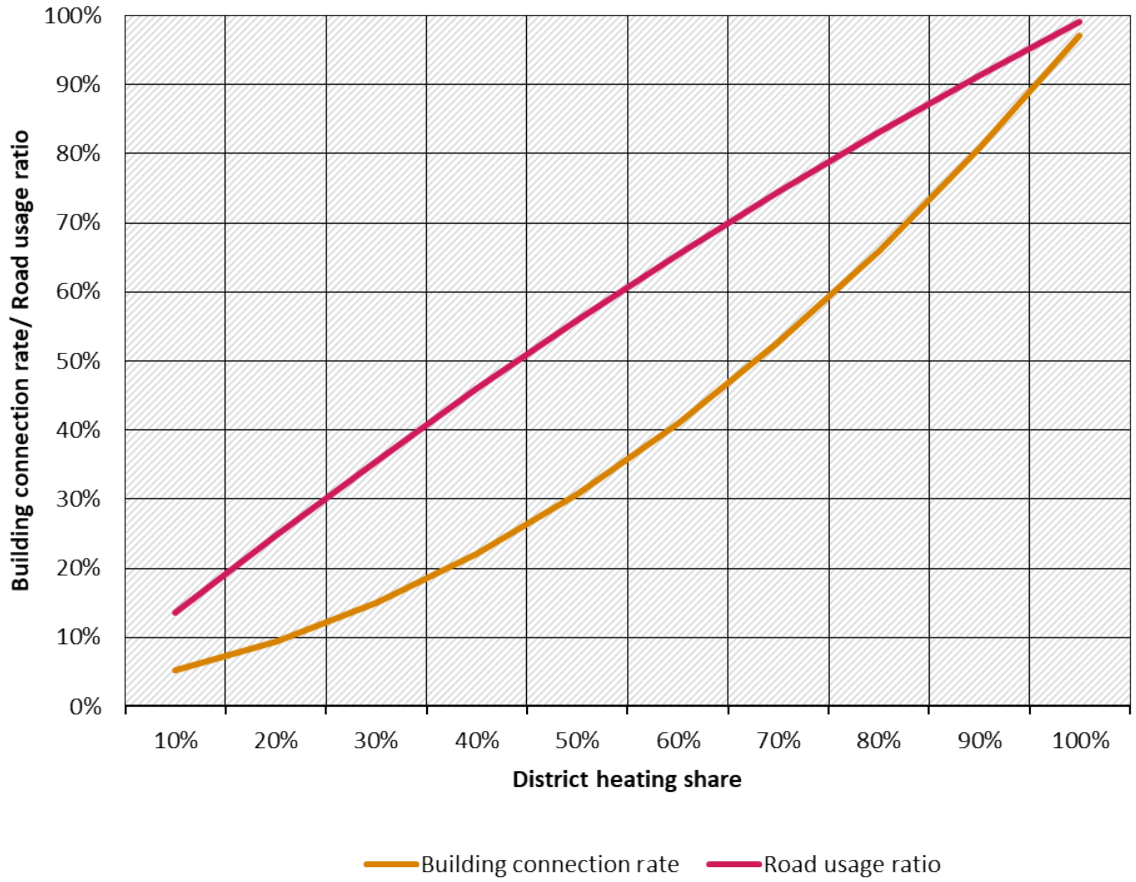
Country	2020	2030	2040	2050
Austria	22%	19%	16%	13%
Belgium	2%	3%	5%	6%
Bulgaria	21%	21%	21%	21%
Croatia	7%	7%	7%	7%
Czechia	19%	20%	20%	21%
Denmark	47%	44%	42%	39%
Estonia	40%	40%	39%	38%
Finland	43%	42%	40%	39%
France	5%	6%	6%	7%
Germany	9%	10%	12%	13%
Greece	2%	4%	6%	7%
Hungary	11%	14%	18%	21%
Ireland	1%	3%	4%	6%
Italy	4%	5%	6%	6%
Latvia	39%	39%	39%	38%
Lithuania	45%	43%	41%	38%
Luxembourg	14%	13%	13%	13%
Netherlands	5%	5%	5%	6%
Poland	24%	23%	22%	21%
Portugal	2%	3%	5%	6%
Romania	15%	17%	19%	21%
Slovakia	23%	22%	21%	21%
Slovenia	13%	16%	18%	21%

Country	2020	2030	2040	2050
Spain	1%	3%	5%	6%
Sweden	52%	48%	43%	39%

To estimate the potential and scale of district heating networks, we perform a bottom-up spatial analysis using high-resolution raster data at the hectare level. This data includes the number of buildings and the total road length per cell, enabling detailed assessment of heat demand density and infrastructure needs. By applying country-specific district heating shares, we estimate the number of buildings likely to be connected to district heating systems within each area. Additionally, we use the road usage ratio—representing the proportion of roads typically used for pipe installation—to calculate the required network length. This approach allows for a realistic and geographically differentiated assessment of district heating deployment potential across regions.

Figure 68 presents the building connection rate and road usage ratio as a function of the district heating share. This ratio was derived from the average ratios between connection rate and length of road used and reflects a decreasing share of additional road length with increasing building connection rate.

Figure 68: Average building connection rate and road usage ratio as a function of the district heating share

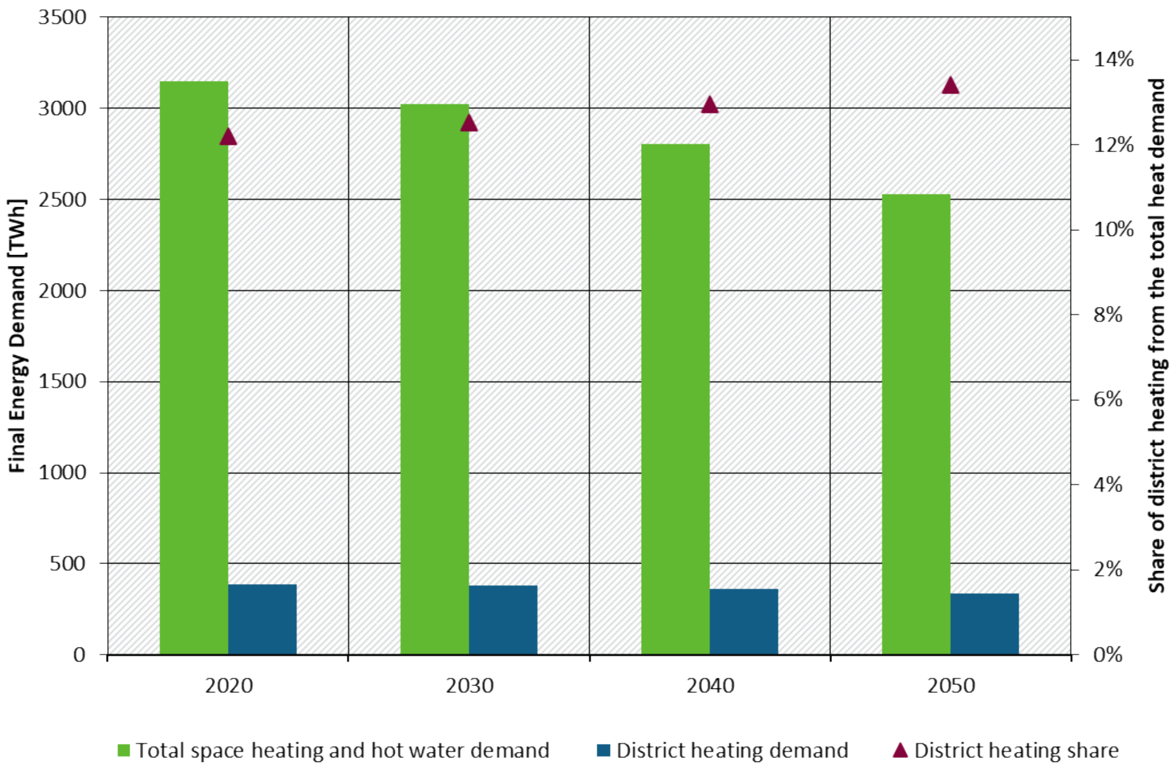


Source: Own calculation IREES based on (Research Data Centre of the Federal Statistical Office and the Research Data Centre of the Statistical Offices of the Federal States 2021); (Fraunhofer IEG et al. 2020); (Jochum 2017).

3.2.5.1.3 Overview of results EUBase Scenario

Figure 69 presents the district heating final energy demand and share of the total space heating and hot water demand in the EU-25. The district heating final energy demand reduces from roughly 384 TWh/a in 2020 to 339 TWh/a in 2050. Despite the decrease in the absolute final energy demand the share of district heating in the EU-25 slightly increases from 12.2% in 2020 to 13.4% in 2050.

Figure 69: EU-25 District heating demand and share of district heating from total space heating and hot water

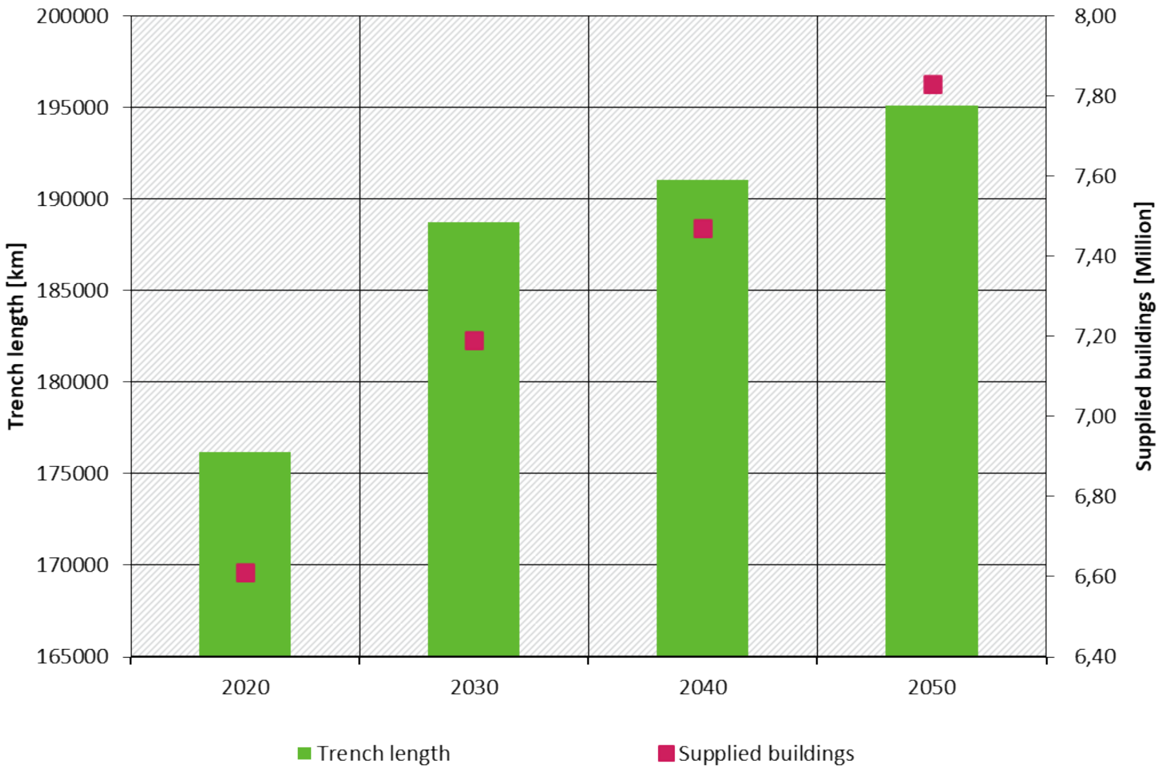


Source: Own calculation IREES

Figure 70 presents the total trench length and the number of supplied buildings in the EU-25. The trench length increases from approx. 176 thousand kilometers in 2020 to 195 thousand kilometers in 2050 whereas the number of buildings supplied with district heating increases from 6.61 million buildings in 2020 to 7.83 million in 2050.

As district heating networks expand toward 2050 to support decarbonization goals, the linear heat density—defined as the amount of heat delivered per meter of network—tends to decline. This is primarily due to ongoing building refurbishment and energy efficiency improvements, which significantly reduce the heat demand per building. While more buildings may become connected to district heating systems over time, the overall demand per unit length of network decreases as renovated buildings require less thermal energy. This reduction in linear heat density can affect the economic performance and design of future networks, highlighting the importance of aligning network planning with renovation strategies to ensure cost-effective and efficient expansion. A reduction of the average linear heat densities of 2.18 MWh/m*a in 2020 to 1.74 MWh/m*a in 2050 is observed with an average 1.96 MWh/m*a for the period between 2020 and 2050.

Figure 70: **EU-25 District heating trench length and number of supplied buildings**



Source: Own calculation IREES

3.2.5.2 Target scenarios

3.2.5.2.1 General description

The target scenarios, EUTarget and EUSupreme, represent increasingly ambitious pathways for transforming the EU building sector beyond the baseline. The EUTarget and the EUSupreme scenarios diverge from the EUBase scenario in several ways. In EUTarget, the level of ambition is increased for the majority of underlying drivers, including the renovation rate, renovation standards, and the transition from fossil energy carriers to renewable energy carriers. This is done to ensure that by 2050, the direct GHG emissions of the buildings sector reach zero. Furthermore, the EUSupreme scenario introduces additional ambitious measures, including (i) slightly higher renovation rates than those in the EUTarget scenario, (ii) sufficiency measures, and (iii) more stringent restrictions on the use of fossil energy carriers and biomass.

3.2.5.2.2 Main assumptions

In modeling the district heating sector, the primary assumptions differentiate the EUTarget and EUSupreme scenarios based on the development trajectories in the building and supply sectors, while maintaining consistency in other technical parameters. These scenarios assume varied growth rates and technological advancements in building efficiency and energy supply methods, influencing the demand and integration of district heating systems. Factors such as building connection rates in relation to the share of district heating and road usage ratios for infrastructure deployment are calculated based for the share of district heating presented in Table 29. This approach ensures that any differences in the outcomes are directly attributable to the variations in building and supply sector developments, providing a clear analysis of how advancements in these areas can drive the evolution, costs, and impact of district heating systems.

Table 29: District heating shares from space heating and hot water demand in residential and non-residential buildings in the EUTarget and EUSupreme scenarios

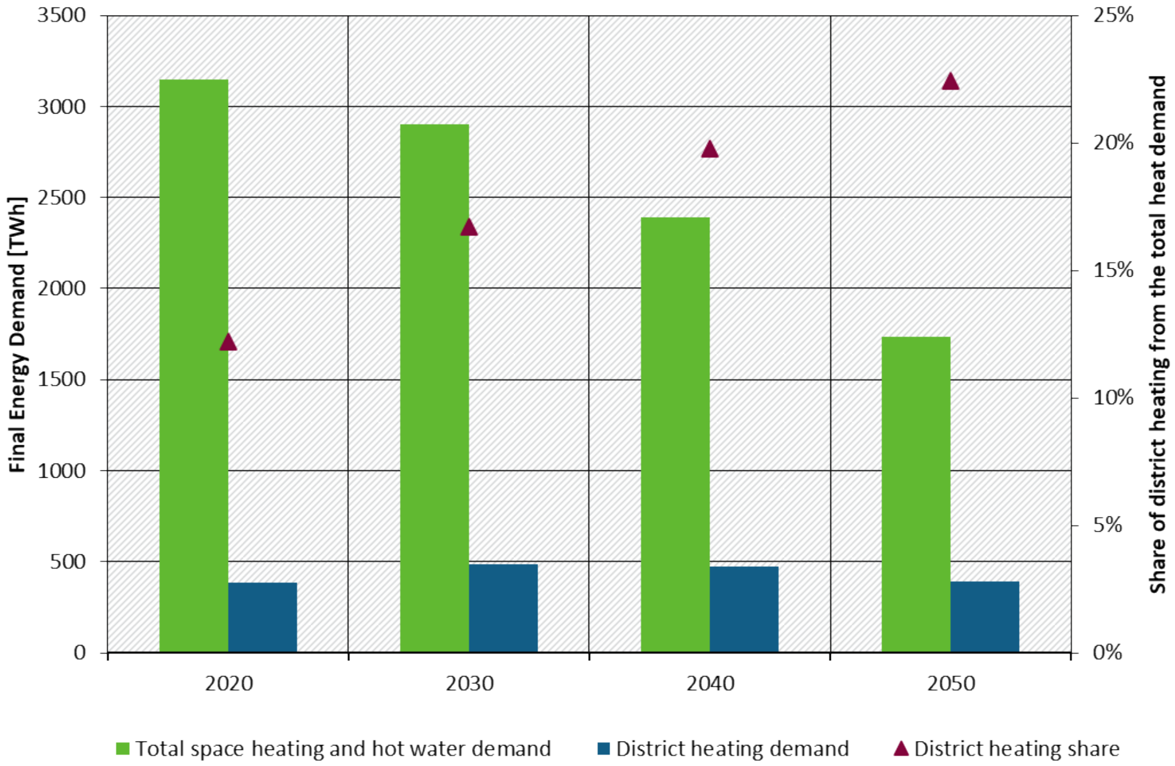
Country	2020 Target	2030 Target	2040 Target	2050 Target	2020 Supreme	2030 Supreme	2040 Supreme	2050 Supreme
Austria	22%	23%	22%	22%	22%	15%	19%	24%
Belgium	2%	8%	13%	18%	2%	10%	15%	20%
Bulgaria	21%	25%	27%	29%	21%	23%	27%	32%
Croatia	7%	11%	14%	17%	7%	10%	14%	19%
Czechia	19%	23%	26%	29%	19%	23%	28%	32%
Denmark	47%	46%	44%	42%	47%	41%	43%	45%
Estonia	40%	41%	41%	42%	40%	39%	42%	44%
Finland	43%	43%	42%	42%	43%	41%	43%	45%
France	5%	11%	15%	18%	5%	10%	15%	20%
Germany	9%	14%	18%	22%	9%	15%	19%	24%
Greece	2%	8%	12%	16%	2%	10%	14%	19%
Hungary	11%	18%	24%	29%	11%	23%	28%	32%
Ireland	1%	8%	13%	18%	1%	10%	15%	20%
Italy	4%	10%	13%	17%	4%	10%	15%	19%
Latvia	39%	40%	41%	42%	39%	39%	42%	44%
Lithuania	45%	44%	43%	42%	45%	39%	42%	44%
Luxembourg	14%	18%	20%	22%	14%	15%	19%	24%
Netherlands	5%	10%	15%	18%	5%	10%	15%	20%
Poland	24%	27%	28%	29%	24%	23%	28%	32%
Portugal	2%	8%	12%	17%	2%	10%	14%	19%
Romania	15%	21%	25%	29%	15%	23%	28%	32%
Slovakia	23%	26%	28%	29%	23%	23%	28%	32%
Slovenia	13%	19%	24%	29%	13%	23%	28%	32%
Spain	1%	7%	12%	17%	1%	10%	15%	19%
Sweden	52%	49%	45%	42%	52%	41%	43%	45%

Note: The development of the district heating shares follows the modeling results from the buildings sector (cf. Chapter 3.2.3)

3.2.5.2.3 Overview of results EUTarget

Figure 71 presents the district heating final energy demand and share of the total space heating and hot water demand in the EU-25. The district heating final energy demand increases from roughly 384 TWh/a in 2020 to 472 TWh/a in 2040 and 389 TWh/a in 2050. Despite the slight increase in the absolute final energy demand the share of district heating in the EU-25 almost doubles between from 12.2% in 2020 to 22.4% in 2050. This apparent contradiction is explained by the significant reduction in overall heating demand due to ambitious building refurbishment measures assumed in the scenario. As energy efficiency improves and the total heat demand drops, district heating networks expand to supply a larger proportion of this smaller demand. In essence, while the volume of final energy demand delivered by district heating remains steady, its relative importance grows as it supplies more buildings.

Figure 71: EU-25 district heating demand and share of district heating from the total space heating and hot water demand

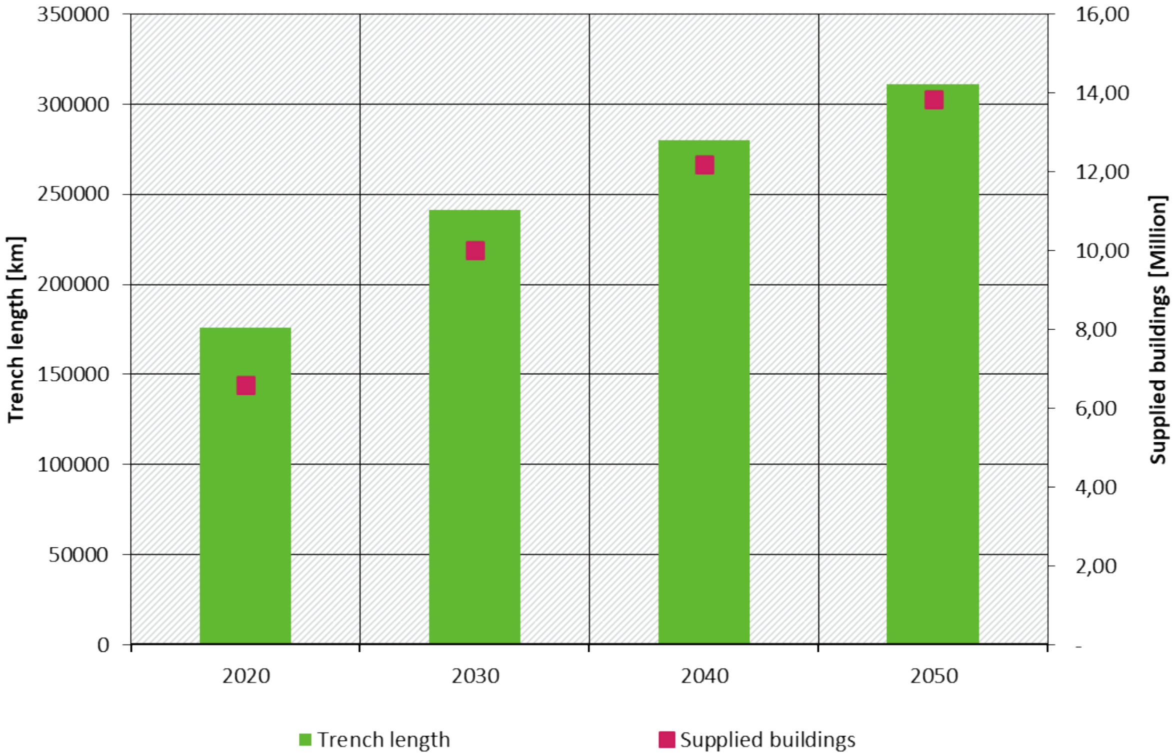


Source: Own calculation IREES

Figure 72 presents the total trench length and the number of supplied buildings in the EU-25. To counter the drastic heat demand reduction and to supply 22.4% of the total space heating and hot water demand in 2050 the trench length must increase from ca 176 thousand kilometers in 2020 to 310 thousand kilometers in 2050 whereas the number of buildings supplied with district heating increases from 6.61 million buildings in 2020 to 13.8 million in 2050.

Like the EUBase scenario as district heating networks expand toward 2050 to support decarbonization goals, the linear heat density—defined as the amount of heat delivered per meter of network—tends to decline. This is primarily due to ongoing building refurbishment and energy efficiency improvements, which significantly reduce the heat demand per building. While more buildings become connected to district heating systems over time, the overall demand per unit length of network decreases as renovated buildings require less energy. A reduction of the average linear heat densities of 2.18 MWh/m*a in 2020 to 1.68 MWh/m*a in 2050 is observed with an average 1.78 MWh/m*a for the period between 2020 and 2050.

Figure 72: EU-25 District heating trench length and number of supplied buildings

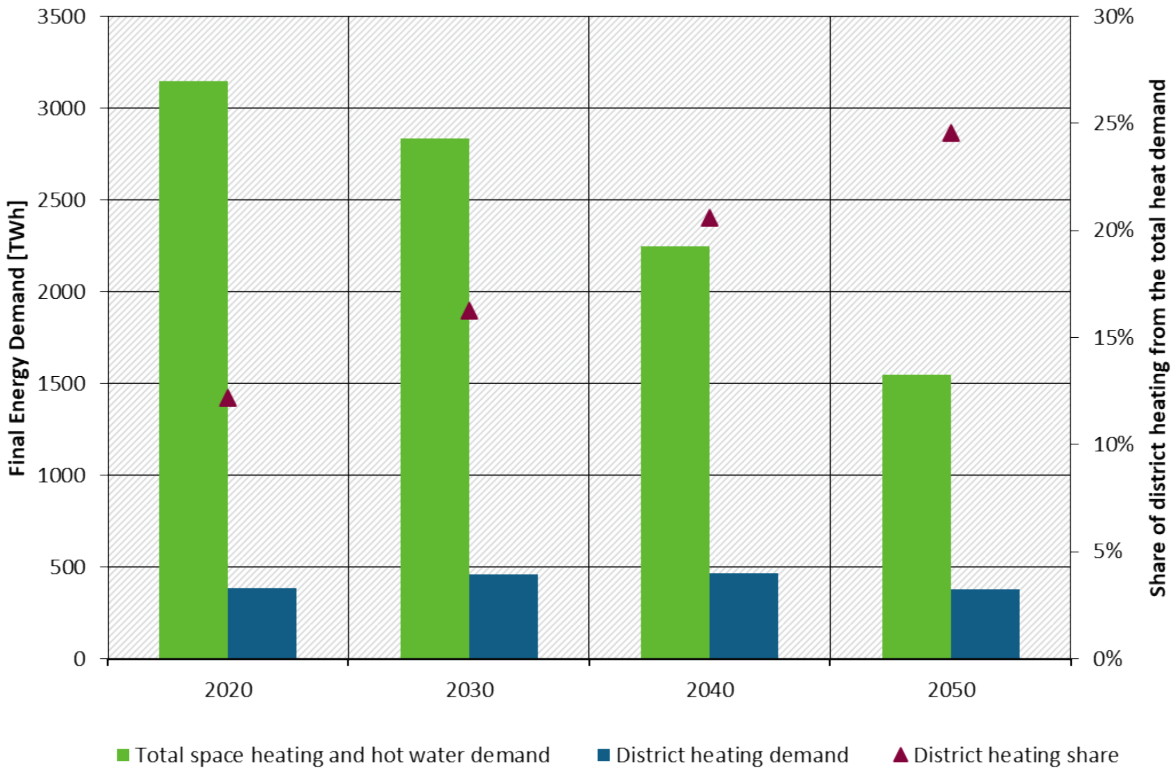


Source: Own calculation IREES

3.2.5.2.4 Overview of results EUSupreme

Figure 73 presents the district heating final energy demand and share of the total space heating and hot water demand in the EU-25. The district heating final energy demand increases from roughly 384 TWh/a in 2020 to 464 TWh/a in 2040 and 380 TWh/a in 2050. At the same time the total space heating and hot water demand goes from 3148 TWh in 2020 to 2389 TWh in 2040 and 1734 TWh in 2050. Hence, despite the slight increase in the absolute final district heating energy demand the share of district heating in the EU-25 doubles between from 12.2% in 2020 to 24.6% in 2050. This is explained by the significant reduction in overall heating demand due to ambitious building refurbishment measures assumed in the scenario. As energy efficiency improves and the total heat demand drops, district heating networks expand to supply a larger proportion of this smaller demand. In essence, while the volume of final energy demand delivered by district heating remains almost the same in 2020 and 2050, its relative importance grows as it supplies more buildings. In the years 2030 and 2040, there is a noticeable increase in district heating demand, despite the overall long-term trend of decreasing heat consumption due to building refurbishment. This temporary rise is explained by the rapid expansion of district heating networks outpacing the rate of energy efficiency improvements in buildings. As new, previously unconnected buildings are integrated into the district heating system, many of them have not yet undergone renovation and therefore still exhibit high heat demand. As a result, the total district heating demand temporarily increases during this period before declining again toward 2050, as refurbishment efforts gradually reduce the specific heat demand of the building stock.

Figure 73: EU-25 District heating demand and share of space heating and hot water

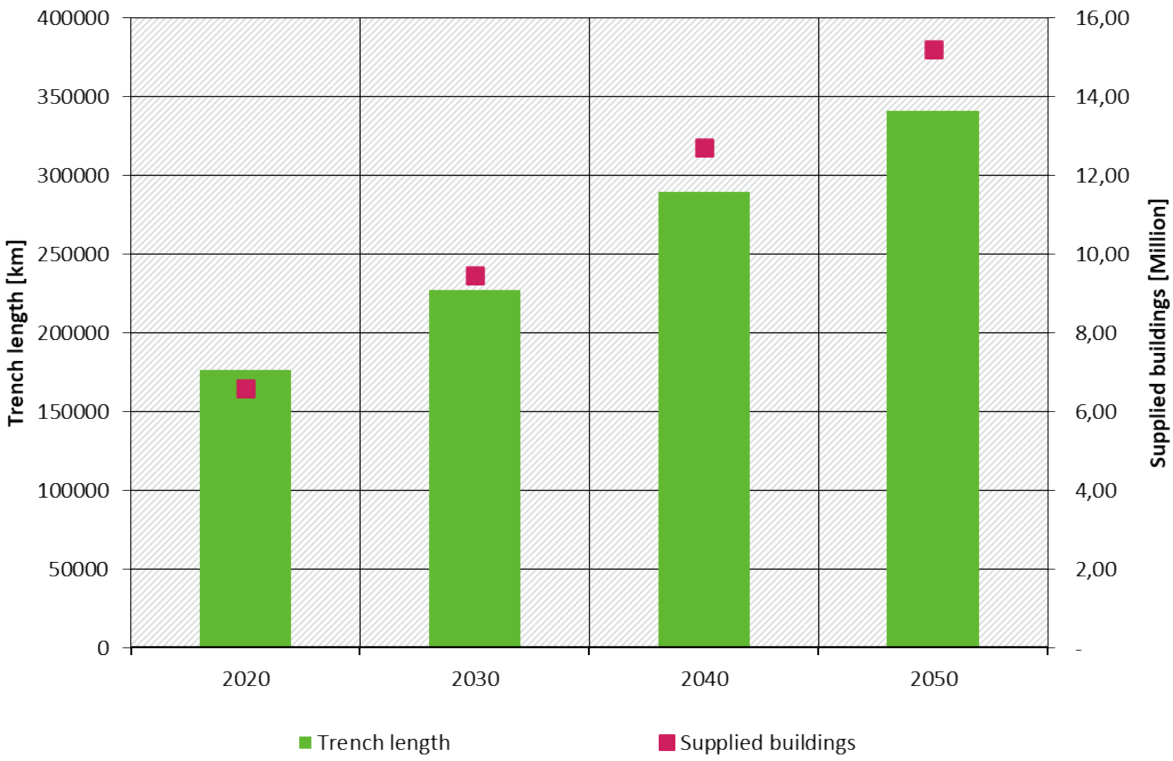


Source: Own calculation IREES

Figure 74 presents the total trench length and the number of supplied buildings in the EU-25. The district heating model is driven by the share of district heating heat projected in the buildings model, which sets the target for how much of the space heating and hot water demand should be met by district heating. To achieve this, the district heating model actively expands the network by increasing both the total pipeline length and the number of buildings connected. This ensures alignment with the building model's demand trajectories, aiming to supply a growing share of the heat demand even as overall consumption declines due to efficiency measures. To counter the drastic heat demand reduction and to supply 24.6% of the total space heating and hot water demand, the trench length needs to increase from approx. 176 thousand kilometers to 340 thousand kilometers in 2050, whereas the number of buildings supplied with district heating increases from 6.61 million buildings in 2020 to 15.2 million in 2050.

The average linear heat density over the years as well. A reduction of the average linear heat densities of 2.18 MWh/m*a in 2020 to 1.60 MWh/m*a in 2050 is observed with an average 1.73 MWh/m*a for the period between 2020 and 2050.

Figure 74: EU-25 District heating trench length and number of supplied buildings



Source: Own calculation IREES

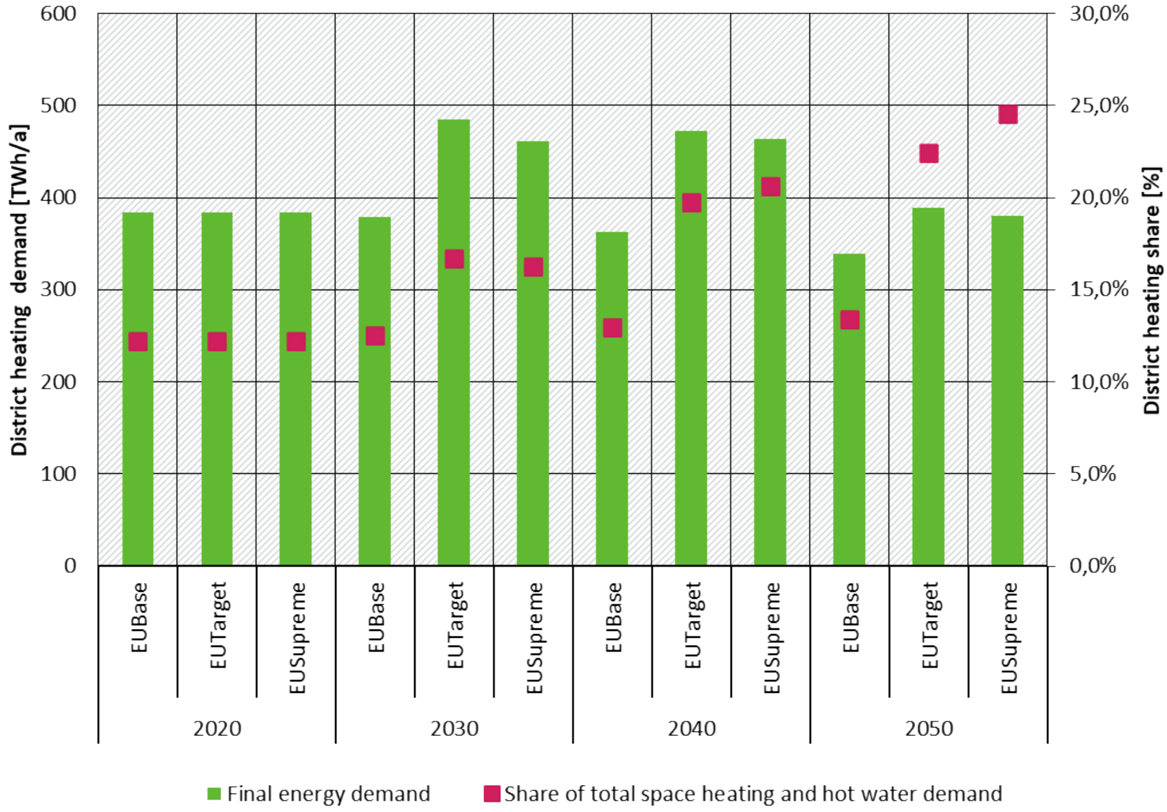
3.2.5.2.5 Comparison

Figure 75 shows the district heating final energy demand and share of total space heating and hot water demand across EUBase, EUTarget and EUSupreme scenarios. Based on the modeling results, a modest increase from 12.2% in 2020 to 13.4% in 2050 in the share of district heating is observed in the EUBase scenario. In the EUTarget and EUSupreme scenarios the share in 2050 increases to 22.4% and 24.6% respectively. The final energy demand supplied by district heating reduces from 384 TWh/a in 2020 to 339 TWh/a in EUBase scenario in 2050 and 380 TWh/a in EUSupreme in 2050. In EUTarget a slight increase of the absolute district heating final energy demand to 389 TWh/a in 2050 is observed.

The development of the district heating network is based on the proportion of district heating to the total space heating and hot water demand in residential and non-residential buildings, as illustrated in section 3.2.3. A direct connection to the results of the building model is established, ensuring that all assumptions regarding energy demand, refurbishment rates, and the targeted share of district heating are consistently transferred to the district heating model without modification. This alignment guarantees that the district heating model operates on the same foundational inputs, particularly regarding the share of heat to be supplied by district heating and guides the expansion of the network accordingly. As a result, the district heating model focuses on increasing network length and building connections to meet the demand share defined by the building sector, maintaining consistency across both modeling frameworks. Hence, in the EUTarget scenario, although the share of district heating is lower compared to the EUSupreme scenario, the absolute district heating demand is actually higher. This is a result of the differing assumptions in the building model: the EUTarget scenario assumes a slower or less comprehensive refurbishment of the building stock, leading to higher overall heat demand. Since the district heating model directly adopts these assumptions without modification, it reflects the higher absolute energy demand, even if the relative share of district heating is smaller.

Consequently, more energy is supplied via district heating in the target scenario despite its lower market penetration.

Figure 75: Comparative analysis of district heating final energy demand and share of total space heating and hot water across the EUBase, EUTarget and EUSupreme scenarios



Source: Own calculation IREES

Figure 76 compares the projected district heating trench length and buildings supplied by district heating in the EUBase, EUTarget and EUSupreme scenarios. Based on the modeling results the trench length increase from 176 thousand kilometers in 2020 to 195 thousand kilometers in 2050 in the EUBase scenario. In the EUTarget and EUSupreme scenarios the trench length in 2050 increases to 310 thousand and 340 thousand kilometers respectively. The number of supplied buildings increases from 6.61 million buildings to 7.83 million in 2050 in the EUBase scenario. In the EUTarget and EUSupreme scenarios the number of supplied buildings increases to 13.83 and 15.22 million respectively. The EUTarget and EUSupreme scenarios differ from the EUBase scenario mainly due to assumptions made in the building model, such as a shift away from fossil energy sources, higher refurbishment and demolition rates, improved renovation standards (EUTarget) and an even more restrictive use of fossil energy sources and biomass and additional sufficiency measures (EUSupreme). Thus, higher shares of district heating are observed in the EUTarget and EUSupreme scenarios, leading to a higher number of buildings supplied by district heating.

Figure 76: Comparative analysis of district heating trench length and supplied buildings across the EUBase, EUTarget and EUSupreme scenarios

Source: Own calculation IREES

3.2.6 LULUCF

The sector Land Use, Land-Use change, and Forestry (LULUCF) is the only sector with natural carbon sinks. These are generated by biomass growth on agricultural and forest land. In the LULUCF sector, forests form the largest area in EU, covering 40% of the EU territory, followed by Cropland (29%) and Grassland (17%). In 2023, net GHG emissions and removals from the sector were reported to amount to -198 Mt CO_2e.[43] Compared to 2008, when net removals amounted to -358 Mt CO_2e, this is a reduction of 160 Mt CO_2e, indicating a drastic decline in natural carbon sinks. However, according to EEA, the net LULUCF sink has stabilised since 2019. Net carbon removals in 2023 were reported for the categories Forest land (-274 Mt CO_2e) and Harvested Wood Products (-31 Mt CO_2e). All other categories, including Cropland and Grassland formed sources of GHG emissions of about 107 Mt CO_2e. An important source of emissions are organic soils resulting from drainage of peatlands. These can be found under forests, grasslands and croplands. Despite the fact that organic soils under these three land categories cover only 17 Mha (4.7%) in the EU (2,9 Mha under grassland, 1,2 Mha under cropland, and 13 Mha under forests), emissions amount to 105 Mt CO_2e (more than 50% of total LULUCF) per year, presenting a large potential for emission reductions through rewetting.

In 2021, according to EEA, biomass accounted for 56% (i.e. 125 Mt of oil equivalent (Mtoe)) of the overall EU's renewable gross final energy consumption. This share is expected to increase because many EU Member States rely more and more on biomass in their transition towards

[43] see https://climate-energy.eea.europa.eu/topics/climate-change-mitigation/land-and-forests/data for a visualization of emission developments in the LULUCF sector

climate neutrality according to their NECPs[44]. The rate of extraction of biomass, especially from forest ecosystems constitutes an important driver for the development of the natural sink as biomass harvest constitutes an emission in national GHG inventories.

3.2.6.1 EUBase scenario

3.2.6.1.1 General description

The most important legislation for the sector is the LULUCF Regulation. It sets national targets for net GHG emissions and removals from the sector that sums up to a net removal target for the EU of -310 Mt CO_2e in 2030. To achieve the target, the net sink needs to be increased by more than 110 Mt CO_2e. In the EUBase scenario measures by MS towards the target are being implemented. However, it does not assume that the target is met. This describes the continuation of the current situation where national policies achieve a reversion of the decline in the net sink, but the intensity of activities is not sufficient to achieve the required level of net removals. The measures include an increase in forest area through new forest plantations, a limitation of wood harvest to stabilize net removals from forests, and an increase in the share of longer-living wood products and in cascade use of wood. Moreover, the EUBase scenario realizes potentials for reducing emissions in the sector through the rewetting of organic soils, especially those that are currently used as grassland and cropland. The protection of grassland from conversion to cropland is an implemented mitigation measure and assumed to continue in the EU under the scenario, assuming no net loss of grassland. Another activity for storing carbon in vegetation and soil on agricultural land are agroforestry systems or short rotation plantations. Trees are established on agricultural area, either as plantations of fast-growing tree species, that are harvested after five to seven years and left for regeneration through resprouting once or twice. Land managers can also introduce single trees, trees in lines, hedges etc. as agroforestry systems. Such measures are expected to become more attractive as they can generate revenue for farmers through biomass production but form also important adaptation measures to avoid soil erosion and to improve microclimate and can increase biodiversity in agricultural areas. Other measures assumed in the LULUCF sector include a reduction of peat extraction from wetlands and the reduction of net land take for infrastructure.

In the EUBase scenario several other strategies and plans at EU level are implemented which will lead to a change in land use patterns and in biomass supply. Some of those are expected to have opposing trends. This is for example true for the implementation of the Renewable Energy Directive (RED) and the National Energy and Climate Plans (NECPs) which further the demand for biomass for material and energy related use.

Consequently, the LULUCF target is partly in opposition to trends of increased biomass use for energy, because biomass extraction leads to emissions in the LULUCF sector. The diverging trends lead to a situation where – despite the measures implemented aiming at reaching the target - the EU target under the LULUCF Regulation of -310 Mt CO_2e in 2030 is very likely not met.

3.2.6.1.2 Main assumptions

The EUBase scenario for LULUCF is implemented by making assumptions on the development of areas under different land use categories, namely forests, cropland and grassland, settlements and others. The details of the scenario assumptions including target values and reference years are presented in Table 30.

In the EUBase scenario, solid biomass demand peaks by 2030 (see Figure 15 in chapter 3.1.1.5). The supply of domestic wood for energy, however, continues to increase due to decreased

[44] https://www.eea.europa.eu/publications/the-european-biomass-puzzle

imports (see Figure 16) and substitution of crop-based bioenergy with woody biomass from short rotation coppices and forests for the use as advanced (second generation) fuels. This results in more extraction of wood for energy use from domestic forests that puts pressure on the EU forest sink. Main driver for this development is the implementation of RED III and the large share of biomass use for energy in NECPs.

Forests are among the LULUCF categories with both high potential for reducing emissions, but also high potential for increasing removals. Deforestation emissions in the EU in 2020, due to conversion of forests to other land uses, were reported to be 33 Mt CO_2e/year. For the EUBase scenario it is assumed that forests continue to be lost at a similar level (mainly due to infrastructure projects) and therefore no significant reduction of emissions is achieved in this matter.

Establishing new forests can be realized on agricultural land, i.e. cropland or grassland. There are trade-offs with agricultural production but synergies with timber production in the long-term (beyond 2050). In the EUBase scenario we assume that an increase of forest area through new forest plantations by 1% of current forest area, i.e. a cumulative 1.6 Mha by 2050 compared to 2020, can be achieved with subsequent increases in biomass carbon stocks and thus CO_2 removals.

In existing forests carbon stocks can potentially be increased. The potential depends on how much of the annual increment in forests is already being harvested. However, tradeoffs regarding reduced wood harvest need to be considered. In the EUBase scenario, we assume that maintaining the forest sink compared to 2020 can be achieved by stabilizing the harvest rate in forests at about 84% of increment. In 2050, this amounts to 614 Mm^3 (511 Mm^3 roundwood and 103 Mm^3 of woodfuel (wood directly harvested for energy use)). In addition, about 20 Mm^3 are expected to be delivered from short rotation coppices (SRC) to meet increasing biomass demands.

More limited removals can be achieved through changes in the production of harvested wood products (HWP). An increase in the share of longer-living wood products and increased cascade use of wood comes with potential trade-offs with other wood uses and energy use. The reason for this is that an increasing lifetime of products reduces available recycling and waste wood streams. In the EUBase scenario it is assumed that, also associated with increased harvest rates compared to today, the carbon stock in the HWP pool can be slightly increased.

On cropland and grassland there is large potential for reducing emissions in the sector through the rewetting of organic soils. The EUBase scenario assumes the active rewetting of 20% of cropland, 33% of grassland and 30 % of forests on organic soils to wetlands by 2050. These values are assumed to represent a medium ambition level by judgement of the project team and in exchange with experts at a project workshop. Furthermore, emissions from grassland converted to cropland were reported to be 35.8 Mt CO_2/year in 2020. This translates to conversion of 9 Mha in 2020. The EUBase assumes that these emissions can be avoided through reduced grassland conversion to cropland to net zero through effective regulation. Agroforestry systems are currently covering only small areas in the EU. In the EUBase scenario it is assumed that 0.3 Mha of coppice or agroforestry areas are established, leading to increased carbon stocks in vegetation and soil. This rather low ambition level reflects past trends of the establishment of agroforestry systems in EU countries.

In the EU, wetlands are being converted to peat extraction causing emissions. In the EUBase it is assumed that peat extraction is reduced until 2050 by 50% compared to 2020. Moreover, the reduction of land consumption, due to increase of area used for settlements, can also reduce GHG emissions. In 2020, 6.5 Mha of other land categories were included in the category of land converted to settlements, this is equivalent to an average annual rate of 0,325 Mha converted into settlements. At the same time about 0,08 Mha of settlements turned into other land uses. The EU Roadmap to a Resource Efficient Europe formulates the aim to achieve no net land take of infrastructure and settlements by 2050. The EUBase scenario assumes that this target is not being met, but that net land take of infrastructure and settlements is reduced by 50% until 2050 compared to 2020.

3.2.6.1.3 Results

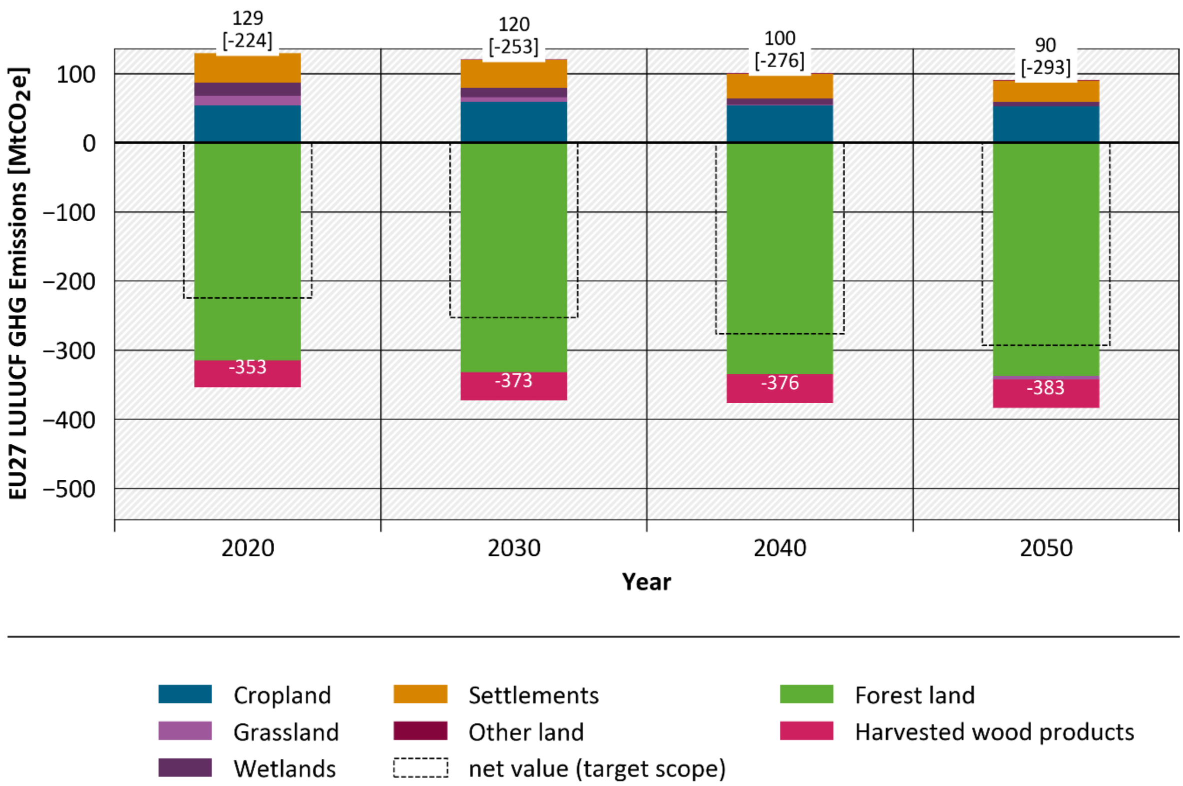
The development of GHG emissions and removals from the LULUCF sector are described in Figure 77. Categories including new and old forests show increasing removals until 2050 compared to 2020 from -315 Mt CO_2e to -338 Mt CO_2e, a similar level observed in EU countries in 1990. This is both due to increased net removals in existing forests and the establishment of new forest area in EU countries. Overall, the sink of forests and Harvested Wood Products increases by about 7% compared to 2020.

In the cropland category emissions remain roughly the same: after a slight increase from 2020 to 2030, emissions drop back to the level in 2020. There are two opposing trends in emissions underlying this development. Firstly, emissions increase due to continued gross conversion of grasslands into cropland. Secondly, areas with high emissions (drained peatlands) that are being rewetted leave the category of cropland and are included in wetlands. This causes emissions from cropland to decrease.

The grassland category shows decreasing emissions continuously and a switch from a net source to a net sink until 2050. This is due to lands with organic soils being rewetted and taken out of production. Moreover, land converted from cropland to grassland is gaining carbon. Emissions from wetlands and settlements can be reduced significantly until 2050, contributing more than 11 Mt CO_2 (settlements) and 13 Mt CO_2 (wetlands) reduction of emissions to the LULUCF net balance.

As a result, the net LULUCF sink is projected to increase from -224 Mt CO_2e in 2020 to -290 Mt CO_2e in 2050 (+30%, Figure 77). However, the EU net LULUCF target of -310 Mt CO_2e in 2030 is missed by about 58 Mt CO_2e.

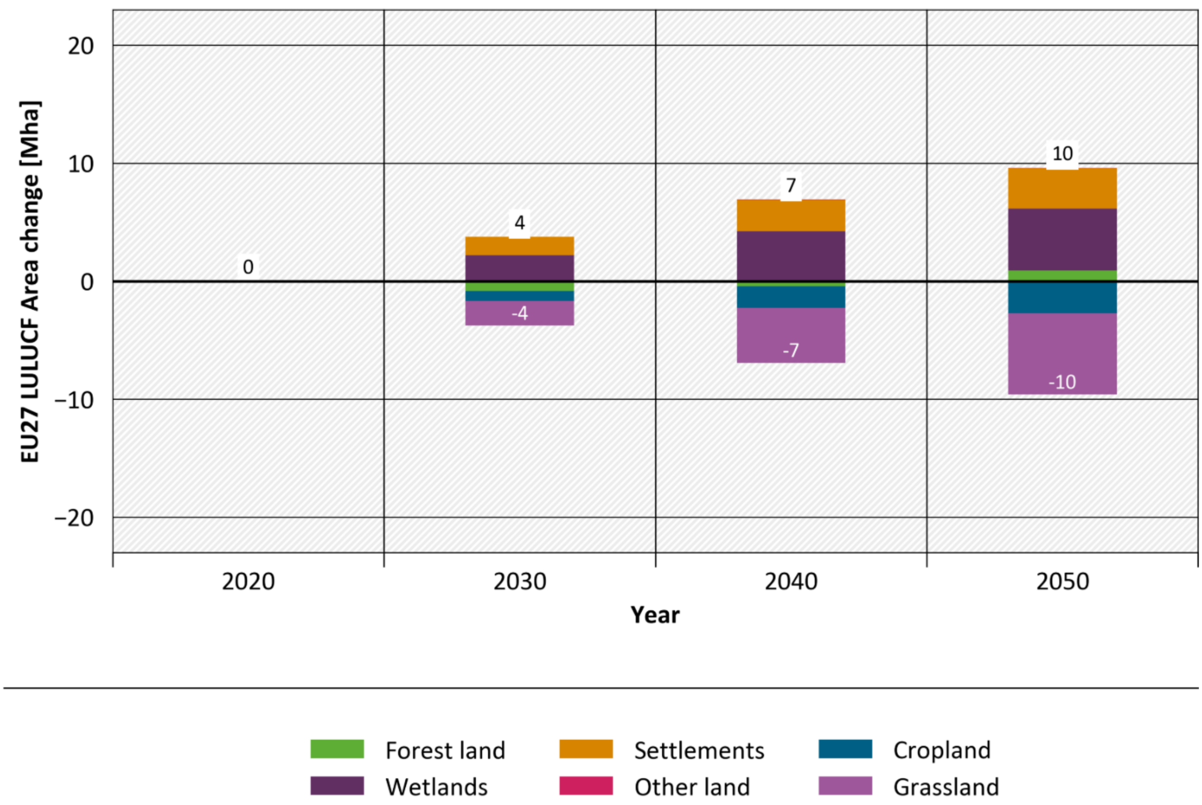
Figure 77: Emissions and removals from the LULUCF sector for different land use categories in the EUBase scenario



Source: Own calculation Oeko-Institut

The observed development of emissions and removals are results of the assumptions that affect the area distribution between the different land categories (Figure 78). The above-described assumptions result in a slight increase in forest area from 167 Mha in 2020 to about 169 Mha in 2050. Stronger increases can be observed in the settlements and wetlands categories. In the EUBase scenario the conversion of land to settlements continues (though at a reduced rate leading to lower emissions compared to 2020 as described above). At the same time, rewetting of organic soils leads to a strong increase in wetland area (+5 Mha until 2050). These increases are at the expense of cropland and grassland that are both decreasing by almost 10 Mha in total until 2050. Cropland areas are reduced by 2% (3 Mha), grassland area by 8% (7 Mha). These two are the main area categories targeted by rewetting and enhancement of settlement area.

Figure 78: Changes in the area for different land use categories over time in comparison to area share in 2020 in EUBase



Source: Own calculation Oeko-Institut

3.2.6.2 Target scenarios

3.2.6.2.1 General description and differences to EUBase scenario

The EUTarget and the EUSupreme scenarios for the LULUCF sector differ from the EUBase scenario in the main assumptions due to differences in the underlying scenario narratives. These differences can be observed from area changes between specific land use categories as well as the intensity of land use within the land use categories. Measures for enhancing net removals in the land-use sector are intensified. This includes afforestation, rewetting, and agroforestry measures. In order to increase forest area in the EU further, cropland and grassland areas are converted into forest land. Moreover, activities leading to net emissions, like deforestation, peat extraction and the conversion of land to settlements and infrastructure are further constrained compared to EUBase. Both, increased removals by sinks and reduced emissions by sources, are the result of measures implemented to increase net removals by the sector as required by the LULUCF Regulation.

The EUTarget scenario is characterized by a reduced demand for total wood supply from forests by 2050 compared to the EUBase scenario and the current level (-6%). This helps increasing net removals from existing forests leading to higher carbon stocks. These can only be stabilised in the medium and long-term if forests are structurally and genetically diverse enough to produce forest stands that are resilient carbon stocks also under intensifying climate change conditions. Moreover, higher afforestation rates are assumed leading to an increase in forest area and net removals in the EU and therefore allow for a reduction of harvest intensity per area.

The same level of wood supply as in the EUTarget scenario is assumed for the EUSupreme scenario. This is because two opposing trends are assumed. While efficiency of wood use and thus carbon stocks in products can be further enhanced in EUSupreme, the availability of waste wood is reduced. This is because more recycling cycles and longer lifetimes of wood products reduce streams of waste wood. These are the result of assumed policies implemented to stregthen the recovery of used wood and efficiency of recycling. The shortage of used wood for energy increases the demand for fresh wood from forests and thus compensates for a reduction of wood demand that is assumed in EUSupreme to reduce pressure on forests. However, in the intensified bioeconomy wood demanding sectors, like construction, can build also on increased supply of wood from SRC plantations, e.g. for fibreboards and insulation products. The additional area for wood supply outside forests can be realized due to a reduction in demand for crop production and grassland due to assumed dietary changes (see assumptions in the agriculture sector).

3.2.6.2.2 Main assumptions

While in the EUBase scenario it is assumed that annual emissions from deforestation are stabilizing, in the EUTarget scenario measures that achieve a reduction by 50% are considered, 75% in the EUSupreme scenario. This can be achieved by improved planning, especially of large infrastructure projects that are often negatively affecting the forest area. The EUTarget scenario assumes that forest area increases through new forest plantations by 5%, i.e. 7 Mha by 2050 compared to 2020. This is 5.4 Mha more than in the EUBase scenario. In the EUSupreme forest area can be increased by even 10 Mha until 2050. This can only be achieved with targeted policies like incentive schemes and restoration programs. Moreover, changes in dietary preferences are needed to reduce pressure on land resources from agricultural production.

In existing forests, the EUTarget scenario expects wood harvest to be reduced on average over the simulation time to 67% of annual increment, which is considerably lower than in the EUBase scenario, resulting in increased carbon stocks in EU forests. There are risks associated with this measure as not all forest types are suitable for further stock increases. Therefore, it is assumed that the intensity of wood extraction cannot be decreased more in the EUSupreme scenario. A reduced harvest intensity results in lower wood supply in EU countries to meet the demand for wood. In both scenarios it is assumed that reduced harvest is targeting wood that is harvested for energy purposes. This requires a reduction in wood from forests used directly for energy. But also wood from newly established SRC plantations can compensate for that reduction. In 2050 total harvest as roundwood and woodfuel amounts to 573 Mm^3 in both scenarios. This is due to two opposing trends leading to similar levels of wood harvest from forests: The EUTarget scenario assumes measures that retain carbon stored in products longer compared to the EUBase scenario (e.g. through higher recycling rates). The EUSupreme scenario assumes that even more carbon can be stored in harvested wood products (HWP) compared to the EUTarget scenario. Here, measures are established to increase residence time of carbon in HWP by 25%. Such measures can include improved product design, policies for the reuse of wood products and more recycling.

More recycling and longer lifetimes, however, also reduce the availability of waste wood at the end of lifetime of products. To compensate for a reduction of wood supply from the waste stream, it can be assumed that demand for fresh wood is increased compared to the EUTarget scenario. This increased demand is also met by an increase in wood supply from SRC plantation systems.

In the cropland and grassland category, measures for rewetting organic soils form the most important mitigation activity already in the EUBase scenario. While efforts on grassland and cropland can be increased, no additional forests with organic soils are rewetted in the EUTarget scenario. The area for rewetting by 2050 increases to 50 % for cropland, to 60 % of grassland and remains at 30 % for forests. In the EUSupreme scenario the efforts are increased leading to rewetting of 67 % of cropland, 78 % of grassland and 70 % of forests on organic soils. These estimates are based on expert judgement of the project team and an extrapolation of relative rates from experience in Germany. As for afforestation, rewetting and taking agricultural land out of production requires targeted policies and private investments. This could include incentive programs for wetland restoration and voluntary carbon markets. These are assumed to be accompanied by policies for dietary changes to reduce demand for agricultural products such as feed for cattle and thus reduce pressure on areas.

No difference from the EUBase is assumed for grassland conversion in the target scenarios, i.e., emissions from grassland conversion can be avoided. This is due to the fact that grassland conversion is already banned by current policies in EU countries and these policies are assumed to continue under both target scenarios. However, the area for coppice or agroforestry systems is assumed to increase. Compared to only 0.3 Mha in 2050 under conditions of the EUBase scenario, in the EUTarget scenario 6.9 Mha of coppice or agroforestry area are established, 13.6 Mha in the EUSupreme scenario.

In the EUBase it is assumed that peat extraction is reduced until 2050 by 50% compared to 2020. EUTarget and EUSupreme scenarios both assume that additional policies will reduce such emission completely until 2050. There are more ambitious policies regarding peat extraction in Germany (complete ban by 2040). However, it is unlikely that such policies can be established at EU level given considerable reliance on peat for horticulture in many EU countries.

Assumptions for the reduction expansion of settlements are handled more strictly in the target scenarios. Both EUTarget and EUSupreme scenario assume that by 2050 no net land take of infrastructure and settlements is taking place. It is assumed that reducing net conversion of areas to settlements to zero by 2050 is already an ambitious assumption, given that such land conversion occurs mainly for infrastructure projects that are considered necessary for economic development.

For an overview of the differences in assumptions between the three scenarios we refer to Table 30.

Table 30: Assumptions in the EUBase and target scenarios

Category	Description of measure	Assumption in EUBase Scenario	Assumption in EUTarget Scenario	Assumption in EUSupreme Scenario
Forests	Reduction of deforestation emissions	Stabilizing annual emissions reported in 2020	Reducing 50% of annual emissions reported in 2020	Reducing 75% of annual emissions reported in 2020
	Afforestation	Increase forest area through new forest plantations by 1%, i.e. 1.6 Mha by 2050 compared to 2020	Increase forest area through new forest plantations by 5%, i.e. 7 Mha by 2050 compared to 2020	Increase forest area through new forest plantations by 6%, i.e. 10 Mha by 2050 compared to 2020
	Increase carbon stocks in existing forest	Maintain the forest sink compared to 2020 by stabilizing the harvest rate at about 70% of increment	Increasing the forest sink compared to 2020 by reducing the harvest rate to about 67% of increment	Increasing the forest sink compared to 2020 by reducing the harvest rate to about 67% of increment (same EUTarget)
Harvested wood products	Increase the share of longer-living wood	Measures to stabilize HWP pool	Measures to stabilize HWP pool despite decreased harvest rate, e.g. by increasing	Increase residence time of carbon in HWP by 25%, increase share of long-living products

Category	Description of measure	Assumption in EUBase Scenario	Assumption in EUTarget Scenario	Assumption in EUSupreme Scenario
	products and increased cascade use of wood		lifespan of products/amount of products (=carbon stored in products)	
Cropland and grassland	Rewetting of organic soils	Rewetting of 20% of cropland, 33% of grassland and 30% of forests on organic soils to wetlands by 2050	Rewetting of 50% of cropland, 60% of grassland and 30% of forests on organic soils to wetlands by 2050	Rewetting of 67% of cropland, 78% of grassland and 70% of forests on organic soils to wetlands by 2050
	Reduction of grassland conversion	Reduction of grassland conversion to zero	Same as EUBase	Same as EUBase
	Short rotation coppice and agroforestry	Establish 0.3 Mha of coppice/agroforestry area	Establish 6.9 Mha of coppice/agroforestry area	Establish 13.6 Mha of coppice/agroforestry area
Wetlands	Reduction of emissions from peat extraction	Peat extraction is reduced until 2050 by 50% compared to 2020	A peat extraction ban is implemented until 2050	A peat extraction ban is implemented until 2050 (same EUTarget)
Settlements	Reduction of land consumption due to increase of area used for settlements	Net land take of infrastructure and settlements is reduced by 50% until 2050 compared to 2020	No net land take of infrastructure and settlements by 2050	No net land take of infrastructure and settlements by 2050 (same EUTarget)

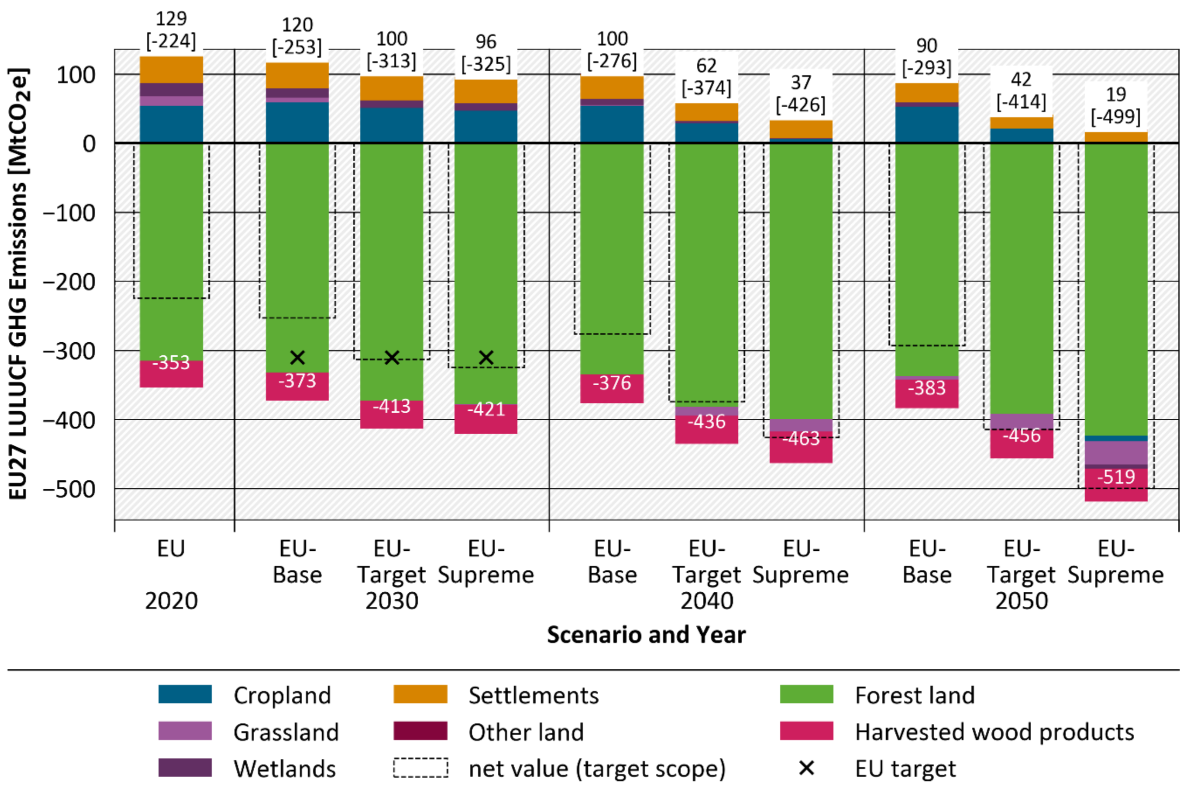
Source: Own assumptions Oeko-Institut

3.2.6.2.3 Results

Results for emissions and removals from the LULUCF sector under the EUBase, EUTarget, and EUSupreme scenarios are presented in Figure 79. In the EUTarget scenario, the forest sink in EU increases until 2030 and stabilizes at a level of about -380 Mt CO_2e. This is due to reduced intensity of wood harvest and an expansion of forest area. Despite the reduction of harvest levels in EU forests, the net removals from HWP can be stabilised over the simulation period, slightly above levels of 2020 at around -40 Mt CO_2e. Emissions from grasslands decrease and finally even switch to a net sink. Similarly, emissions from wetlands and settlements are reduced significantly (-70%) through the increase in rewetting of organic soils and avoiding the conversion through infrastructure and buildings. Furthermore, cropland emissions decrease (-62%) following rewetting and the establishment of agroforestry systems. As a result, the net LULUCF sink in the EUTarget scenario is projected to increase from -224 Mt CO_2 in 2020 to -414 Mt CO_2 in 2050. This represents an increase of 85% between 2020 and 2050. Consequently, the EU net LULUCF target of -310 Mt CO_2 in 2030 is clearly met under this scenario.

In the EUSupreme scenario the forests sink increases continuously and reaches -400 Mt CO_2 in 2040 and -420 Mt CO_2 in 2050. The increase well above the levels reached in EUTarget is due to additional forest area that can be established in EU countries. The carbon sink on already existing forest area instead remains at similar levels as in EUTarget (not shown). As in the EUTarget scenario, emissions from grasslands decrease and switch to a net sink after 2030. Due to strong rewetting efforts and through establishing agroforestry and SRC systems, also the categories of cropland and wetlands become a net sink after 2040. As described above, taking the land out of agricultural production requires targeted policies like incentive schemes but also measures supporting changes in dietary preferences. Emissions from settlements can be reduced significantly (-54%). As a result, the net LULUCF sink is projected to more than double and increase from -224 Mt CO_2 in 2020 to -500 Mt CO_2 in 2050, representing a 123% increase. The EU net LULUCF target of -310 Mt CO_2 in 2030 is clearly met under this scenario.

Figure 79: Emissions and removals from the LULUCF sector for different land use categories in the scenarios



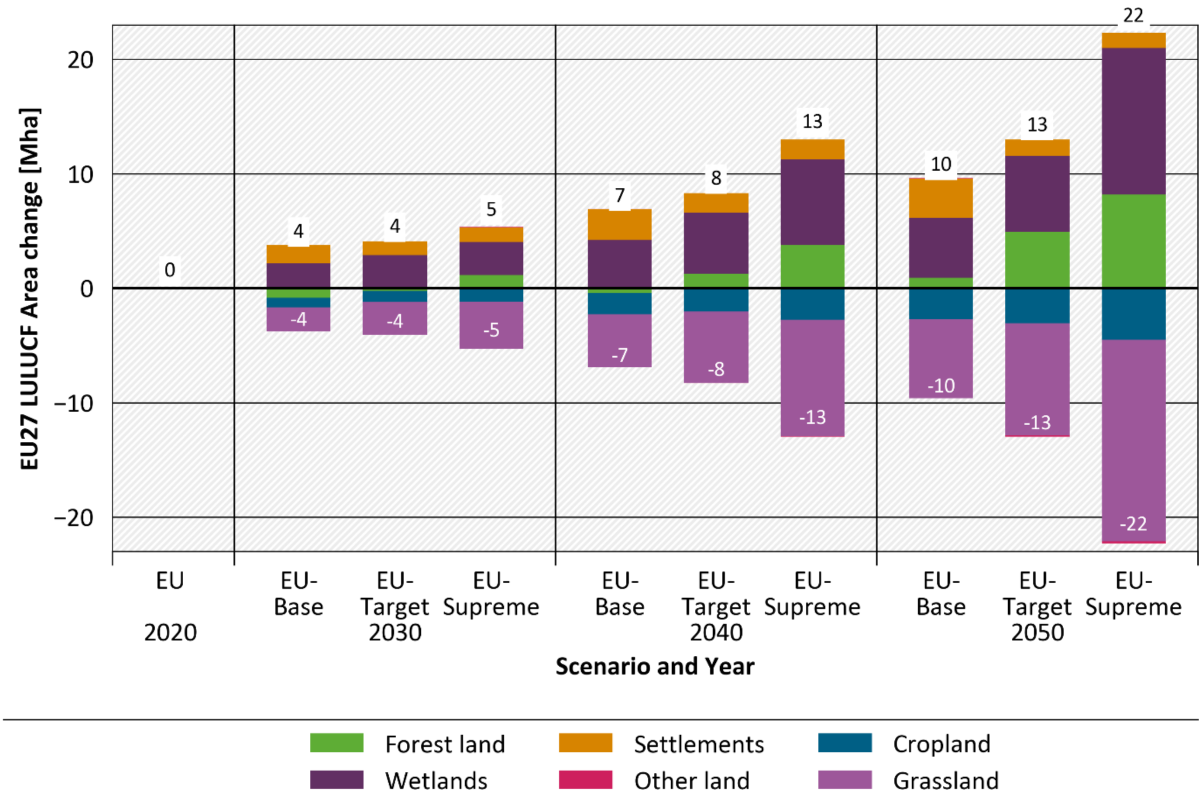
Source: Own calculation Oeko-Institut

The assumptions underlying the EUTarget scenario affect the distributions between the different area categories (Figure 80). Policies targeting afforestation let the forest area increase by 7 Mha until 2050. The conversion of land to settlements is clearly reduced compared to the EUBase scenario. They increase only by 1.4 Mha, 2 Mha less compared to the EUBase scenario. As in the EUBase scenario, rewetting of organic soils as an effective measure to reduce emissions from this carbon pool, leads to a strong increase in wetland area, here by 7 Mha, at the expense of cropland and grassland. Cropland areas are reduced by 3% (3 Mha), grassland area by 12% (11 Mha).

The assumptions underlying the EUSupreme scenario affect the distributions between the different area categories (Figure 78). Policies like incentive schemes and restoration programs are assumed to let forest area increase by 10 Mha until 2050. The conversion of land to settlements is even reduced at similar levels as in the EUTarget scenario where already rigid policies against such land conversions are being implemented. The category increases only by 0.7 Mha. As in the EUTarget scenario, rewetting of organic soils leads to a strong increase in wetland area, here by 13 Mha, at the expense of cropland and grassland. Cropland areas are reduced by 4% (5 Mha), grassland area by even 21% (19 Mha). These reductions are the cause of the conversion of cropland and grassland into forest land, wetlands and settlements.

Dietary changes towards more plant-based products with a reduced land demand enable this shift in land use, leading to a reduction in emissions and an increase of natural carbon sinks (for Details see Chapter 3.2.7 Agriculture).

Figure 80: Area changes for different land use categories over time in comparison to area share in 2020 in EUBase, EUTarget and EUSupreme scenario



Source: Own calculation Oeko-Institut

3.2.6.3 Comparison

The comparison of the three scenarios shows in summary the following patterns. In 2030, there are mainly differences between the two more ambitious scenarios EUTarget and EUSupreme compared to EUBase scenario. While in both target scenarios the LULUCF target is met, the measures assumed in EUBase do not result in a sufficient increase in net removals in the sector. This is due to both, an insufficient fast reduction of emissions, the mere stabilization of the forest sink instead of an increase and relatively small areas available for afforestation and SRC plantations. As discussed above, biomass removals from forests for the use of bioenergy are a key contributor to the differences. Moreover, in the EUBase scenario other measures required for significant increases of the net sink, such as a rapid phase-out of peat extraction, reduction of land conversion to settlements, and, most importantly regarding emission reduction: the rewetting of organic soils, are implemented only at a rather conservative speed and with low intensity in the short-term towards 2030. In comparison, in the EUTarget and the EUSupreme changes can be observed with higher implementation speed, due to faster and also more effective policy implementation.

The two scenarios EUTarget and EUSupreme among themselves show only small differences in 2030. Only until 2050 larger differences emerge. This is due to the fact that some measures are implemented rather late or have longer lead times such as measures targeting the lifetime of carbon in products. The two scenarios demonstrate that the underlying assumptions and narratives will have an impact on GHG emission pathways. Compared to the EUBase scenario, the EUSupreme scenario showcases a reduction in emissions due to additional measures that require additional land to become available, linking directly to the development in the agriculture sector, e.g. dietary changes towards the Planetary Health Diet leading to lower milk and meat consumption and thus feed production on agricultural land. The far-reaching dietary shift is a long-term process which is ‘completely implemented’ from 2030 on until 2050. However, this highlights the long-term benefits of the sufficiency and efficiency principles within the EUSupreme scenario's narrative.

Overall, the differences between EUTarget and EUSupreme are smaller than could be expected. This is also due to opposing effects, e.g. a reduction in wood supply from waste streams leading to more demand for wood from the forest. But also assumptions on behavioral changes, efficiency and sufficiency do not lead to significant reductions in GHG emissions in the short run. Specifically, the implementation and real-world impacts of measures like the Planetary Health Diet have a rather slow acceleration rate and will primarily impact land use related emissions and removals in EU only after 2030.

3.2.7 Agriculture

The EU agricultural sector contributes 12% to total EU emissions in 2020. From 2005 to 2022, agricultural emissions decreased slightly by approximately 5% (EEA 2022). However, this trend is expected to remain unchanged, posing a threat to climate protection efforts in EU agriculture due to stagnation. Emissions from the agricultural sector are dominated by direct emissions from livestock farming. Nearly 60% of emissions are CH_4 emissions from enteric fermentation and CH_4 and N_2O emissions from manure management. In addition, there are emissions from fodder cultivation and from excretions left on pastures which are reported under N_2O emissions from agricultural soils. Due to the biological processes in animal husbandry and the management of soils, the technical reduction potential is limited. The agricultural sector will therefore remain the sector with the highest residual emissions in a GHG-neutral Europe. The level of residual emissions will depend crucially on the demand for animal products.

3.2.7.1 EUBase scenario

3.2.7.1.1 General description

The EUBase scenario serves as the reference scenario for the other two target scenarios (EUBase and EUSupreme) in this project. For the agricultural sector several strategies and plans at EU level, which, if fully implemented, could lead to a change in production, exist. These include namely the Farm to Fork Strategy with targets for organic farming, mineral fertilizers and pesticides. Furthermore, the Biodiversity Strategy and the Carbon Farming Initiative.

However, there is a lack of specific and binding legislation to enforce these goals. As a result, in the EUBase Scenario, current production and its trends are continued.

In concrete terms, the EUBase scenario assumes that some measures that have so far been promoted through the Common Agricultural Policy (CAP), are continued. These include organic farming, the provisioning and expansion of biodiversity areas, the promotion of legume cultivation and the establishment of agroforestry systems. In addition, the rewetting of agriculturally used peatland sites is included to the same extent as the assumptions in the LULUCF sector, see chapter 3.2.6.1.2). In the field of productivity in livestock farming and crop yield moderate increases are adopted which vary across the EU member states. This is based on the assumptions of the EU agricultural outlook (European Commission: Directorate-General for

Agriculture and Rural Development 2021). In the area of technical measures, anaerobic digestion of manure, nitrogen-reduced feeding and the use of low-emission application technology in combination with better storage are taken into account.

Other technical measures such as the use of nitrification inhibitors, acidification of manure and the use of feed additives to reduce methane emissions from fermentation are not considered in the EUBase scenario. This is a dynamic field and, in this study, the EUBase scenario reflects the policy landscape of 2022, a time when there were no incentives to implement these technical measures on a large scale.

3.2.7.1.2 Main assumptions

Main drivers in the agricultural sector are the development of the agricultural land use, including the development of the nitrogen input[45] and the development of the livestock numbers as well as the implementation of technical mitigation measures. In addition to changes in animal numbers, the development of carcass weight and milk yields are crucial assumptions. These factors not only determine production levels but also impact emissions. The expansion of organic farming and biodiversity areas leads to more extensive agricultural production and reduces nitrogen usage. Technical mitigation measures, such as anaerobic digestion of manure and nitrogen-efficient feeding, also help lower greenhouse gas emissions. For the EUBase scenario, assumptions were made regarding the utilization of agricultural areas, the trends in livestock numbers, and the adoption of technical reduction measures in livestock farming. Detailed description on these assumptions is provided in the text below and in Table 31.

Given the ongoing demand of land for essential purposes, e.g. infrastructure development and the establishment of natural carbon sinks in the LULUCF sector, the utilised agricultural area (UAA) is projected to decline by 2050. Changes in utilization of agricultural land are primarily associated with an increasing proportion of organic farming, the expansion of biodiversity areas, the rewetting of peatlands and the establishment of agroforestry systems. These developments are consistent with the assumptions outlined in the LULUCF sector (see chapter 3.2.6.1.2). Both the reduction in UAA and the extensification (organic farming, introduction agroforestry) means less productive area and reduction in fertilizer use.

Crop yields in this study are aligned with projections from the EU agricultural outlook in the EUBase.

The assumptions outlined in Table 1 are based on the calculation of trend changes, development from other sectors through the sector coupling of the models (e.g. LULUCF) or based on own expert judgement if no further information is available.

[45] A brief overview of the procedure for calculating nitrogen inputs is given in the model description (see chapter 2.3.6).

Table 31: Overview of measures considered in the EUBase scenario

Main parameters and measures	Description of assumption	Description of implementation and effects in model
Agricultural area (UAA)	Through expansion of settlements, infrastructure, PV on open land, rewetting of peat soils, 3% UAA will be lost by 2050.	Adoption of model results from LULUCF sector to LISE model. Reduction in UAA means less productive area and reduction in fertilizer use.
Development of organic farming area	Increase of organic farming area until 2050 reaching 19% of UAA	Extrapolation of the development of the last 5 years (2015-2020) into the future on Member State level. The expansion of organic farming leads to a reduction in crop yields, lower performance in animal husbandry and less use of synthetic N-fertilizers, since the use of mineral fertilizers is prohibited in organic farming.
Development of fallow land for biodiversity purposes	Increase of fallow land for biodiversity to 5% of total cropland area until 2030. After 2030 the constant value at 5% of cropland area.	Decrease of productive area. Reduction in nitrogen input.
Development of agroforestry systems	Increase of agroforestry systems to 1% of total UAA until 2050.	Decrease in area for annual crop production. Reduction in nitrogen input, increase of carbon sink in LULUCF sector.
N-efficient feeding	Increase of N-efficient feeding until 2050 by 5%.	Reduction of N-accumulation. This leads to reduced emissions from storage and application of manure.
Anaerobic digestion of manure	Increase of anaerobic digestion of manure by 3% in 2030, 5% in 2040 and 10% on Member State level until 2050.	Update on the basis of current fermentation rates at MS level. This leads to reduced CH_4 and N_2O emissions from manure management.

Source: Own assumptions Oeko-Institut

Animal numbers, productivity and technical measures

The development of the livestock numbers for the EUBase scenario in the EU until 2050 is difficult to estimate. Since 2016/2017, animal numbers have been decreasing for almost all animal types, except poultry due to economic reasons. The persistence of this market-driven decline is unclear. In view of increasing environmental requirements and stricter targets in terms of climate protection, biodiversity and animal welfare, it is assumed that animal numbers will decrease until 2050 in the EUBase scenario.

The EU short term outlook (EC 2021) provides market development for animals or animal products until 2031. This data is used to model the development of animal numbers in the EUBase scenario. However, there is no data available after 2031. The driving factors mentioned above will continue in the years beyond 2030. Therefore, the trend changes are also used for the period 2030/2040 and 2040/2050 as no better data is available.

Carcass weights and milk yields show a large range between different EU Member States. The productivity of animal production has been increasing in almost all Member States over the last years. Based on the current carcass weights und milk yields productivity, in the EUBase Scenario, productivity is expected to increase in many EU Member States.

Milk yield is a key determinant of GHG emissions. Therefore, the assumptions are presented in greater detail in the following section. First of all, the individual countries have been aggregated into clusters. The clustering is mainly based on the intensity of current production processes. For each cluster a percentage value was assumed for the development of productivity. The value ranges between 5% and 30% for the period 2020 until 2030. It is assumed that after 2030 no further productivity improvements take place. In total milk yield from 2030 onwards increases from 7,474 kg/animal and year in 2020 to 8,428 kg/animal in 2030 on EU average. The following table includes the assumptions and the country cluster.

Table 32: Overview of country cluster for productivity increases for milk yield (national average milk yield)

Milk yield in 2020 in litre/cow/a	Member State Cluster	Assumption in yield increase until 2030
Between 3,200 and 6,000	BG, HR, RO, PL, IE	130%
Between 6,000 and 7,500	FR, CY, LV, LT, MT, AT, SI	120%
Between 7,500 and 8,500	BE, DE, GR, IT, LU, HU, PT, SK	110%
Between 8,500 and 9,000	No country included in this category	105%
>9,000	CZ, DK, EE, ES, NL, FI, SE	No increase – stagnation or moderate decrease of average milk yield in particular due to increase of organic farming

Besides the development of the animal numbers and the productivity there are some technical measures available, which reduce CH_4 and N_2O emissions from manure management. These include anaerobic digestion of animal manure and nitrogen efficient feeding. Both measures are already taken into account in the EUBase scenario (see Table 32).

Consumption of animal products

No own assumptions were made on the development of the consumption of animal products. The development of the animal numbers is based on the EU environmental outlook. There is an ongoing trend on reduced consumption of animal products in the EU. Additionally, price increases resulting from higher animal welfare or environmental production standards could affect the demand for animal products.

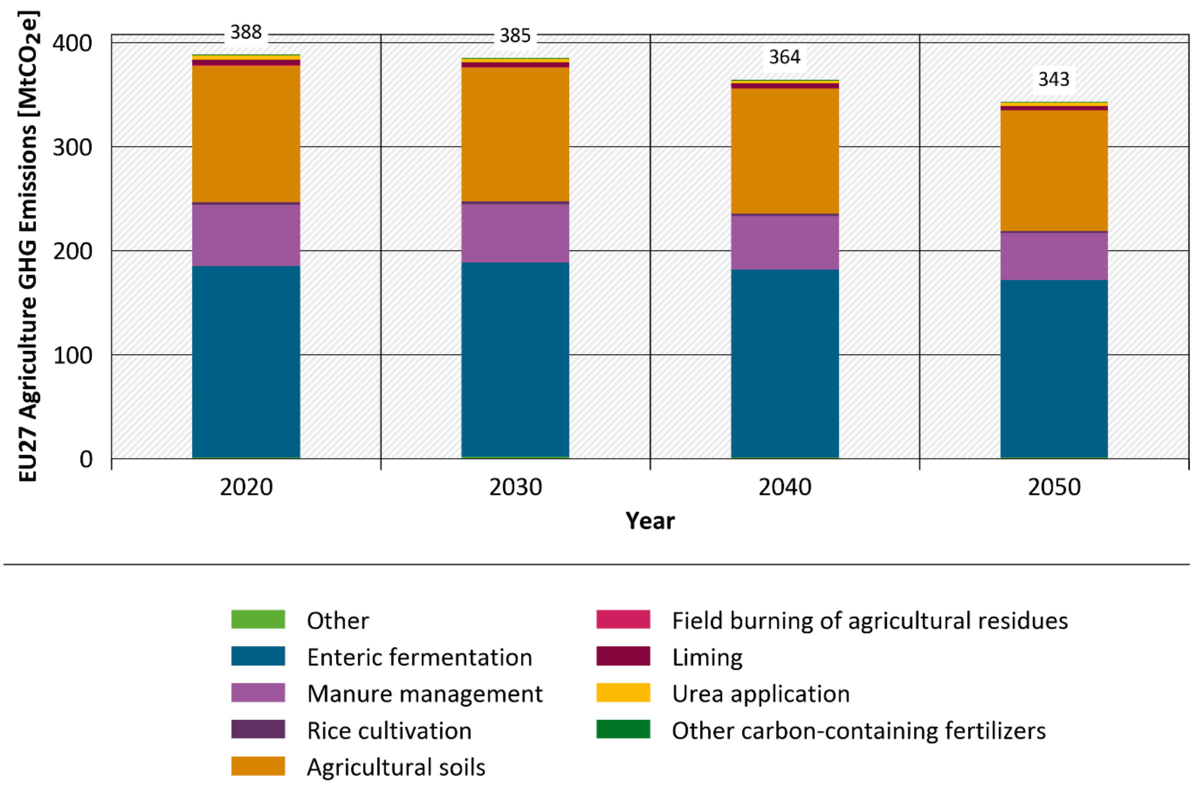
3.2.7.1.3 Results

In the EUBase scenario, emissions from the agricultural sectors decrease from 388.2 Mt CO_2e in 2020 by 45 Mt CO_2e to 342.8 Mt CO_2e in 2050 (see Figure 81), corresponding to a total reduction of 12%. The most important emission reductions of 15 Mt CO_2e can be achieved by reducing N_2O emissions from agricultural soils due to increasing N-efficiency and expansion of organic farming. Further reductions can be achieved by reducing the agricultural production area as a result from the increase in settlements, rewetting of organic soils and setting areas aside for biological diversity.

Another 14 Mt CO_2e is reduced by manure management. Increased anaerobic digestion of manure, better management and N-efficient feeding are the main drivers for emission reduction. Emissions from enteric fermentation decreased only by 13 Mt CO_2e or 7% compared to 2020. This small decrease in emissions can be explained by productivity increases and thus increase in the amount of manure per animal.

Until 2030, total agricultural GHG emissions decline slightly by 1% of emissions, or 3.1 Mt CO_2e in the EUBase scenario compared to 2020 levels. However, despite this overall reduction, CH_4 emissions from enteric fermentation increase by 2% over the same period, primarily due to productivity gains. Main emission reduction in 2030 is related to a better manure management, increased nitrogen efficiency and the expansion of extensive farming methods and an increased area for biodiversity purposes. In 2040 and 2050, the implementation of these measures will continue to increase. At the same time, livestock numbers further decrease. Between 2030 and 2050, the ongoing overall decline in livestock numbers is resulting in a net emissions decrease. The reduction of herd sizes across all member states is projected to outweigh productivity gains.

Figure 81: Development of total GHG emissions in the agricultural sector in EUBase

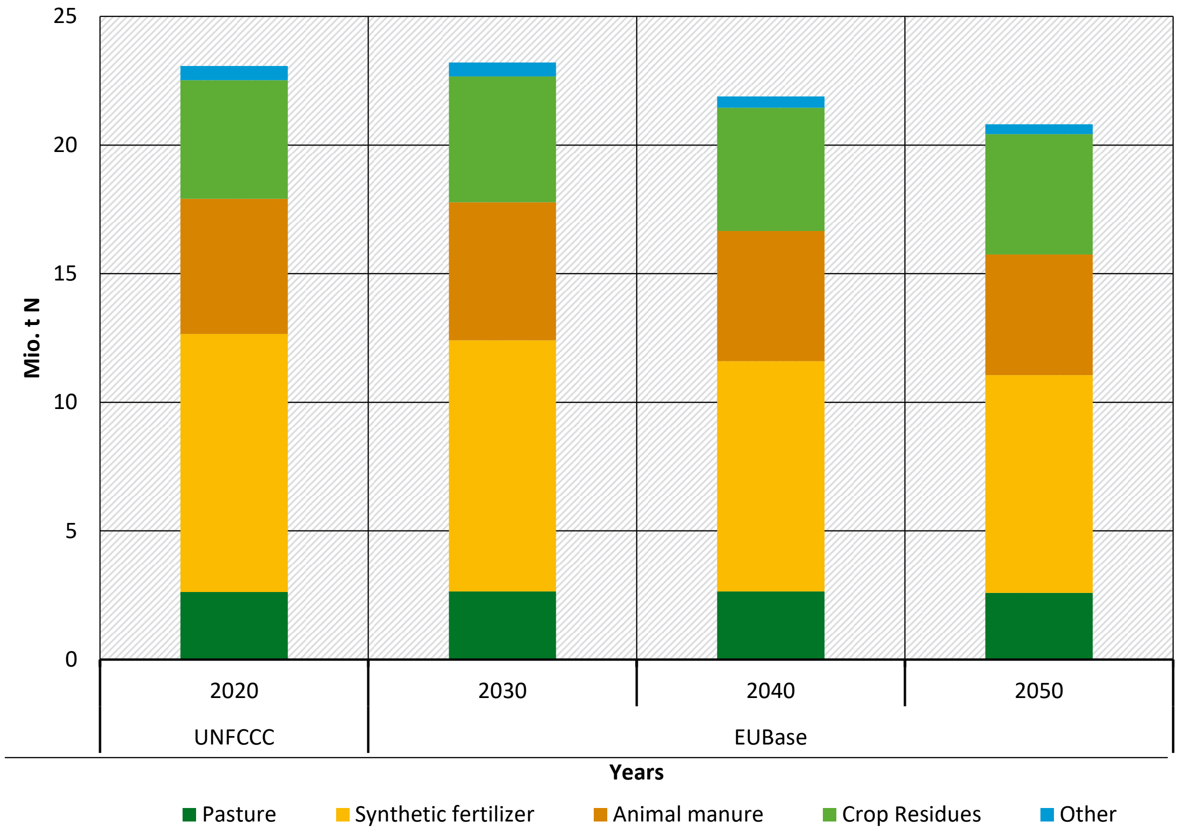


Source: Own calculation Oeko-Institut, based on EEA 2022, Eurostat database, EC 2021

Until 2050, total agricultural area is decreasing by about 3% through an expansion of infrastructure and settlements. Thus, almost 5 Mha of agricultural area is lost within the next 30 years. Another 3 Mha will be used for new land use practices like agroforestry, paludicultures (rewetting of organic soils) or increases of biodiversity area. Organic farming area almost doubles until 2050 and increases by 12.6 Mha, from 10% in 2020 to 19% of total agricultural land by 2050.

Nitrogen input to agricultural soils from synthetic and organic fertilizer, but also from animal manure and manure left on pastures and crop residues decreases by 11% until 2050. Main reduction stems from decreased use of synthetic fertilizer, driven by N-efficiency improvements, including better utilization of animal manure. Until 2030 there is almost no reduction in total N-input to soils. N-input from animal manure remain constant as there is no reduction from animal manure due to increasing productivity in animal husbandry (increased milk yield, increased carcass weights). However, until 2050 N-input decreases, because of further improved N-efficiency, increased area of organic farming, other land use production methods with lower nitrogen demand (agroforestry, cultivation of legumes, paludicultures) and a general loss of agricultural area. Figure 82 shows the development of the nitrogen input to agricultural soils until 2050.

Figure 82: Development of total nitrogen input on agricultural soils in the EUBase scenario

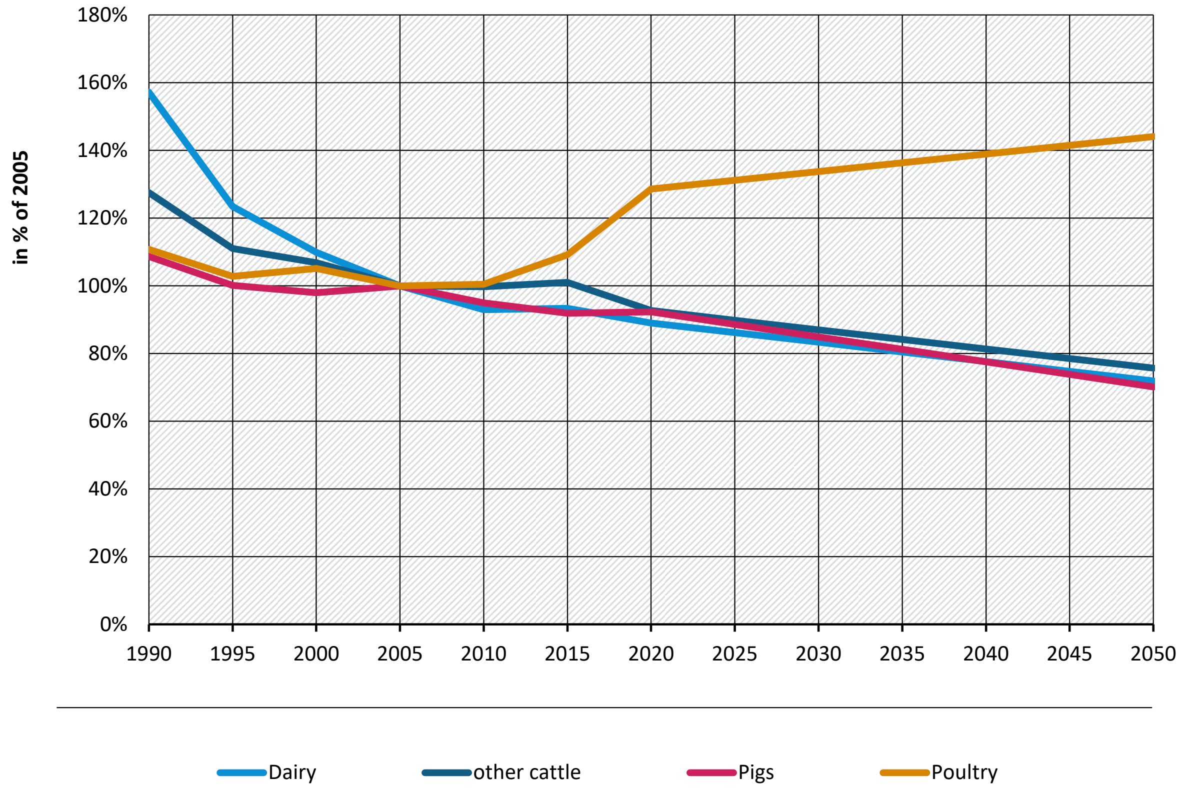


Note: Other includes N-input from sewage sludge, compost or digestates etc.
Source: Own calculation Oeko-Institut, based on EEA 2022, Eurostat database, EC 2021

According to the EU agricultural short-term outlook, a reduction in livestock numbers will take place until 2030 for all animal groups except poultry. In the EUBase scenario it is assumed that this trend will continue until 2050. Compared to 2020, total livestocks decrease by 14% or almost 11 million livestock units until 2050.

Reduction rates differ for the individual animal species. The highest decline is expected for pig farming with 24% until 2050, followed by a decline in cattle stocks by 19%. Increases are expected in sheep and goat farming (7%) and poultry farming with about 12% until 2050.

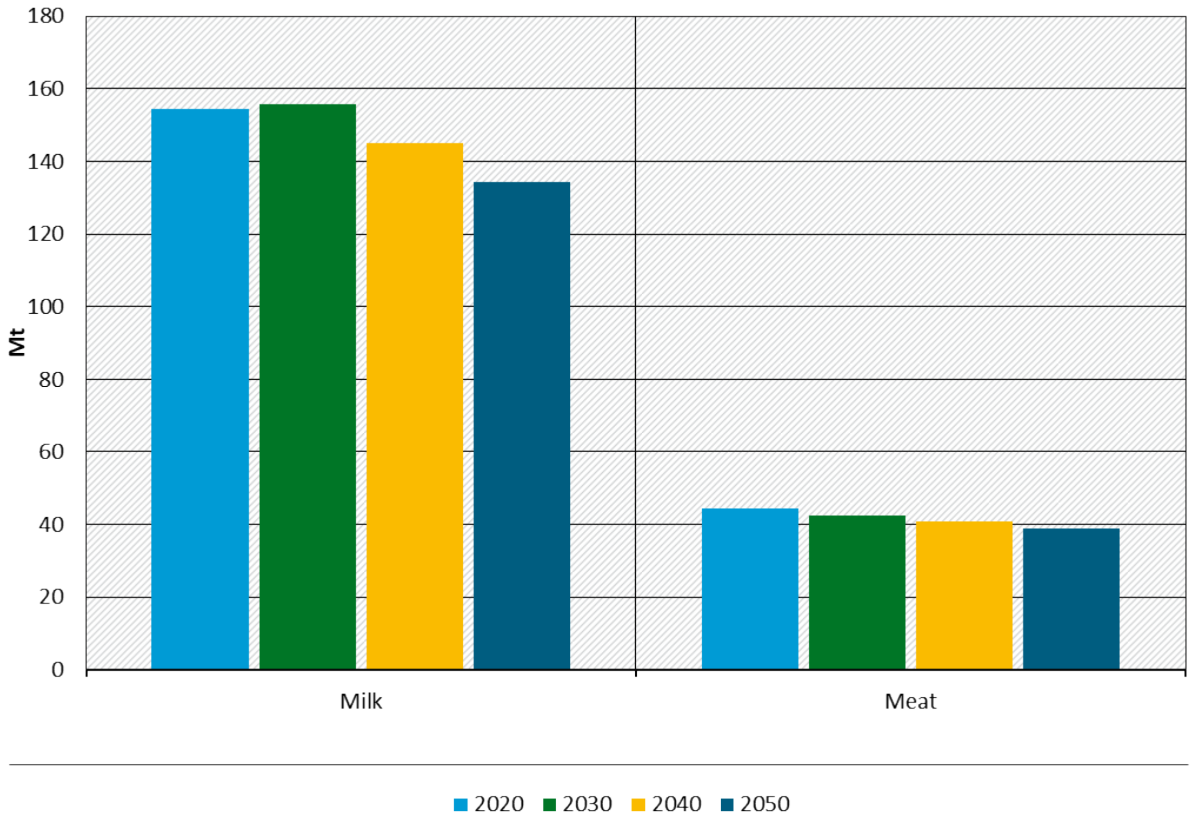
Figure 83: Development of livestock in the EUBase scenario



Source: Own calculation Oeko-Institut, based on EEA 2022, Eurostat database, EC 2021

The trend of reduced livestock numbers is reflected in milk and meat production patterns. Due to increases in milk yields cow milk production increases until 2030 by 1% compared to 2020 levels, while meat production already decreases by 4%. However, in the post-2030 years, the increase in milk yield cannot compensate for the reduction in dairy livestock and the cow milk production is reduced by almost 20 Mio. t (-13%). In the same period, meat production decreases by 5.5 Mio. t, the increase in poultry meat cannot compensate for the reduction of beef and pork (-12%), see Figure 84.

Figure 84: Development of milk and meat production in EUBase



Source: Own calculation Oeko-Institut, based on EEA 2022, Eurostat database, EC 2021

3.2.7.2 Target scenarios

3.2.7.2.1 General description and differences to EUBase scenario

In general, the EUTarget and the EUSupreme scenarios for agriculture differ from the EUBase Scenario in the main assumptions on the implementation of technical solutions, on production levels of animal products, as well as on the extend of biodiversity / unproductive land. The EUTarget specifically intends to answer the question of which emission reductions can be achieved through technical measures. The production of animal products remains at the level of the EUBase scenario. Technical measures as an increase of digestion of animal manure, use of feed additives to reduce CH_4 emissions from enteric fermentation and the use of nitrification inhibitors to reduce N_2O emissions from input of synthetic fertilizer and manure spreading are included.

This contrasts with the EUSupreme which explores the question of how much GHG reduction can be achieved with measures on the demand side. For this the implementation of the nutritional recommendations of the "Planetary Health Diet" for the European population is taken into account. The “Planetary Health Diet” is a global eating plan that aims to improve human health and protect the environment. The EAT-Lancet Commission developed this diet, which is mainly plant based. This means it is full of fruits, vegetables, whole grains, legumes and nuts, while consumption of animal products is greatly reduced. This aims to feed a growing world population while reducing the environmental impact of food production, such as greenhouse gas emissions, land use, and biodiversity loss.

This also enables more extensive land use, since less land is required for animal feed, leaving more land available for other uses (e.g. organic farming area or grassland based ruminant husbandry). The latter means that a small quantity of milk and meat products will continue to be available for export. At the same time, more products for plant-based nutrition could be produced.

3.2.7.2.2 Main assumptions

The assumptions between the three scenarios differ in terms of the main drivers and are as follows:

Development of utilized agricultural area (UAA): In both target scenarios, the total UAA for traditional annual crop cultivation and grassland is further decreasing compared to the EUBase. There is a higher share of rewetting of organic soils, agroforestry and biodiversity area which leads to a decreasing area. In the EUTarget the change in land use compared to the EUBase is small and partly compensated by increasing yields. In the **EUSupreme** changes are much higher due to increase of organic farming, biodiversity area, agroforestry and higher shares of rewetted farmland.

Consumption of animal products: In the EUBase and EUTarget scenario no own assumptions were made on the development of the consumption of animal products. The development of the animal numbers and thus the production of animal products is based on the EU environmental outlook. The EUSupreme is based on the Planetary Health Diet. It is assumed that the EU citizens follow these recommendations. In this case, the development of animal product production follows the reduced demand resulting from the move towards a healthy diet. The following table shows the consumption of animal products from the Planetary Health recommendation compared to current consumption. To offset the decline in animal product consumption, people are increasingly eating legumes and nuts. In addition, the consumption of fruits and vegetables is rising sharply.

Table 33: Overview of current consumption level of animal products compared to recommendations from Planetary Health

Product	Current Consumption	Planetary Health kg/cap/year
Milk (in Milk Equivalent)	261	91
Bovin/Goat/Sheep	12	3
Pig	32	3
Poultry	24	11

Source: Agri_short term outlook, (Willett 2019)

Livestock farming: The **EUTarget** follows the EUBase regarding the size of the livestock numbers, but a higher level of technical measures is implemented. This includes the use of feed additives as well as digestion of manure and nitrification inhibitors for slurry spreading and synthetic fertilizer application. In the EUSupreme livestock numbers are drastically reduced, due to a significantly lower demand for milk and meat in line with changes in consumption following the recommendation of the planetary health diet. It is assumed that livestock numbers show a linear decrease until 2050 starting from today. The ruminant's feeding is based on grassland, and the amount of grazing is higher than in the other scenarios. To reduce competition with human food on arable land, ruminants in this scenario are increasingly fed with grassland-based feed. By reducing livestock numbers and thus livestock density, sufficient grassland is available. Milk production on grassland will be continued in line with the availability of grassland for fodder production. Any surplus of milk production beyond domestic demand will be exported. Slurry fermentation share is higher than in EUBase but lower than in the EUTarget due to a reduction in livestock density and thus limited availability of animal manure for digestion.

Feeding additives are not implemented in the EUSupreme due to remaining uncertainty with regard to long-terming reduction potential, feed and harbour risk for animal health etc.[46]

Organic farming: Analogue to the EUBase, in the EUTarget scenario organic farming area increase is based on a continuation of the current trends. In the **EUSupreme** scenario 25% of UAA will be achieved by 2030 based on the targets of the farm to fork strategy. Until 2050 a linear increase to 30% by 2050 is assumed, based on the goal of the German Sustainability Strategy, which envisages an expansion of organic farming to 30% of the UAA. However, increasing the organic farming area to 25% of total UAA in the EU until 2030 is quite ambitious and requires political will and appropriate funding.

Crop production: There is a slight yield increase in the EUTarget and the EUSupreme against the EUBase scenario. However, with the higher proportion of organic farming, the average yields are lower in the EUSupreme. Due to the risen extensification (organic farming, wooden crops and paludicultures[47]) the total fertilizer use is decreasing in both target scenarios. Furthermore, in the EUTarget the use of nitrification inhibitors for mineral fertilisers is assumed. This technology is not used at all in the EUSupreme scenario due to remaining uncertainties with regard to long-term reduction potential and effects on other environmental goods (Biewald 2025)[48].

Table 34 provides an overview of the detailed assumptions made in the three scenarios.

Table 34: Overview of measures considered in the EUTarget and the EUSupreme and differences to the EUBase

Agriculture	EU Base	EU Target	EU Supreme
UAA	-3% (-4.9 Mio. ha) until 2050 compared to 2020	-6% (-8.7 Mio. ha) until 2050 compared to 2020	-7% (- 10.2 Mio. ha) until 2050 compared to 2020
Animal yield and animal efficiency	Based on EU Agricultural outlook, slight difference due to own assumptions on development of organic farming with lower yields	Same as EUBase for animal production, slight increase for plant-based production	Same as EUTarget for plant-based production, decrease in milk yield due to increase of grassland-based milk production
Crop yields	Based on the EU agricultural outlook, remain constant after 2030	Increase of yields for key crops and countries which are currently producing below 70% of the mean yield. It is assumed that they are reaching the average yield level until 2050.	Same as EUTarget

[46] Due to a lack of long-term data on larger animal populations, its use is fraught with uncertainty - particularly with regard to the long-term reduction potential, which in Germany is around 15%. Feeding trials show a diminishing effect over time. The potential is lower for animal-friendly feeding with a high proportion of grass than for maize silage. Its use could also increase the proportion of concentrated feed and harbour risks for animal health, for example through higher butyric acid and alcohol levels in the rumen as well as possible skin irritation and genotoxicity (Kuhla 2025).

[47] Utilization of rewetted peatland sites. The products can be utilized for material or energy purposes, for example as a peat substitute in horticulture or as insulation and building material.

[48] Nitrification inhibitors must be persistent to work effectively, but this also allows them to reach deeper soils layers and water bodies. Despite the environmental use, their authorization under REACH lags behind that of plant protection products. As a result, potential risks to health and ecosystems remain under-assessed. Some substances are even classified as reproductive toxins, which would disqualify them as plant protection products, and their effects on soils and aquatic life are still uncertain.

Agriculture	EU Base	EU Target	EU Supreme
Increase organic farming	13% of UAA in 2030 and up to 19% in 2050	Same as in EUBase	25% of UAA in 2030 based on target of farm to forck strategy. Until 2050 further increase up to 30%
Increase biodiversity area	5% of UAA on MS level until 2030 (constant if already higher)	Same as in EUBase	10% of UAA until 2030
Increase in legumes cultivation	3% in total cropland area until 2030, 5% until 2050	3% in total cropland area until 2030, 6% until 2050	Necessary amount for Planetary Health Diet-consumption[49]
Expansion of agroforestry	0,25% of total UAA until 2030, 1% until 2050	1% cropland, 0.5% grassland in 2030, 5% cropland, 2.5% grassland until 2050	2.5% of total UAA, 10% until 2050
Increase in N efficiency – increase in the imputation of the minimum nitrogen content of agricultural fertilizers	55% in 2030 (increase of 5% compared to 2020) and increase to 65% in 2050	Faster and higher increase, due to high gas and fertilizer prices: 60% in 2030, up to 70% in 2050	Same as EUTarget
Increase in N efficiency in lifestock feeding*	+1,5% in 2030 and +5% in 2050	+3% in 2030 and +5% in 2050	Same as EUTarget
Increase in anaerobic digestion of animal manure	10% of manure in stable until 2030 and 22% in 2050	15% of manure in stable until 2030 and 70% in 2050	15% of manure in stable until 2030 and 50% in 2050[50]
Development of animal numbers	Livestock units: -5% until 2030 and -14% until 2050	Same as in EUBase	Production levels based on reduced demand (Planetary Health Diet for Europe) in 2050, linear reduction path from 2030 on.
Nitrification inhibitors	No use	Applied for the total amount of synthetic nitrogen input in 2050 (Reduction in emissions by total of 34%) (Perez Dominguez et al. 2020) Applied to 50% of manure spreaded to soils.	No use

[49] The planetary health diet includes recommendations for the consumption of pulses (75g daily) (Willet et al., 2019). Additionally, legumes remain important for animal feed. Therefore, the development of the legume cultivation area is based on the quantities needed for both human consumption and animal feed.

[50] We assume that the animals are more widely distributed across the area due to the sharp decline, therefore the capture rates decrease compared to the target scenario.

Agriculture	EU Base	EU Target	EU Supreme
Feed additives	No use	100% of dairy cows and 50% of other cattle until 2050 with 15% reduction enteric fermentation CH_4 (Perez Dominguez et al. 2020, Kuhla 2025) No application in organic farming	No use
NH3 mitigation of manure/slurry (in stable, tank and application on soils)	Reduction in line with the obligation of the NEC regulation	Effect of N reduced feeding, NEC regulation and increased anaerobic digestion of manure; effect of innovative stables is not represented by the model	Same as EUTarget

Development over time – if the modeling years of 2040 and 2050 are not mentioned, constant levels as 2030 are assumed, thus there is no change against the values outlined for 2030.
Source: Own assumptions Oeko-Institut.

3.2.7.2.3 Results

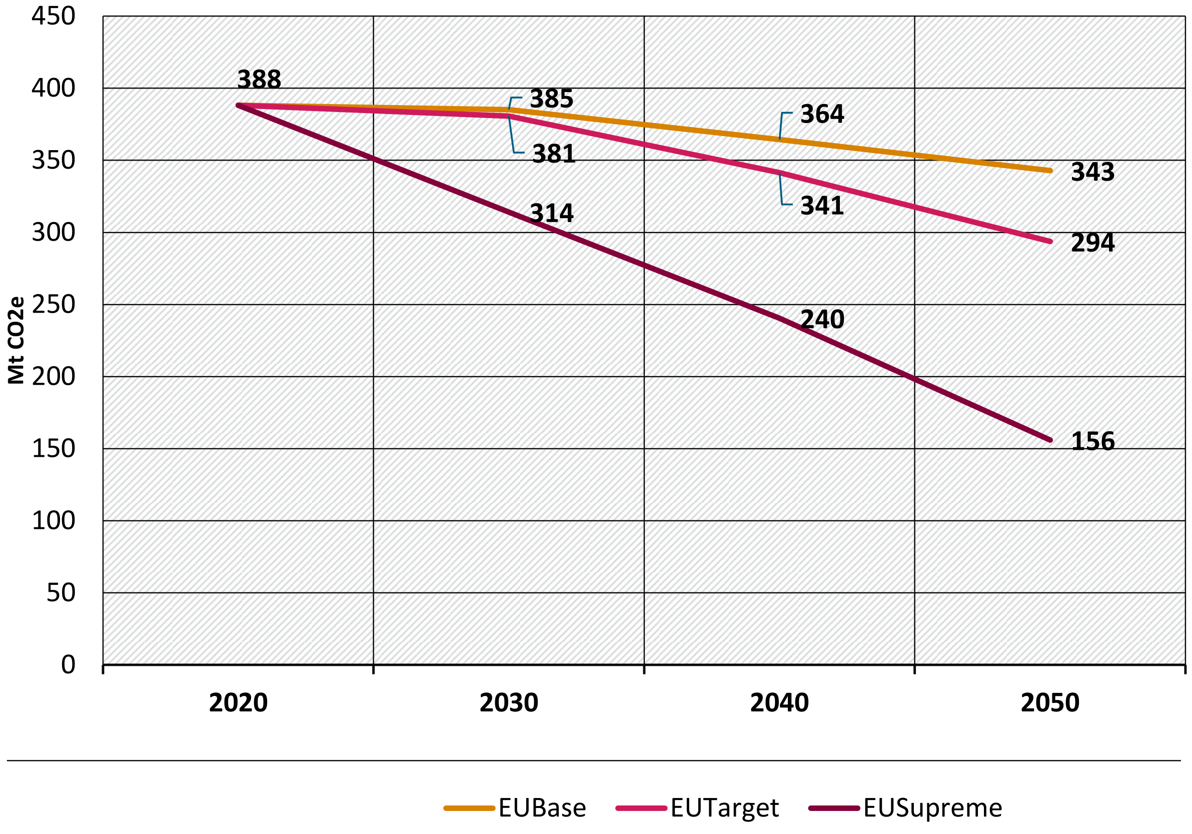
In comparison to the EUBase scenario, additional emission reduction is achievable by implementing technical measures and reducing the consumption of animal products, combined with a decrease in livestock numbers (see Figure 85). By implementing technical mitigation measures the EUTarget scenario was able to decrease the GHG emissions from agriculture from 388 to 294 Mt CO_2e, or by -24% compared to 2020 levels, by 2050. In comparison to the EUBase scenario this is a further reduction of about 50 Mt CO_2e or almost -15% in 2050.[51] To achieve a more ambitious reduction in emissions, robust measures on the demand side and a reduced consumption of animal products are required (here in line with the recommendations of the planetary health diet). A corresponding implementation on the supply side leads to a 60% reduction in emissions compared to 2020 levels, which corresponds to a reduction of -187 million tons of CO_2e against the EUBase by 2050 (see EUSupreme against the EUBase scenario, see Figure 85). A large share of this reduction is due to demand side changes. However, given the large differences between current consumption of animal products and recommendation from Planetary Health Diet (see Table 33) there are drastic decrease of production of animal products. These results highlight the significant impact of demand side measures the large effect of demand side measures and the limited effects of technical mitigation measures in the agricultural sector.

By 2030, only minor emission reductions are achieved in the EUBase and EUTarget scenarios (-1% and -2%, respectively). This is based on the fact that technical mitigation measures are only partially adopted in 2030. In contrast, the EUSupreme scenario achieves a significant emission reduction of -19% compared to 2020 levels, driven by the initial transformation of the food and agricultural sector by implementing demand side measures to reduce consumption of animal products. This significant decline until 2030 merely reflects the premise of achieving the Planetary Health Diet recommendation by 2050 and presents only the assumption of a linear dietary change until 2050. In practice, the change in eating habits may indeed take a longer

[51] Further mitigation potential may become relevant, for CH_4 emission reduction for enteric fermentation e.g. use of the feed additive using 3-Nitrooxypropanol (3-NOP) as active substance (Bovaer) with an emission reduction ranging from 30% for dairy cows to 45% for other cattle.

period of time. This progress by 2030 is only achievable if the sector's 2050 target is clearly defined and there is certainty about the direction of future development.

Figure 85: Development of GHG emissions in all three scenarios



Source: Own calculation Oeko-Institut, based on EEA 2021, Eurostat database, EC 2021

There are large differences in the emission reduction between the different groups of emissions in 2050 (see Figure 86). CH_4 emissions from enteric fermentation are only reduced by **8%** compared to the EUBase in the EUTarget by adding feed additives. However, this low mitigation potential represents a conservative assumption, as only **15%** of mitigation are assumed.[52] By increasing the anaerobic digestion of manure from 7% in 2020 to 70% - according to the assumption for the EUTarget - of the manure produced in the stable a further emission reduction of **33%** compared to the EUBase is achieved. However, achieving digestion rates of up to 70% of produced manure is an ambitious target that will require strong policy support and well-designed incentives. In the area of N_2O emissions from soils, the reduction potential is **18%** through a further increase in nitrogen efficiency, but also through other measures such as further peatland rewetting, agroforestry or legumes cultivation.

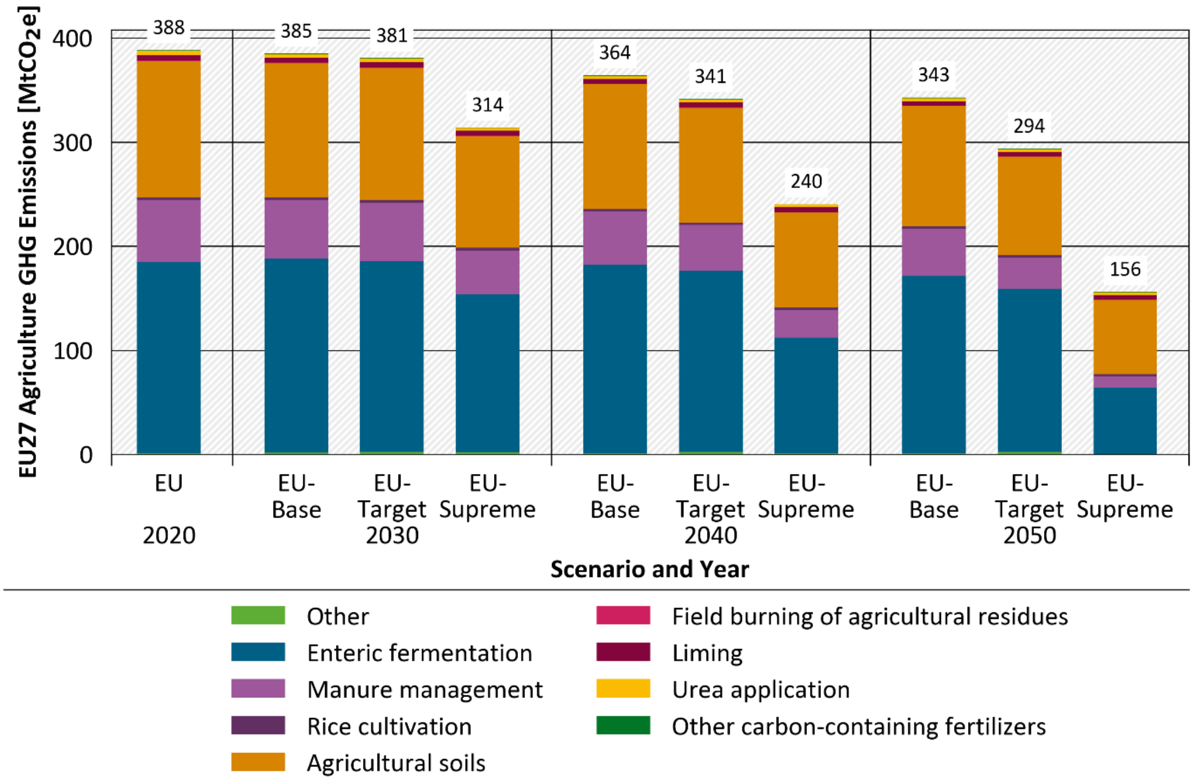
The level of GHG emission reduction in the EUSupreme depends largely on the development of livestock numbers, but also on yield assumptions. For CH_4 emissions from enteric fermentation a reduction of **63%** below the EUBase is achieved by reduction in livestock numbers taking into account a yield reduction due to grassland-based feeding for ruminants.[53] Emissions from

[52] Other studies like the Ecampa (JRC 2020) show higher mitigation potential by implementing more measures to reduce CH_4 emissions from enteric fermentation in combination – feed additives, vaccination breeding etc.

[53] When dairy cows are fed on grassland-based diets, their milk yield is typically lower compared to a cropland-based feeding. This reduction in milk production leads to lower CH_4 emissions from enteric fermentation per cow, simply because the cow is producing less and therefore consuming less feed overall.

manure management are reduced even further, as technical mitigation measures like anaerobic digestion of manures of up to 50% of manure produced in stable is also assumed. In total this leads to an emission reduction of **76%** compared to the EUBase. N_2O emissions from soils are also further reduced compared to the EUBase. Despite the continued importance of nitrogen fertilizer in agricultural production, achieving a 38% reduction represents an ambitious mitigation for this source category. The main effects stem from changes in land and farm management such as the adoption for organic farming, paludicultures, agroforestry, and the extensification of grassland, which reduced nitrogen demand.

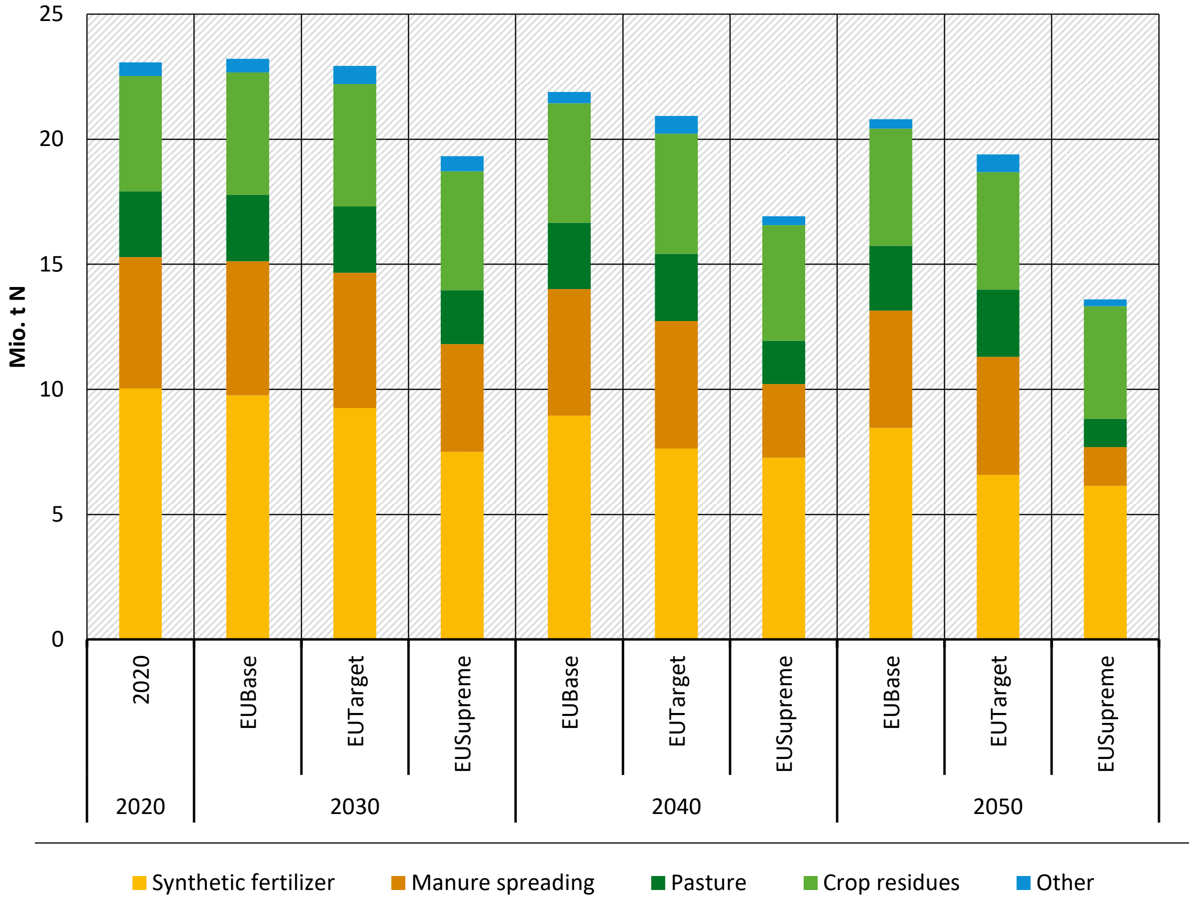
Figure 86: Differences in GHG emissions between all scenarios in 2050



Source: Own calculation Oeko-Institut, based on EEA 2021, Eurostat database, EC 2021

Compared to the EUBase scenario, nitrogen input from synthetic and organic fertilizers, as well as from residues left on pastures and crop fields, can be further reduced in both the EUTarget and the EUSupreme scenario. Until 2030 total nitrogen input is reduced by 1% in the EUTarget scenario compared to 2020, while until 2050 a reduction of 16% takes place. There are only minor differences in nitrogen input between the EUBase and the EUTarget scenario. The primary reason for the reduced nitrogen input in the EUTarget is the application of nitrification inhibitors, which enhance nitrogen utilization. Additionally, further nitrogen reduction is achieved by reducing the need for fertilizer through practices such as rewetting organic soils, implementing agroforestry, and promoting the use of legumes. In the EUSupreme scenario, nitrogen input has decreased by 16% in 2030 compared to 2020 and by 41% until 2050 compared to the same base year (see Figure 87). The substantial reduction in nitrogen input in the EUSupreme results from multiple factors. Firstly, there is a significant decrease in animal manure due to reduced livestock numbers. Secondly, the demand for nitrogen in animal feed is also markedly lower (e.g., in highly intensive grassland with high nitrogen requirements). Additionally, the EUSupreme promotes an expansion of biodiversity areas, adoption of agroforestry systems, cultivation of legumes, and increased rewetting of organic soils, collectively leading to a general decrease in nitrogen demand.

Figure 87: Differences in N-input between all scenarios in 2050

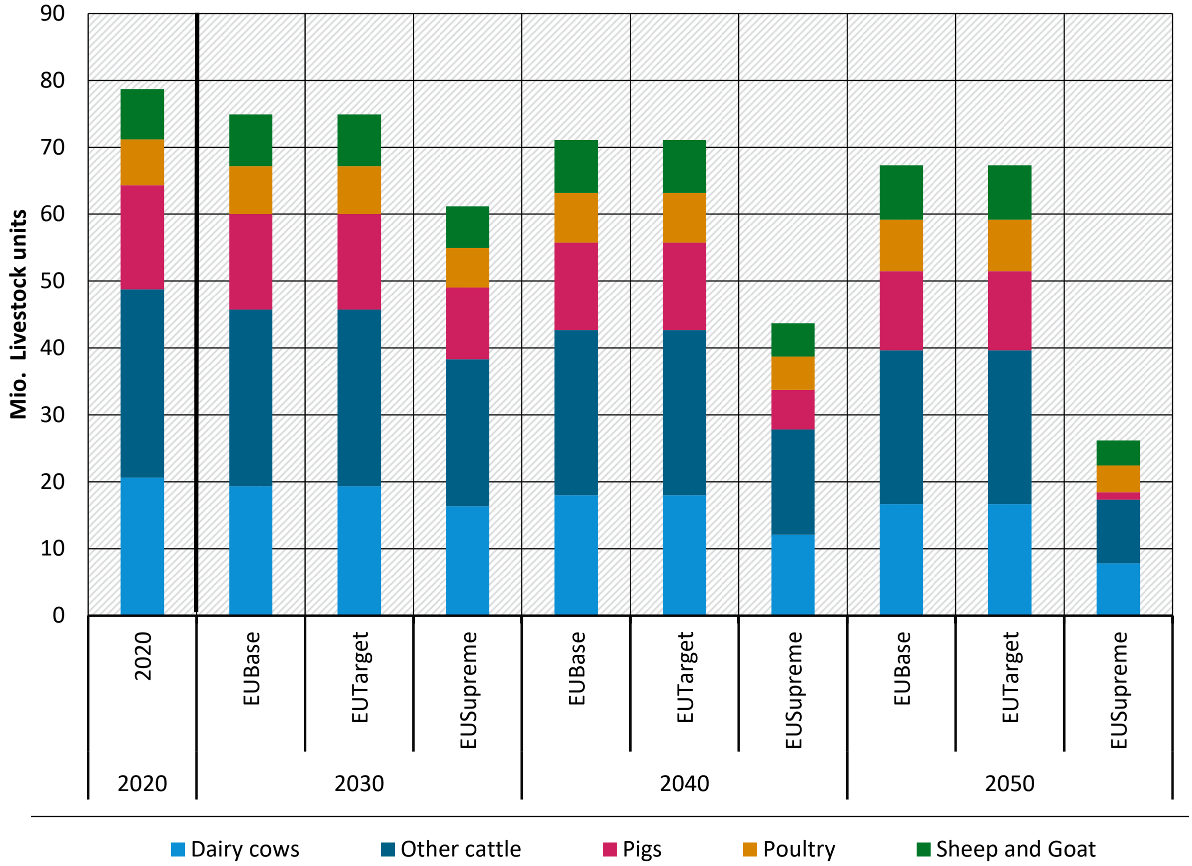


Source: Own calculation Oeko-Institut, based on EEA 2022, Eurostat database, EC 2021

The development of livestock in the EUTarget is similar to the EUBase. Livestock numbers are projected to decline across all animal categories until 2030 except for poultry. The EUBase scenario anticipates that this downward trend will persist through 2050. Compared to 2020 levels, the total number of livestock units is expected to decrease by 5% compared by 2030, 10% by 2040, and reaches a reduction of 14% by 2050.

While in the EUTarget scenario, livestock units remain at the level of the EUBase scenario, there is a significant reduction in livestock units in the EUSupreme scenario. Livestock units in the EUSupreme scenario show a decrease of 22% by 2030, showing a 44% reduction by 2040, and culminating in a 67% reduction by 2050 compared to 2020 levels. Until 2050 this leads to the following reductions in the different livestock categories in the EUSupreme: compared to 2020 dairy cattle is reduced by 62%, other cattle by 66%. The strongest reduction in animal numbers is for pigs with 93% compared to 2020, while the reduction in poultry is moderate at 42% (see Figure 83). This reduction is driven by a drastic shift in consumer demand for animal products, aligning with the recommendations of the planetary health diet proposed by the Eat Lancet commission for the entire EU population (Willet et al., 2019). Additionally, the number of ruminants is not reduced as strongly as the recommendation, as it is assumed that the remaining grassland continues to be used for ruminant grazing. Consequently, there are still available exports of dairy products and beef. However, such a significant reduction in livestock will only be feasible if attractive alternative income models for livestock farms are available (e.g., alternative protein sources, biomass for the bioeconomy) and are well-supported by appropriate instruments.

Figure 88: Development of livestock numbers in EUBase/EUTarget in comparison to EUSupreme



Source: Own calculation Oeko-Institut, based on EEA 2022, Eurostat database, EC 2021

The trend in animal product production is closely linked to the changes in livestock numbers (see Figure 88). While there is only a slight decrease in production in the EUBase/EUTarget scenarios compared to 2020. Due to behavioral and dietary changes, as outlined above, the reduction in animal product production is more pronounced in the EUSupreme. Specifically, compared to 2020 levels, milk production decreases by 67% until 2050, while in the EUBase and the EUTarget there is only a reduction of 13% until 2050 compared to 2020 levels.

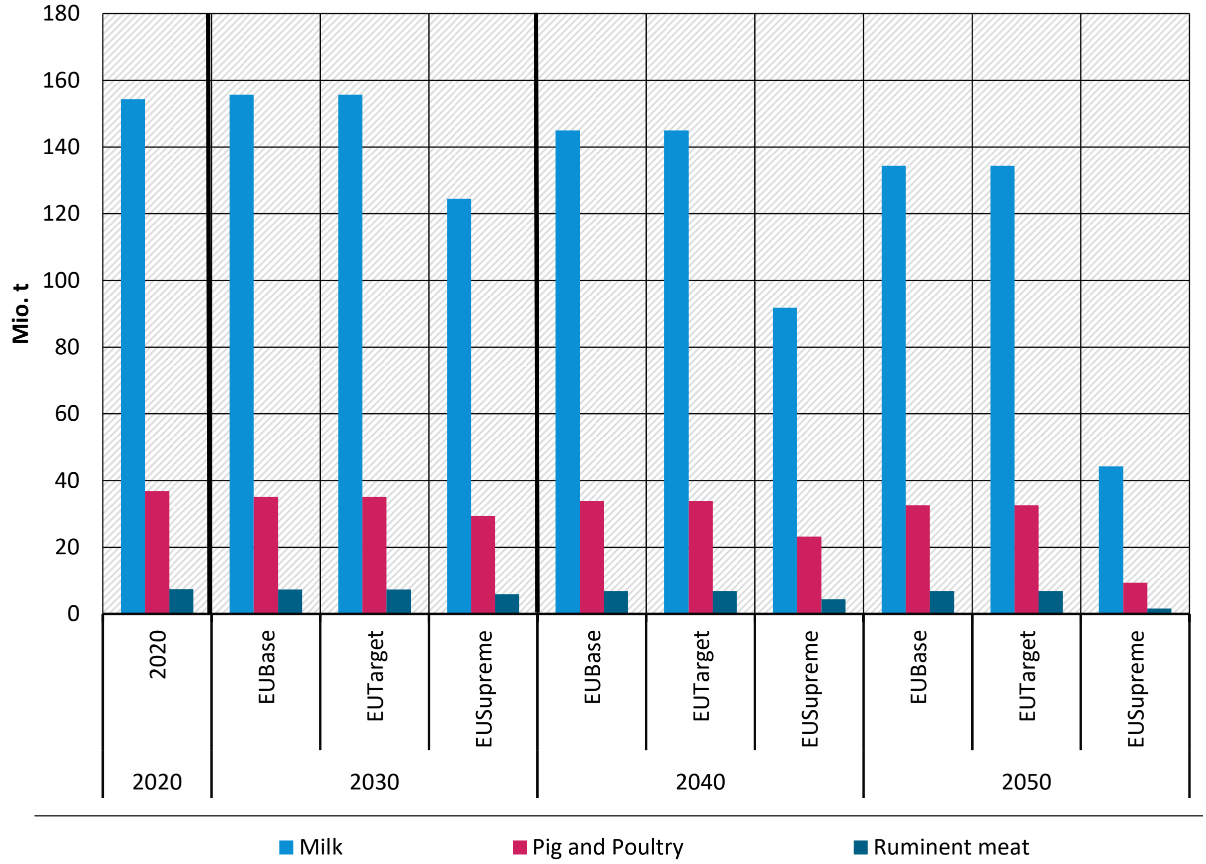
Table 35: Key figures for milk production in 2050 in the different scenarios

	Dairy Cows (Number)	Milk Yield	Production Mt Milk
2020	20,308	7,474	154
EUBase/EUTarget	16,666	8,062	134
EUSupreme	5,873	5,665	44

Source: Own calculation Oeko-Institut

The following Figure 89 shows the development of milk and meat production over time in the different scenarios. In the EUSupreme beef, pork, and poultry meat production decrease by approximately 71% until 2050. In the EUBase/EUTarget production of beef decreases by 15% and production of poultry and pig meat decreases by -12% until 2050 compared to 2020 levels.

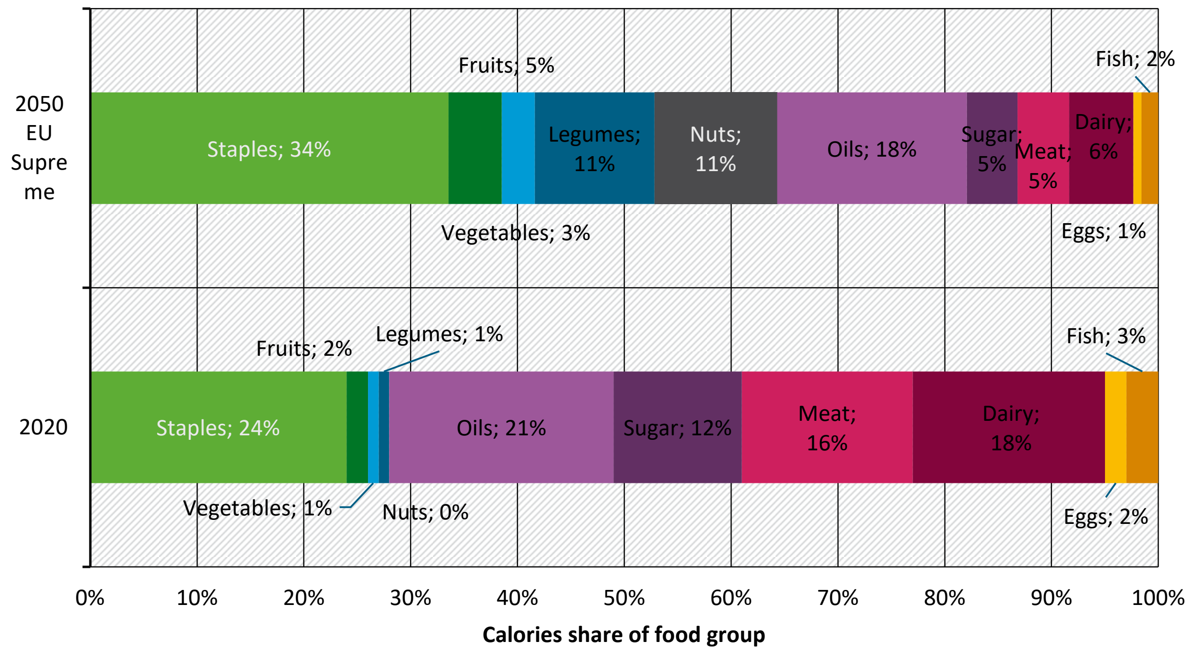
Figure 89: Development of milk and meat production in EUBase/EUTarget in comparison to EUSupreme



Source: Own calculation Oeko-Institut, based on EC 2021

The EUSupreme scenario projects the most significant decline in the production of animal-based products, closely tied to a sharp reduction in their consumption. By 2050, 87% of calorie intake in this scenario is expected to come from plant-based sources, with only 13% derived from animal products. This marks a substantial shift from the dietary patterns of EU citizens in 2020, when 61% of calories came from plant-based products and 39% from animal products. This transition is also driven by growing awareness of the health benefits associated with reduced consumption of animal-based products. The following figure shows the calorie share of consumption for the different food groups in 2020 and the EUSupreme in 2050.

Figure 90: Calories shares of food groups in average EU food consumption in 2020 and in EUSupreme 2050



Source: (Agora Agriculture 2024) for 2020, own calculation for 2050 Oeko-Institut, based on Willet et al 2019

3.2.7.3 Comparison

By comparing the three scenarios—EUBase, EUTarget, and EUSupreme—we observe significant differences in the reduction of livestock numbers, resulting in large variations in production, nitrogen input, and greenhouse gas emissions.

In the EUBase scenario, livestock numbers see a modest decline over the years, with a gradual reduction by 2050. Meat and milk production also decrease slightly, even if yield improvements are assumed. Currently, the lack of adequate instruments means there is little incentive to implement technical reduction measures, limiting their application. As a result, the EUBase scenario achieves a moderate emission reduction of -12% compared to 2020 by 2050.

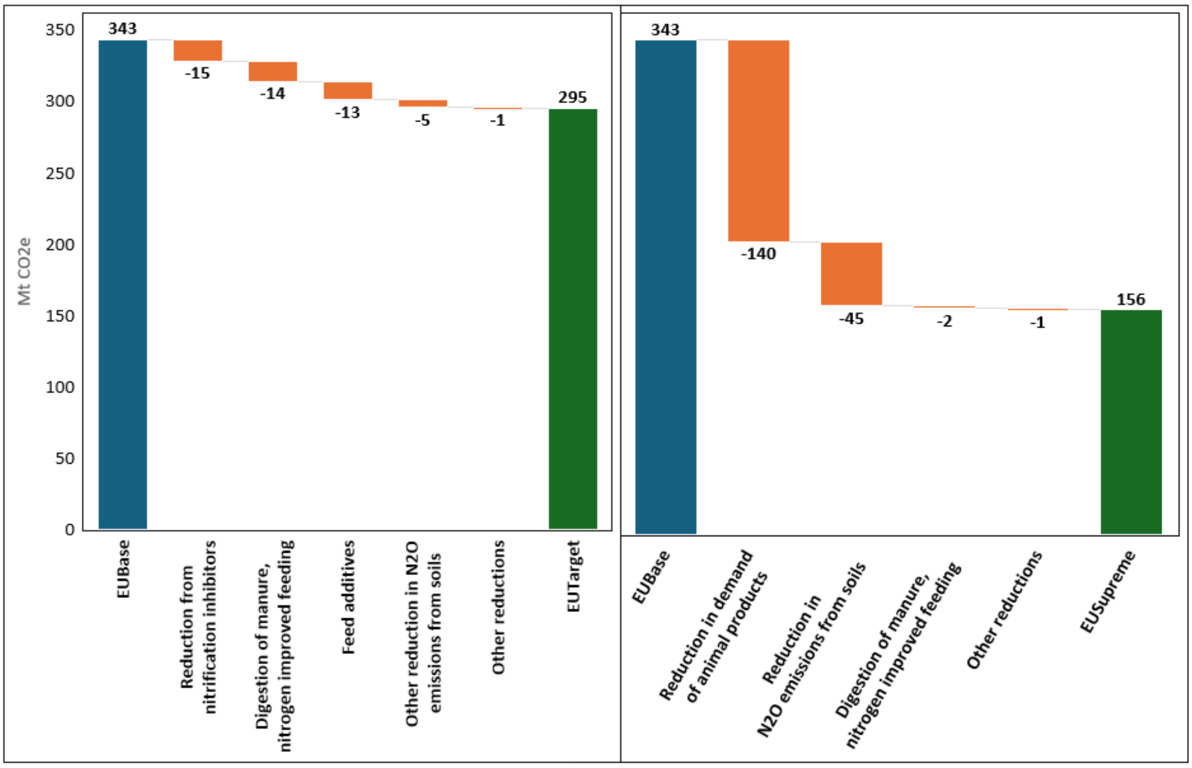
In the EUTarget scenario, livestock numbers and production remain the same as in the EUBase scenario, but more technical mitigation measures are applied. By implementing these measures, emissions in 2050 can be reduced by nearly 50 million tons of CO_2e, representing a further -14% reduction compared to EUBase emissions in 2050. In comparison to 2020 emissions decrease by 24% due to a moderate reduction in livestock numbers and the adoption of technical mitigation measures. This suggests that emission reductions from technical mitigation measures are limited in this sector and high residual emissions remain. However, the contribution of technical mitigation measures to total reduction strongly depends on the assumptions made regarding their GHG mitigation potential and adoption rate. The assumptions in the EUTarget scenario reflect a conservative approach to estimating mitigation potential. A recent study by (Agora Agriculture 2024) indicates that technical measures could achieve a mitigation potential of nearly 30% in livestock farming, assuming a high adoption rate and considering additional mitigation technologies not included here. Due to uncertainties surrounding the long-term effectiveness and environmental impacts of technical mitigation measures such as nitrification inhibitors and feed additives, these options are considered with caution. Furthermore, no additional mitigation technologies are included, as potential overlaps with other measures (e.g.

manure acidification versus anaerobic digestion of manure) remain. As a result, estimates of mitigation potential can vary across studies. This study adopts a conservative approach to account for the uncertainties.

In contrast, the EUSupreme scenario highlights the significant impact of demand-side changes. If the demand of all EU citizens aligns with the nutritional recommendations of the Planetary Health Diet while part of the grassland is still used for milk production for exports (10% of total production), GHG emissions in 2050 can be reduced to 54% below the EUBase scenario, representing a total reduction of 187 million tons of CO_2e against the EUBase. This is reflected by a substantial reduction in livestock numbers: 22% by 2030, 44% by 2040, and 67% by 2050 compared to 2020 levels. This results in a significant reduction in animal product production, with milk production decreasing by 67% and beef, pork, and poultry meat by approximately 71% by 2050 compared to 2020 levels. Such a significant change in demand in relation with reduced demand for nitrogen due to extensification can save up to 187 million tons of CO_2e, strongly lowering the need for compensation through natural or technical sinks or emission reductions in other sectors to achieve the EU target of net zero emissions by 2050. However, to implement this dietary change, it is essential to have strong and robust instruments and an ample supply of attractive plant-based foods.

The following Figure 91 shows the mitigation potential of different measures under the EUTarget and EUSupreme compared to EUBase. It highlights the significant impact of demand-side measures on emission reductions. Additionally, it shows that the absolute mitigation potential of technical measures, such as improved manure digestion and nitrogen efficient feeding, declines, as overall emissions from animal husbandry decrease with decreasing livestock numbers.

Figure 91: Comparison of GHG emission reduction from different measures in the EUTarget and the EUSupreme compared to EUBase for the year 2050



Source: Own calculation Oeko-Institut

3.2.8 Waste

CH_4 emissions from landfilling dominate in the waste sector. In 2020, CH_4 emissions from landfilling of organic waste contributed 73% of total emissions, followed by CH_4 and N_2O emissions from wastewater handling with 19% of total emissions.

According to the IPCC methodology, emissions reported in the waste sector include only CO_2, CH_4 and N_2O emissions from the handling of organic waste (disposal on landfills, biological treatment, incineration without energy recovery) and from wastewater handling. Emissions related to recycling etc. are reported in the industry sector, while emissions from incineration with energy recovery are accounted for in the energy sector.

In the waste sector, there are large differences between the EU member states. While countries like Germany have been implementing ambitious policies for many years, reducing GHG emissions significantly compared to 1990 levels, other countries are only starting to increase recycling levels and separate treatment of biological waste. Furthermore, data quality on the status quo of landfills and wastewater treatment, especially outside of larger agglomerations, is limited: Monitoring of waste landfilled has only been established over time, leading to gaps in information on composition and information on wastewater is scarce in regions without centralised treatment. This leads to the necessity of far-reaching estimations and assumptions during modeling.

3.2.8.1 EUBase scenario

3.2.8.1.1 General Description

The relevant EU legislations for the waste sector are the EU waste directive and the directives on landfill waste and wastewater. The **EU Waste Framework directive**[54] lays down the main principles and rules for waste management, ensuring that waste in the EU is managed in a way that there are no dangers or adverse effects to human health or the environment. One of the main impacts on the amount and treatment of waste generated in this directive is set by the targets for re-use and recycling of different types of waste. The **Directive on landfill waste**[55] sets the operational requirements for landfill sites to regulate and limit this treatment option, introducing mandatory treatment for waste landfilled and reduction targets for biodegradable waste in landfills. The **Urban wastewater directive**[56] regulates wastewater collection and treatment. As outlined in section 3.1.1.1 on the general narrative for the EUBase scenario, the current EU policies serve as a basis for the modeling in this scenario. Since the implementation status of the measures laid out in the directives is differing largely between EU member states, reaching the targets as set in the directives for the EUBase scenario is more ambitious for some countries than it is for others. The following section provides a more detailed explanation of the additional assumptions.

3.2.8.1.2 Main Assumptions

Historic data on waste treatment routes and waste categories is based on UNFCCC GHG inventory data (UNFCCC 2022) and additional information from Eurostat (2024b), Eurostat (2023a), Eurostat (2023b).

In the EUBase scenario, we assume that waste generation (in kg per capita) remains at 2020 levels (except for food waste) with no change until 2050. While the waste hierarchy of reduce, reuse, recycling and recovery is often mentioned in political discussion there are currently no

[54] https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

[55] https://environment.ec.europa.eu/topics/waste-and-recycling/landfill-waste_en

[56] https://environment.ec.europa.eu/topics/water/urban-wastewater_en

concrete EU policies or measures in place that target the amount of waste generated at the level of households. However, policies and measures exist for the adaptation of waste treatment routes. Landfilling of municipal waste is reduced to 10% of waste generated by 2035 compared to 2020. Member States with high waste disposal rates in 2013 (>60%) do not have to reach the target before 2040 (Directive (EU) 2018/850[57]). Waste that is no longer landfilled is partly recycled and partly treated in mechanical-biological treatment (MBT) plants or used for incineration with energy recovery.

While the EU strives to set legally binding targets for food waste reduction of 10% in processing and manufacturing and 30% in retail and consumption[58], those targets have not entered into force at the time of modeling. Since some countries, e.g. Germany (Förster et al. 2024), have already set national targets for food waste reduction, the following targets are set in EUBase: Food waste levels are reduced by 10% compared to current levels until 2030, by 15% until 2040, and by 20% until 2050.

Recycling shares for municipal waste are implemented according to the EU Waste Directive (2018/851/EG[59]) from 2025 onwards with shares of 60% in 2030 and 65% in 2035.[60] Recycling shares remain at this level and are not increased beyond the levels set in the EU Waste Directive in the EUBase scenario in the years 2040 and 2050. Member States with low recycling shares in 2013 (<20%) and high landfill shares (>60%) do not have to reach the target before 2035 (Directive (EU) 2018/851[59]).

Data for wastewater treatment routes and emissions is taken from the EEA database (EEA (2023b)) and the UNFCCC inventory (UNFCCC 2022). Both industrial wastewater and domestic wastewater are considered. However, detailed available data on wastewater treatment is limited for most countries. In the EUBase scenario no assumptions on improvement of wastewater are implemented, since all goals fixed in Council Directive 19/271/EEC[61] target the year 2005 at the latest[62]. Emissions from domestic wastewater thus follow population trends in the individual Member States and emissions from industrial wastewater are assumed to remain approximately at 2020 levels until 2050.

3.2.8.1.3 Results

In the EUBase Scenario, municipal waste generation amounts remain almost stable between 2020 and 2050 (see Figure 92). Small changes between the years are mainly driven by population trends and reduction in food waste. In total, waste generation is reduced by 4% compared to 2020 levels. Landfilling of waste is reduced by 68% in 2050 compared to 2020 levels. The amount of waste previously landfilled is being rerouted to other treatment routes: Amounts in biological treatment[63] are 40% higher in 2050 compared to 2020, amounts of recycling material increase by 24%, while energy recovery and MBT levels increase by 20%. Incineration without energy recovery decreases by 24%.

[57] https://eur-lex.europa.eu/eli/dir/2018/850/oj

[58] https://food.ec.europa.eu/food-safety/food-waste/eu-actions-against-food-waste/food-waste-reduction-targets_en

[59] https://eur-lex.europa.eu/legal-content/DE/TXT/?uri=CELEX%3A32018L0851

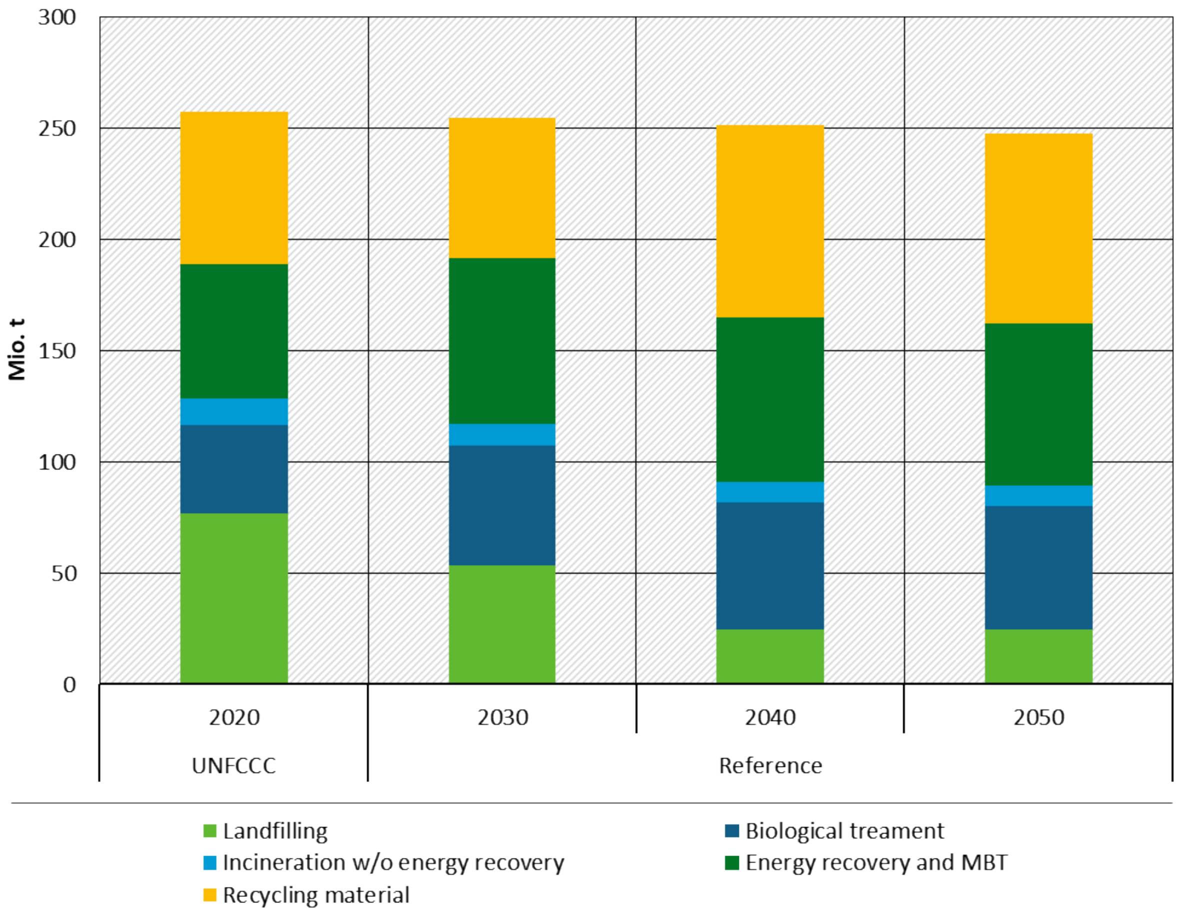
[60] The implementation of the EU Directive on Packaging and Packaging Waste (94/62/EG) could not be considered in the waste modeling, as detailed data on the share of packaging is missing for the single waste categories.

[61] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0271

[62] Directive (EU) 2024/3019 (https://eur-lex.europa.eu/eli/dir/2024/3019/oj) entered into force on 27 November 2024 and could thus not be considered for modeling of this scenario.

[63] This includes anaerobic digestion and composting. No assumption is made on the development of home composting, as there is no data available and thus high uncertainties.

Figure 92: Amounts of municipal waste generation and treatment routes for the EUBase scenario



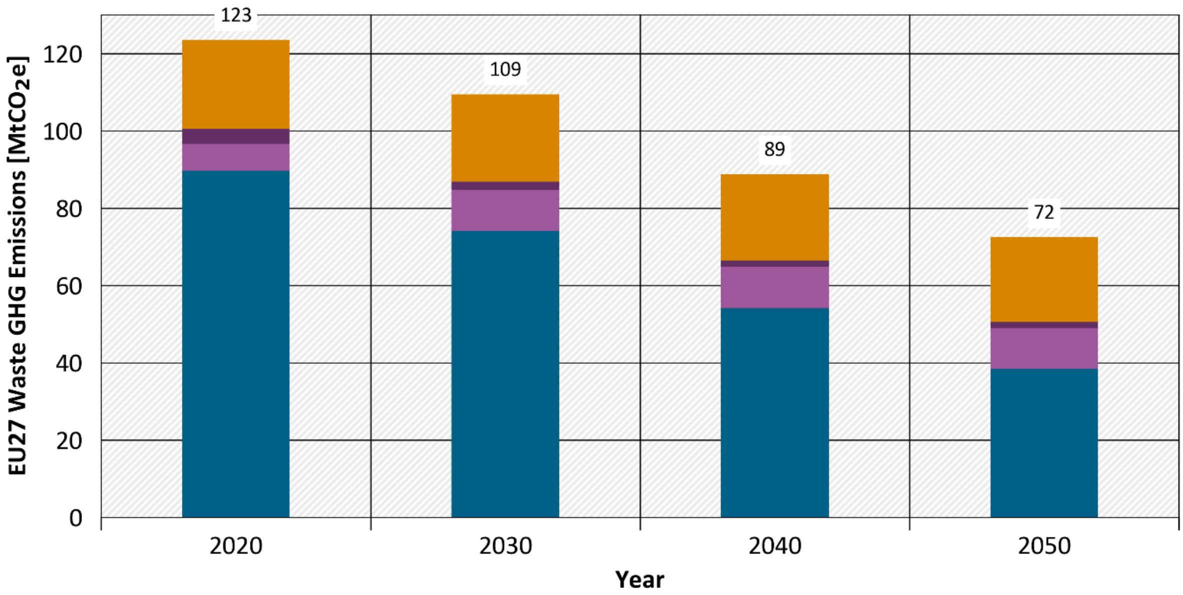
Source: Own calculation Oeko-Institut, based on UNFCCC inventory data (UNFCCC 2022), Eurostat (2023a), Eurostat (2023b), Eurostat (2024b)

By implementing the changes described in the previous paragraph, GHG emissions from the waste sector are reduced by 41% until 2050 compared to 2020 (Figure 93). The development until 2030, however, requires a rapid implementation of the existing technical reduction potentials, since due to the nature of organic decay processes of waste, measures take a certain amount of time to take effect.

Emissions from waste are dominated by solid waste disposal on landfills, however, this is also the area with the largest reduction in emissions: 51 Mt CO_2e, which equals a reduction of 57% between 2020 and 2050. Emissions from biological treatment increase by 4 Mt CO_2e (+54%) while those from incineration[64] decrease by 2 Mt CO_2e (-61%). As described in the paragraph above, achieving those emission reductions is only possible with a rapid implementation of existing technical reduction potentials. Emissions from wastewater treatment decrease by 1 Mt CO_2e, representing a reduction of 4%, but this change is only based on population development, since no measures were analysed for this subsector.

[64] The names for the emission categories are determined by the respective subcategories of CRF category 5, determined by the 2006 IPCC guidelines for National Greenhouse Gas Inventories (IPCC 2006a). The category "Incineration and open burning of waste" contains emissions from waste incineration without energy recovery (waste incineration with energy recovery is reported in category 1) and open burning of waste.

Figure 93: Waste: GHG emissions in the EUBase scenario



Note: The values for *Other* are one order of magnitude smaller than the values for the other categories in the figure. They are thus not visible in the graph.

Source: Own calculation Oeko-Institut, based on UNFCCC inventory data (UNFCCC 2022), Eurostat (2023b), Eurostat (2023a), Eurostat (2024b)

3.2.8.2 Target scenarios

3.2.8.2.1 General Description

The EUTarget and the EUSupreme scenarios for the waste sector differ from the EUBase scenario in main assumptions on the implementation of technical solutions, on waste generation levels and reduction in food waste. The EUTarget scenario follows the assumptions of the EUBase scenario and meets current EU legislation. Additional measures in EUTarget are implemented in the landfill sector through mandatory pre-treatment and increased landfill gas collection. The focus of the EUTarget scenario is to answer the question of which emission reductions can be achieved through technical measures.

The EUSupreme scenario includes additional measures besides the technical options described for EUTarget, partly related to the consumer side. These include the increase of recycling rates, the discontinuation of landfilling of organic waste and reduction in waste generation.

For a general description of the narratives for the target scenarios, please also refer to section 3.1.2.

3.2.8.2.2 Main assumptions

The **EUTarget scenario** builds on the assumptions of the EUBase scenario and meets current EU legislation. In addition, supplementary measures in EUTarget are implemented in the landfill sector through mandatory pre-treatment and increased landfill gas collection. The focus of the EUTarget scenario is to answer the question of **which emission reductions can be achieved through technical measures**.

The **EUSupreme scenario** includes additional measures besides the technical options described for EUTarget, with a focus on circularity and sustainability, targeting the consumer side more strongly than EUBase and EUTarget. The measures include the increase of recycling rates, the discontinuation of landfilling of organic waste and reduction in waste generation.

The assumptions are based on own expert judgement and have been refined by aligning them with the overarching scenario narrative and developments in other related sectors.

Main differences between the three scenarios are as follows:

Development of waste generation: In EUTarget the same level of waste generation is assumed as in EUBase. In EUSupreme there is further reduction in waste generation due to increased recycling rates and a focus on consumer information in order to reduce waste generation overall.

Reduction of food waste levels: Further reduction of food waste compared to EUBase is assumed in both scenarios, with a reduction of 40% compared to 2020 levels in the EUTarget scenario. Through increased customer awareness raising and mandatory rules for shops and restaurants, a food waste reduction of 50% compared to 2020 levels is reached in EUSupreme.

Regulation of landfilling: Landfilling of waste is further regulated in both target scenarios. In EUTarget most of the waste landfilled must be stabilized before going to the landfills. In EUSupreme, the organic content of landfilled waste is reduced to its maximum by increasing separate collection and subsequent treatment of organic waste.

Recycling levels: In EUTarget the same recycling levels as in EUBase are assumed, as those levels reflect current EU legislation and technically feasible options. In EUSupreme, which has a strong focus on enhanced circularity, there is further increase in recycling rates.

Biological treatment of organic waste (anaerobic digestion): In the EUTarget scenario, the share of anaerobic digestion of organic waste is increased compared to EUBase. This is achieved through an increase of centralized collection and treatment of organic waste and subsequent anaerobic digestion. There is an additional increase of the share of anaerobic digested biowaste under the EUSupreme, through an increased customer focus on separate collection of organic waste and less composting.

Wastewater: In both target scenarios, an improvement of wastewater treatment to tertiary treatment is assumed, reaching 80% of all wastewater treatment in EUTarget and 90% in EUSupreme. Incremental improvements are first introduced in countries with high current emission factors for wastewater treatment. In EUTarget, we assume the implementation of the revised EU wastewater directive with an emission reduction of 60% in 2040 compared to 1990, while in the EUSupreme, a higher reduction of 68% in 2040 compared to 1990 is reached.

Table 36: Assumptions in the EUBase and target scenarios

Category	EU Pathways Base Scenario (EUBase)	EU Pathways Target Scenario (EUTarget)	EU Pathways Supreme Scenario (EUSupreme)
Total Waste generation per capita	Constant compared to 2020 levels 575 kg per capita per year, 561 kg considering reduction in food waste	Same as EUBase 575 kg per capita per year, 547 kg considering reduction in food waste	Reduction of plastic waste and paper due to increased prevention, and reuse etc. 539 kg per capita in 2050, 503 kg considering reduction in food waste

Category	EU Pathways Base Scenario (EUBase)	EU Pathways Target Scenario (EUTarget)	EU Pathways Supreme Scenario (EUSupreme)
Food waste	Reduction of 20% compared to 2020 levels until 2050	Reduction of 40% compared to 2020 levels until 2050	Reduction of 50% compared to 2020 levels until 2050
Recycling rates	Target for 2050: Organic waste: 65% Wood: 30% Paper: 85% Synthetics/Plastics: 55%	Same as EUBase	Target for 2050: Organic waste: 75% Wood: 40% Paper: 85% Synthetics/Plastics: 65%
Waste landfilled	Reduction to 10% of municipal waste for MS with waste disposal rates below 60% in 2013 until 2035, 2040 for other MS, constant until 2050	Reduction of landfilled waste to 10% in 2035 in all Member States	Reduction of landfilled waste to 10% in 2035 in all Member States No landfilling of untreated biowaste from 2040 onwards
Landfill gas (CH_4) recovery rates	Increase by 0,2% per year, share in 2050 = 31% in total CH_4 emissions generated (own assumption)	Increase by 0,5% per year, share in 2050 = 45% in total CH_4 emissions generated	Increase by 0,5% per year, share in 2050 = 45% in total CH_4 emissions generated
Landfill stabilization	-	Treatment of 75% of waste landfilled in MBA before final landfilling until 2050	Strong reduction of waste with organic share by treatment in MBA before final landfilling and further reduction in landfilling until 2050
Biological treatment	Share of waste treatment in total biological waste treatment in 2050: Composted: 58% Digested: 42%	Share of waste treatment in total biological waste treatment in 2050: Composted: 40% Digested: 60%	Share of waste treatment in total biological waste treatment in 2050: Composted: 30% Digested: 70%
Wastewater treatment	Constant, based on population trends	Improvement of wastewater treatment to 80% of tertiary treatment in all MS until 2050 Incremental improvements first in countries with high EF, using countries with similar situations but better EF as EUBase Implementation of revised EU Wastewater directive (Reduction of emissions by 60% in 2040 compared to 1990)	Improvement of wastewater treatment to 90% of tertiary treatment in all MS until 2050 Incremental improvements first in countries with high EF, using countries with similar situations but better EF as reference (higher improvement rates than EUTarget) Higher emission reduction than EU Wastewater directive: -68% in 2040 compared to 1990

Category	EU Pathways Base Scenario (EUBase)	EU Pathways Target Scenario (EUTarget)	EU Pathways Supreme Scenario (EUSupreme)
Protein consumption	Constant, based on population trends	Constant, based on population trends	Coupled with changes in consumption

Development over time – if the modeling years of 2030 and 2040 are not mentioned, a linear path is assumed.
Source: Own assumptions Oeko-Institut

In both target scenarios the development of the waste landfilled remains the main driver for emission reductions. While the stabilization of landfilled waste is applied in both target scenarios, additional emission reduction is related to reducing the amount of organic waste as far as possible by enforcing separate collection in EUSupreme. Moreover, the reduction in waste generation is a further driver for emission reduction, as less waste has to be treated. For all other measures there is only a difference in the implementation level of the different measures.

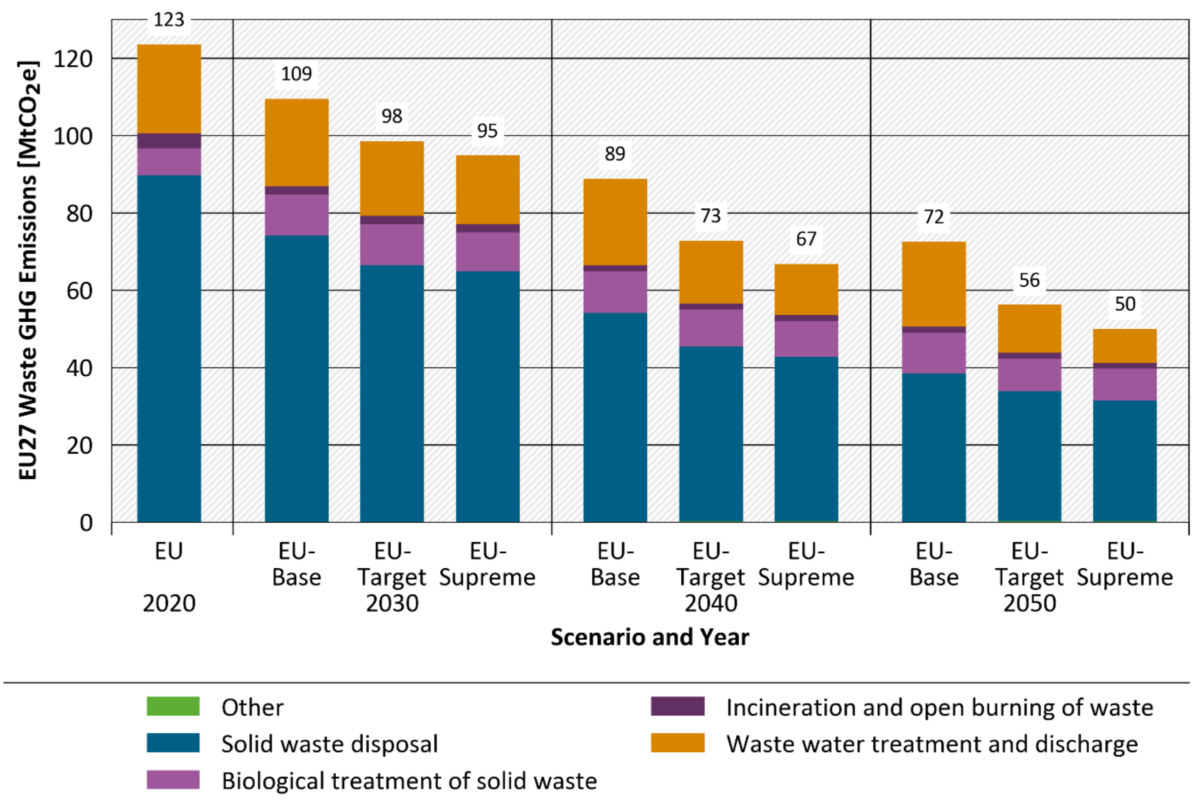
In general, EUTarget incorporates all technically feasible measures. EUSupreme builds on EUTarget and its technical measures by incorporating behavioural changes and additional technical measures focused on advancing circularity. Due to the limited number and impact of available measures in the waste sector, more ambitious scenarios must utilise every possible option to achieve emission reductions.

3.2.8.2.3 Results

Compared to the EUBase scenario, emissions in the waste sector can be further reduced if additional technical measures and the principle of reduce, reuse and recycle are implemented. In EUTarget, GHG emissions in the waste sector decrease by 67 Mt CO_2e or 55% until 2050 compared to 2020 (see Figure 94). In comparison to EUBase, this is a further emission reduction of 16 Mt CO_2e or 22%, mainly due to the implementation of waste stabilization before landfilling. In the EUSupreme scenario, emissions are reduced by 74 Mt CO_2e or 60% compared to 2020 levels. By broadening the reduce, reuse and recycle principle and a ban of biowaste going to landfills an additional emission reduction compared to the EUTarget of 6 Mt CO_2e can be achieved.[65]

[65] The reduce, reuse and recycle principle also affects the amount of waste that is incinerated with energy recovery. Emission reductions from the reduction of waste burned are reported in the energy sector.

Figure 94: Development of GHG emissions in the waste sector in all three scenarios



Note: The values for *Other* are one order of magnitude smaller than the values for the other categories in the figure. They are thus not visible in the graph.
Source: Own calculation Oeko-Institut, based on UNFCCC inventory data, Eurostat (2023a), Eurostat (2023b), Eurostat (2024b)

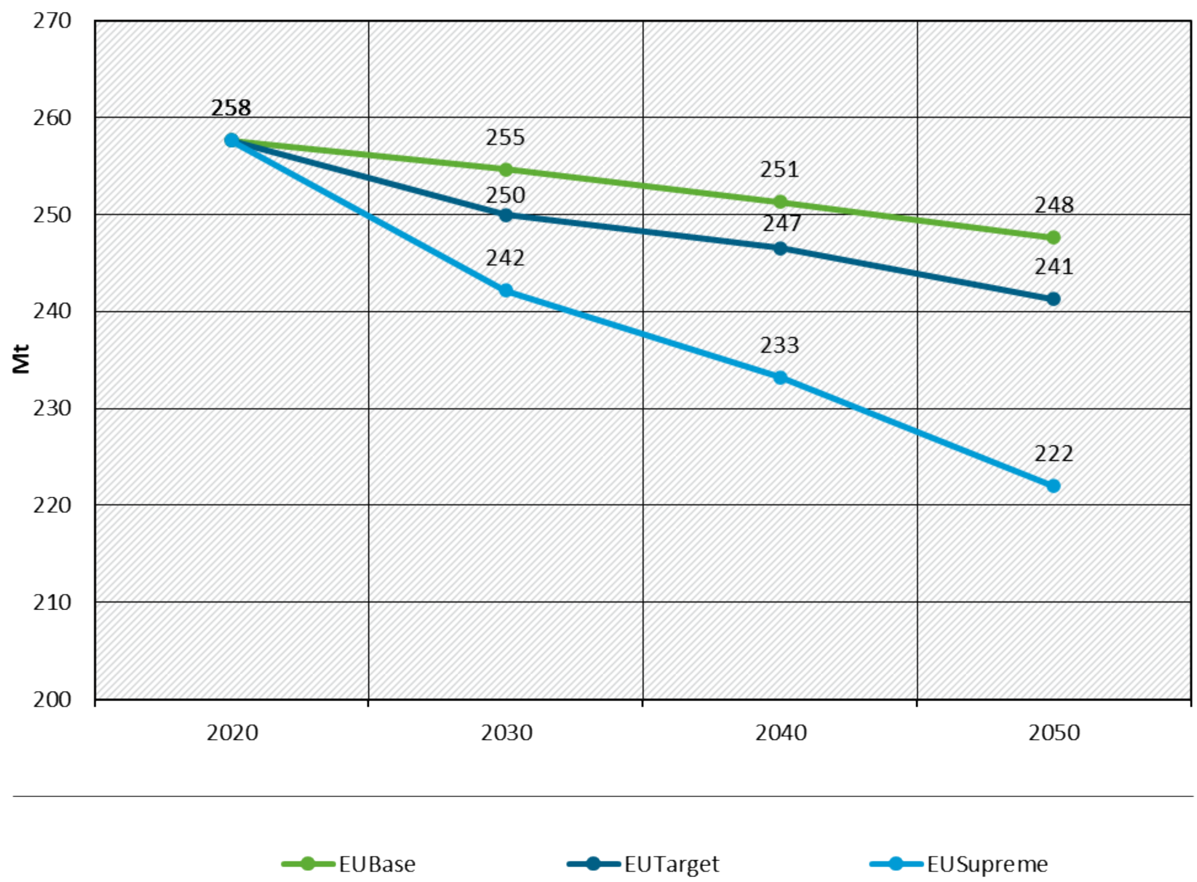
The largest emission reductions in the EUTarget and the EUSupreme scenarios compared to EUBase are achieved by the improvement of wastewater treatment. In the EUTarget scenario, in 2050, a further emission reduction of 10 Mt CO_2e and in the EUSupreme of 13 Mt CO_2e is reached in this category. While in the area of wastewater treatment, health and water safety issues were the main focus of improvements over the last decades, the connection of more and more areas to sewage treatment plants and the introduction of tertiary wastewater treatment as the standard to achieve have a notable impact on emissions from wastewater treatment. This is reflected in the resulting emission reductions. The difference between the two target scenarios lies in the assumption on the level of tertiary treatment (90% in EUSupreme and 80% in EUTarget) but also on the reduction of protein consumption in EUSupreme scenario compared to EUBase and EUTarget. For more information on the transformation of food consumption, see also section 3.2.7.2 on assumptions in the sector Agriculture.

Additional measures to reduce emissions include waste stabilization before landfilling and the prohibition of biowaste disposal in landfills. Stabilizing waste results in an emission reduction of 5 Mt CO_2e (EUTarget compared to EUBase), while the ban on biowaste in landfills contributes another -2 Mt CO_2e (EUSupreme compared to EUTarget) to overall emission reduction. However, methane emissions from landfilling persist, particularly due to waste deposited during historical periods and until 2035.

A more stringent reduction in food waste results in an emission reduction of 2 to 3 Mt CO_2e respectively in 2050 in the EUTarget and the EUSupreme scenarios compared to EUBase. The difference in reduction between EUTarget and EUSupreme is rooted in increased customer awareness raising and mandatory rules for shops and restaurants. This allows for the target of 50% food waste reduction until 2030 to be reached in EU Supreme.

Waste generation is further reduced in the EUTarget and the EUSupreme scenarios compared to EUBase. In EUTarget, waste generated is only reduced by 2% compared to EUBase by further reducing the amount of food waste (see Figure 95). A stronger reduction of waste generated takes place in EUSupreme due to reduction in paper and plastic use and increased prevention, recycling and reuse rates. Waste generation in 2050 is reduced by 14% compared to 2020 or 10% compared to EUBase.

Figure 95: Development of waste generation in all three scenarios



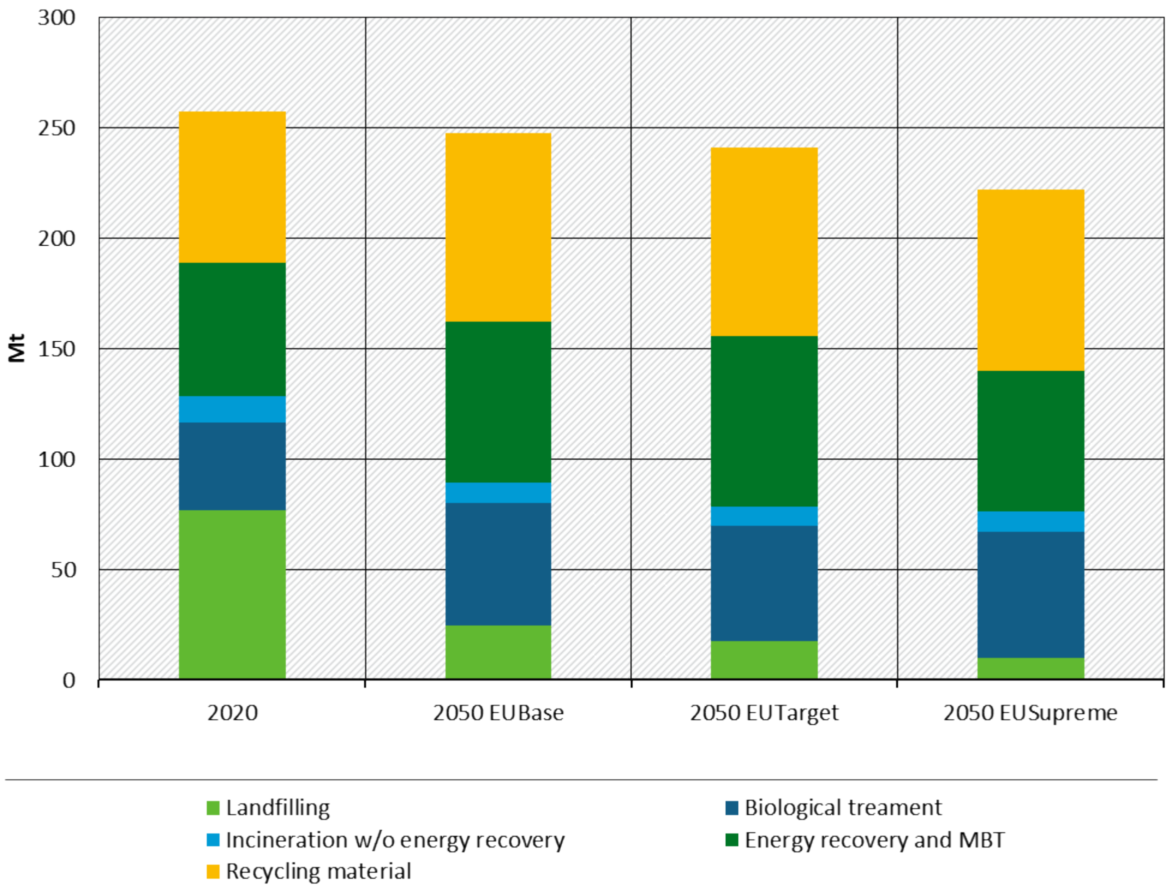
Source: Own calculation Oeko-Institut, based on UNFCCC inventory data, Eurostat (2023a), Eurostat (2023b), Eurostat (2024b)

Figure 96 illustrates the evolution of waste treatment routes across various scenarios in 2050. Notably, there is a substantial reduction in waste being landfilled across all scenarios, including EUBase, where the amount in 2050 is reduced by 68% compared to 2020. Further reduction by 27% in the EUTarget scenario compared to EUBase is achieved through waste stabilization before landfilling, which diverts portions of waste to other treatment methods (such as incineration and mechanical biological treatment). When combined with a ban on biowaste landfilling in the EUSupreme scenario, only minimal amounts of waste remain destined for landfills: waste landfilled in 2050 in the EUSupreme scenario is 40% of the 2050 EUBase amount and 87% below the 2020 amount.

In all scenarios, the amount of bio-waste undergoing biological treatment increases compared to 2020 levels. The specific quantity varies between 52 Mt and 57 Mt based on the proportion of recycling and the extent of food waste reduction, which have opposing effects on the amount of organic waste undergoing biological treatment. Notably, the highest amount occurs in EUSupreme, where rates of separate collection for biowaste have further increased, even with decreasing amounts of food waste.

Furthermore, the amount of waste recycled increases in all scenarios. Levels in 2050 in EUBase and EUTarget are similar at 85 Mt. However, in EUSupreme, the rise in recycling rates is counterbalanced by the reduction in waste generation, resulting in a reduced overall amount of 82 Mt of waste recycling in this scenario.

Figure 96: Comparison of waste treatment routes in all three scenarios in 2050



Source: Own calculation Oeko-Institut, based on UNFCCC inventory data, Eurostat (2023a), Eurostat (2023b), Eurostat (2024b)

3.2.8.3 Comparison

While the EUBase scenario assumes the realisation of current measures and legislation, the EUTarget scenario implements additional technical measures, such as mandatory pre-treatment of waste and increased landfill gas collection, to achieve further emission reductions. The EUSupreme scenario goes beyond technical options, incorporating both necessary technical measures and consumer-side initiatives, including higher recycling and reuse rates, a strong reduction of food waste, and a significant reduction in overall waste generation.

The scenarios demonstrate a clear progression from compliance (EUBase) to optimisation (EUTarget) to transformation (EUSupreme). Each step involves greater ambition, first through technological advances and then through systemic change, highlighting the importance of combining technical and behavioural measures to achieve deeper decarbonization in the waste sector. EUBase assumes the continuation of current EU legislation and its implementation across Member States. It assumes stable per capita waste generation and no significant behavioural shifts or new political instruments. Emissions can be reduced by 41% in 2050 compared to 2020, which implies an ambitious and complete implementation of all regulatory measures.

EUTarget is based on EUBase but incorporates additional technically feasible measures. It emphasises enhanced landfill gas recovery, the mandatory pre-treatment of waste prior to landfilling and improved wastewater treatment. The narrative is technology-driven, while maintaining current consumption patterns. The emission reduction of further 16 Mt CO_2e in comparison to EUBase shows that there is further mitigation by implementing ambitious technical measures.

EUSupreme is the most ambitious pathway. As well as including all measures from EUTarget, it also incorporates behavioural and systemic changes that are aligned with the principles of circular economy. These include stronger waste prevention measures, higher recycling rates, a ban on landfilling untreated biowaste and a reduction in protein consumption due to lower consumption of animal products. The narrative is transformative, presenting a society that reduces waste generation through prevention, re-use and sustainable consumption.

In summary, the comparison of all three scenarios show that significant emission reductions can be achieved in the waste sector by a combination of technical measures and behavioural changes. Implementing more ambitious technical measures in EUTarget allow for further emission reductions beyond the EUBase level. Focusing on technical measures and systemic changes can further reduce emissions as reflected in EUSupreme. The level of emission reductions achieved through behavioural changes depends on the ambition of these changes. Therefore, further reductions in this area beyond EUSupreme are possible. While EUBase achieves a 41% reduction of GHG emissions by 2050, EUTarget increases the reduction to 55% through technical improvements. However, EUSupreme achieves the greatest reduction of 60% combining technical measures with behavioural changes and systemic shifts towards circular economy.

Nevertheless, based on current trends and developments throughout the EU member states, even the achievement of the reductions depicted in the EUBase scenario are ambitious, underlining the need for fast implementation of policies and technical measures, especially surrounding the landfilling of waste.

4 Modeling and assessing the alignment with the EU Taxonomy

A companion report (Eckstein et al. 2025, forthcoming) explores the possibilities to model the effects of the EU Taxonomy. The effectiveness of the EU Taxonomy is discussed and two conceptual modeling approaches derived, which are then contrasted with the models used in the Pathways project. In a second part, the report explores whether the three scenarios of the Pathways project can be considered in line with the EU Taxonomy requirements for sustainable activities and explores ways in which this can be assessed. A summary of the report is provided in the following.

4.1 Introduction

The EU Taxonomy regulation establishes a reporting obligation for large and capital market-oriented companies on the share of economic activities which are deemed sustainable (European Commission 2020). The share of economic activity is defined as the share in investment or turnover, depending on the type of company. To do so, a catalogue of activities and technical screening criteria has been defined in subsequent delegated acts. Each activity must provide a significant contribution to one of six environmental objectives while not harming any of the other five (climate change mitigation, climate change adaptation, water resources, circular economy, pollution prevention and biodiversity).

The effect of the EU Taxonomy will only be indirect, following the use of the information the companies make available by complying with the reporting obligation established by the EU Taxonomy. As proposed by Höck et al. (2020), the risk premium of sustainable companies and projects should be lower, leading to better financing conditions. This is the measurable effect the EU Taxonomy could have on project finance. In this regard, disclosure of the taxonomy compliance of activities could steer financial flows (Lütkehermöller et al. (2020); Kölbel et al. (2020)). Lütkehermöller et al. (2020) describe three ways in which the financial sector can work toward GHG reductions (divestment, i.e., withdrawing investments that are not in line with the climate strategy; direct impact investments (so-called positive impact investment); building corporate commitments (so-called corporate engagement)). However, these are only affective if a majority of investors follows them.

The objective of the report by Eckstein et al. (2025, forthcoming) is twofold: In the first analysis, they investigate how the effect of the taxonomy could be modelled. In a second step, they assess whether the results of the scenarios EUBase, EUTarget and EUSupreme are aligned with the EU Taxonomy and more specifically the technical screening criteria it sets out.

4.2 Modeling the EU Taxonomy

Following the review of the sectoral models applied in this project, the “Cost of capital” approach of modeling the EU Taxonomy can be seen as a realistic alternative to modeling the effects of the EU Taxonomy as it is close enough to current modeling frameworks. In this approach, economic decisions calculated by a model are influenced by changes in the WACC (weighted average cost of capital), which is in turn determined by a scenario of the effectiveness of the EU Taxonomy. This path to modeling the EU Taxonomy still comes with a high burden of model development, even if models are partly already based on economic decision making. Only few models applied in the Pathways project are partly apt for this approach.

In addition, scenarios of the effectiveness of the EU Taxonomy would need to be developed if the EU Taxonomy is modelled directly. These scenarios would at least add an additional variable to the policy mix currently defining the scenarios of climate change mitigation. The link between cost of capital and effectiveness of the EU Taxonomy lacks empirical data, which increases the overall uncertainty of such an approach. Nevertheless, by investigating sensitivities of the cost of capital, the potential boundaries of the effectiveness of the EU Taxonomy could be evaluated.

4.3 Evaluating the scenarios for EU Taxonomy alignment

The second objective of this report is to evaluate the alignment of the scenarios EUBase, EUTarget and EUSupreme with the EU Taxonomy. Due to the data availability and model variables of the different sectoral models, such an analysis comes with major uncertainties and quantitative results can only be generated in limited cases. The overall qualitative assessment, however, gives an indication of the compliance of the three scenarios with the indicators.

4.3.1 Approach to the analysis

The analysis comes with considerable uncertainties which are linked to the mismatch between the criteria covered by the EU Taxonomy and the modeling approach. This is mirrored in the results the models provide and variables they work with to simulate the transformation related to climate change mitigation.

The detailed approach and discussion of the evaluation is described by Eckstein et al. (2025, forthcoming). Some overarching principles and limitations underly the EU Taxonomy alignment analysis:

- Only some of the sectors covered by the EU Taxonomy are modelled in the Pathways project
- Only one environmental objective of the EU Taxonomy is covered by the analysis (climate change mitigation)
- Only substantial contribution is analysed, DNSH compliance is not analysed.
- Only parts of each substantial contribution criterion are assessed.
- Actor size distribution remains unconsidered.

The alignment of the scenario results with each of the substantial contribution has been ranked on the same scale, applying a scoring metric of 1 to 5 (no compliance – limited compliance - medium compliance - good compliance – full compliance). In the presentation of results in the following sections, these scores are translated into numbers from 1 (no compliance) to 5 (full compliance). The assignment of evaluation results to these categories is part of the expert judgment underlying the whole analysis. The complete analysis is therefore a qualitative assessment, even if percentage values of compliance with certain criteria can be calculated to underpin the assessment. The reader is referred to Eckstein et al. (2025, forthcoming) for further details.

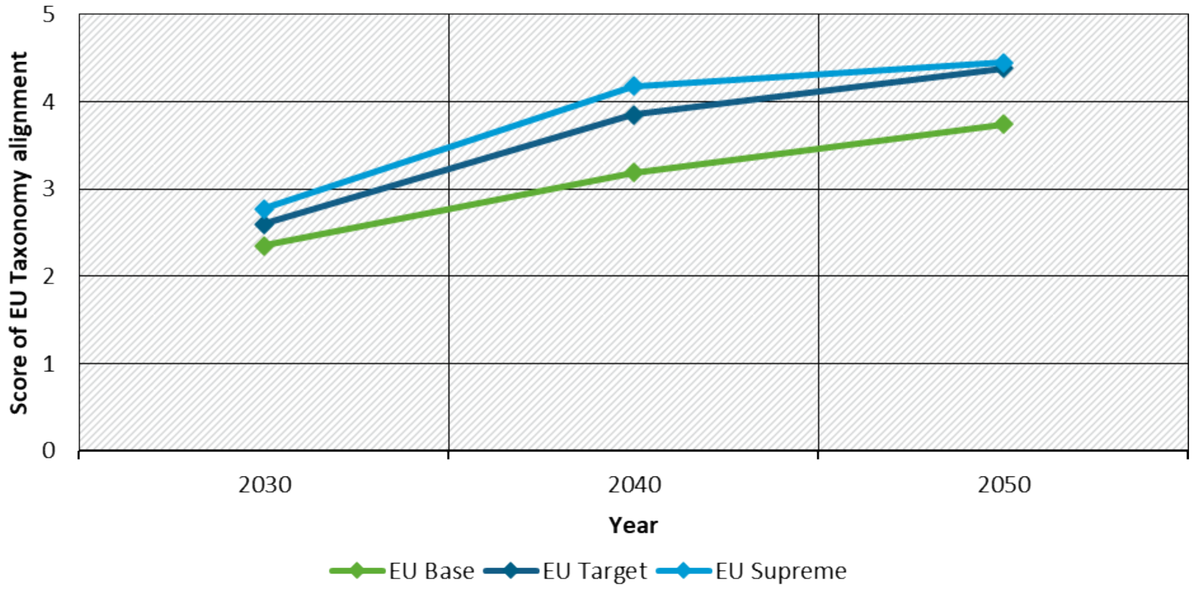
4.3.2 Results of the evaluation

Figure 98 to Figure 100 give the results of taxonomy alignment assessment for the 29 activities assessed for the years 2030, 2040 and 2050 of the three scenarios EUBase, EUTarget and EUSupreme. The average of all sectoral averages[66] as an aggregate is shown in Figure 97. This aggregate figure shows that across all activities evaluated, EUTarget and EUSupreme reach the same value of alignment in 2050, while EUSupreme reaches higher values of compliance in 2030

[66] This composite of averages is preferrable over the average of all indicators to compensate for the fact that ta different number of activities have been evaluated per sector.

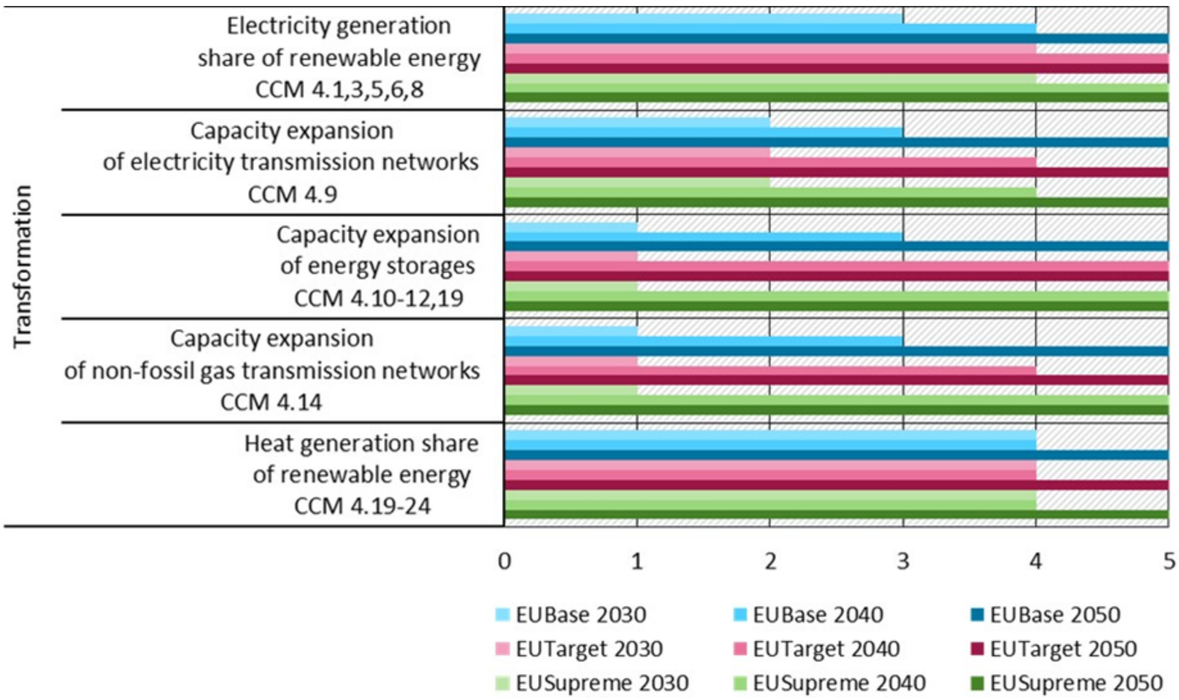
and 2040. However, all assessments based on this number need to consider the uncertainties of the underlying analysis. Details of the sectoral results can be found in the annex of Eckstein et al. (2025, forthcoming).

Figure 97: Aggregate score of EU Taxonomy alignment determined from the average of sectoral averages in each scenario and year



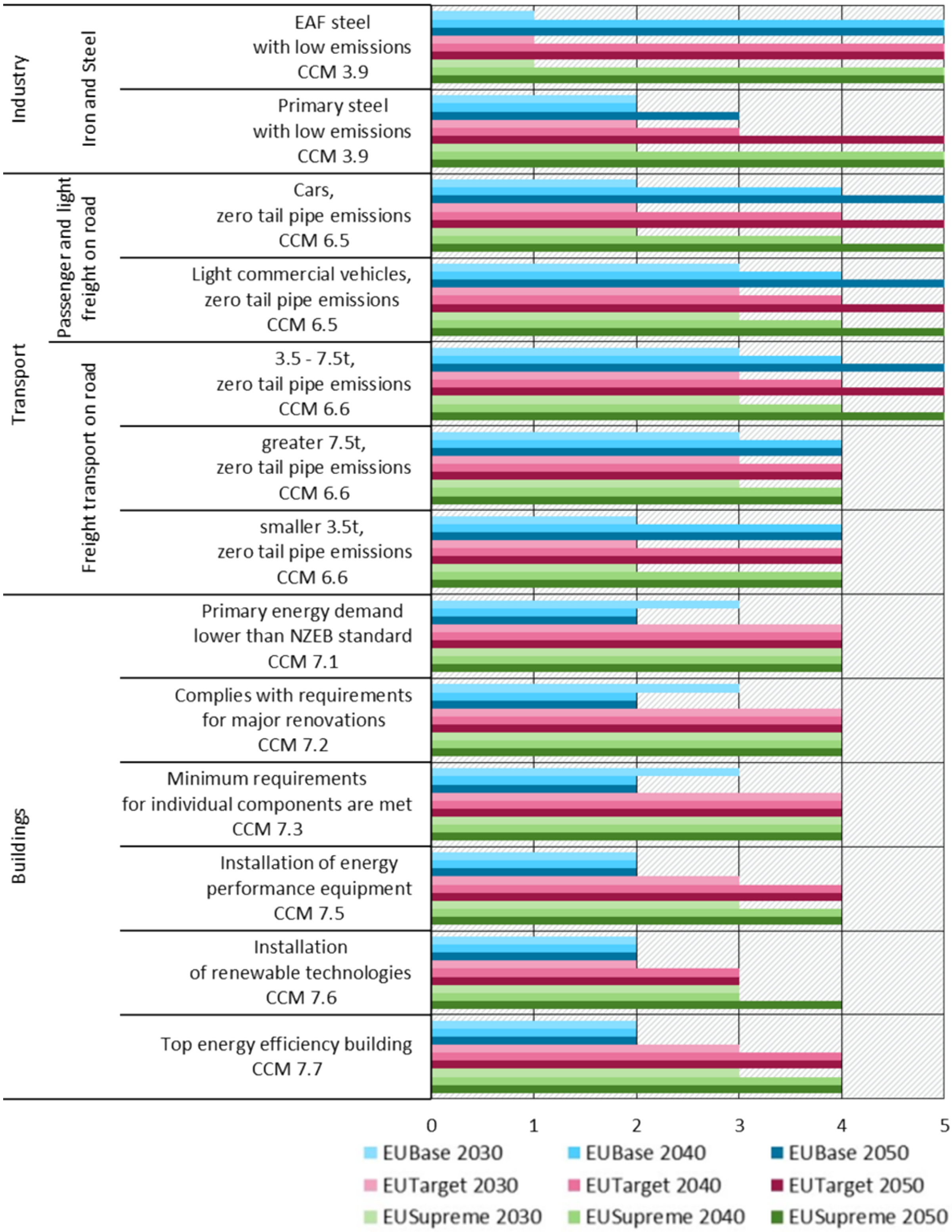
Source: Own elaboration by Fraunhofer ISI

Figure 98: Results of the taxonomy alignment analysis for the transformation sector



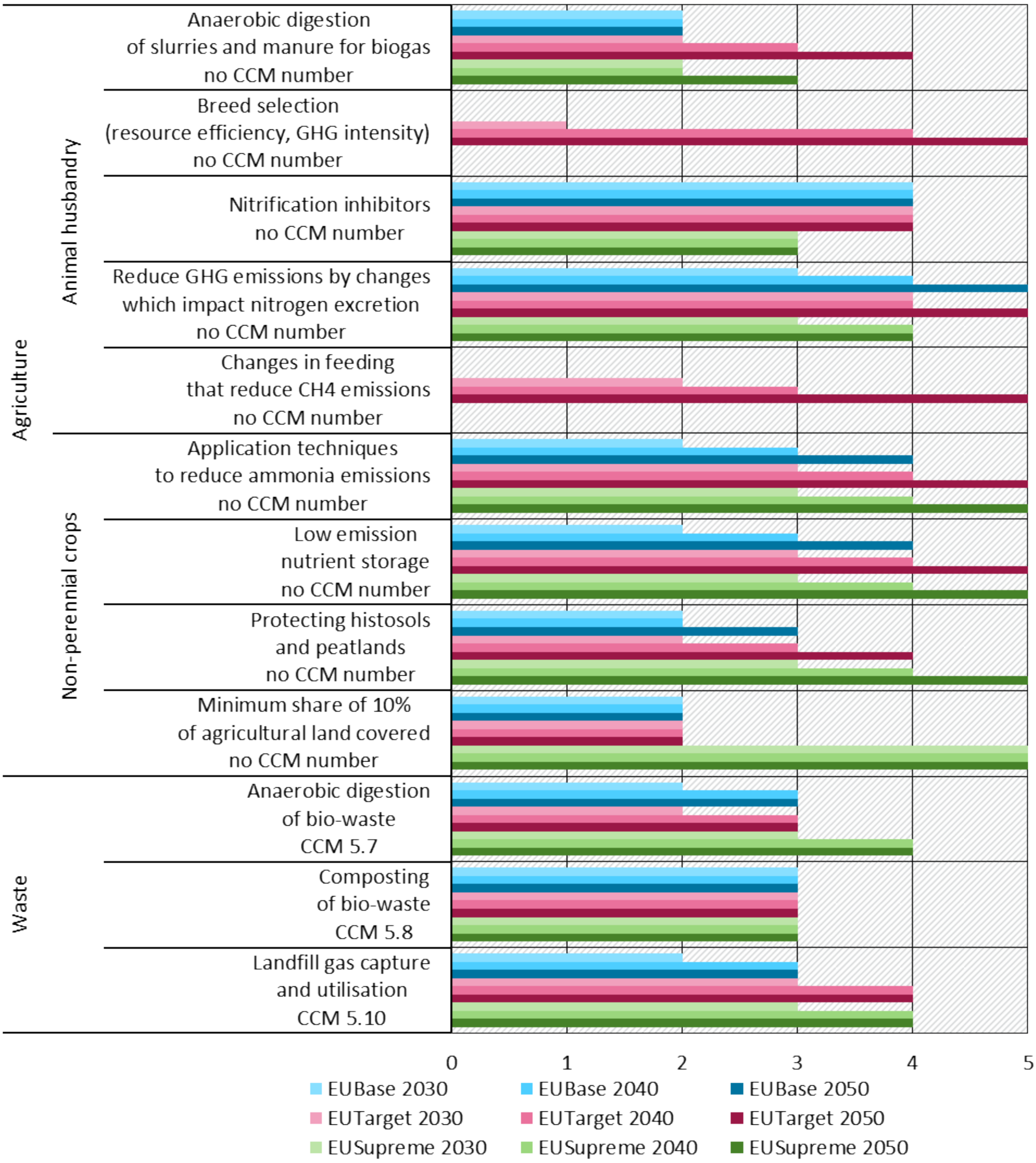
Source: Own elaboration by Fraunhofer ISI

Figure 99: Results of the taxonomy alignment analysis for energy demand sectors



Source: Own elaboration by Fraunhofer ISI

Figure 100: Results of the taxonomy alignment analysis for non-energy sectors



Source: Own elaboration by Fraunhofer ISI

4.3.3 Discussion and conclusions on EU Taxonomy alignment

In summarizing, the two target scenarios reach EU Taxonomy alignment earlier and to a higher degree compared to EUBase. This is the case across most of the sectors where differences appear between the scenarios. As discussed above, there are a few sectors or criteria for which no difference in EU Taxonomy alignment was found.

Between the two target scenarios, EUSupreme reaches an equal or higher EU Taxonomy alignment compared to EUTarget. By design, EUTarget relies more heavily on technical solutions than EUSupreme. In the results of EU Taxonomy alignment this reliance on technical solutions only shows for the two activities of the agricultural sector, which are exclusively considered in this scenario (nitrification inhibitors and changes in feeding to manage methane emissions).

This performance also shows in the last row of the evaluation table, which gives the average value of sectoral averages. The better performance of EUSupreme can be traced back to a few single activities in the agricultural sector[67], faster transformation of primary steel making and improved waste treatment[68] while there are only limited differences in transformation[69] and none in transportation and buildings.

The analysis comes with considerable uncertainties, which are linked to the approach. This is again linked to the mismatch between the criteria covered by the EU Taxonomy and the modeling approach briefly discussed above. Because these reasons are inherent in the models, they cannot be overcome without changes to the models[70].

The research question underlying the analysis is nevertheless of value. By simply reading the technical screening criteria, it becomes apparent that not all of them are currently formulated in a way that by complying with them, the overarching target of climate neutrality is reached. This points to the often-raised concern that the criteria are not fit to define climate neutral activities. In the industry sector, surely an installation complying with the benchmark will not suffice to comply with the target – while standards in transport and other sectors are much stricter. However, it is interesting to better understand under which circumstances actors comply with the EU Taxonomy, where circumstances will be reflected in the scenario definitions such as those underlying the three scenarios of the Pathways project. Whenever actors comply with the EU Taxonomy, this should lead to EU Taxonomy alignment in certain sectors, which in turn should show in the model results. However, this EU Taxonomy alignment is likely not achieved by the policy instrument which the EU Taxonomy is today but is rather the result of the other policy instrument, as is the case in the Pathways project. This is due to the indirect effects of the EU Taxonomy: While the EU Taxonomy is expected to influence the access to finance for climate friendly economic activities, it does not ban other kinds of activities or limit their access to project finance. Other policy instruments therefore currently dominate in terms of effectiveness as long as the information provided by the EU Taxonomy is not picked up by a majority of financial players to channel investments into sustainable activities.

For some sectors, such as industry, energy supply and transport, the key indicators discussed in this report may present a less direct but more complete measure of EU Taxonomy alignment (GHG emissions, renewable energy share or energy carrier). However, the analysis performed in this section gives a quick overview of the evaluation of some criteria, such as is the case for the sectors agriculture and buildings. Together with the overview of the indicators given in Figure 98 to Figure 100 for the other sectors, the results of this analysis provide a good impression of the compatibility of the different scenarios with the target of climate neutrality. Even if EU Taxonomy alignment can only be assessed in some cases due to the technical limitations discussed in detail above, the results present a valuable overview of alignment with the overarching target of climate neutrality.

[67] More agricultural land covered by high diversity landscape features, improved protection of histosols and peatlands; however less changes in feeding and breed selection to reduce nitrogen excretion nd GHG emissions and less anaerobic digestion

[68] Better performance in biowaste treatment

[69] Faster uptake of nuclear energy in EUTarget, faster capacity expansion of green gas grid in EUSupreme

[70] Potentially with the exception of industry by running the model again with higher data granularity, which requires more resources.

5 Summary and outlook

The final report in the project “Pathways to an EU in 2050 with net-zero GHG-emissions” presents the modeling assumptions and results for stylized GHG pathways to the year 2050 for the EU. The three scenarios allow to look at the effect of current policies on the EU’s climate and energy targets (EUBase scenario), a technology- and Member State policies-oriented pathway towards net-zero GHG emissions by 2050 (EUTarget) and a scenario focusing on the role of behavioural options to reach GHG-neutrality by 2050 based on strong sustainability and sufficiency strategies (EUSupreme). This summary and outlook section attempts an interpretation of those results in light of current policies and national as well as EU-wide mitigation strategies.

1. The analysis clearly shows that **current policies are neither in line with the EU’s 2030 targets nor do they allow for reaching net-zero emissions by 2050**. Despite the implementation of ambitious mitigation measures in the transport and energy sector where electrification, use of synthetic fuels and the further increased use of renewable energies result in strong emission reductions, neither the 2030 target for the ETS nor for the ESR is reached. Too slow progress in industry and buildings along with limited action in the agriculture sector are key factors for too high remaining emission levels. In total, about 40% of the energy carriers in 2050 remain non-renewable, with oil and natural gas still having significant shares. Emissions in the agriculture sector only decrease by 11%. Although the LULUCF net-sink increases between 2020 and 2050 by 30% total net emissions of almost 850 Mt CO_2e remain, a reduction of 82% below 1990 levels.
2. In contrast to the above outlined reference scenario (EUBase), the two target scenarios illustrate distinct pathways for reaching GHG-neutrality by 2050. Despite both scenarios reaching this pre-defined target, the analysis shows significant differences in the resulting 2050 energy carriers and GHG balances.
   In the **EUTarget scenario**, technological mitigation options allow to reach almost zero GHG emissions in the supply sector, the transport sector and the buildings sector. In the supply sector, a significant increase in renewable electricity capacities is required to meet the overall energy demand and de-fossilize the sector itself. The remaining fossil CO_2 generated from waste incineration can partly be reduced by the use of CCS. The transport sector shows a clear split: electrification of road transport allows to strongly reduce the use of carbon-containing fuels. In contrast, international transport remains heavily dependent on carbon-containing fuels, which need to be of non-fossil origin by 2050 to reach the GHG target. This results in imports of non-fossil carbon containing fuels, that partly replace today’s fossil fuel imports. Domestic production of non-fossil carbon-containing fuels is not being built-up due to high energy prices in the EU compared to other parts of the world. In the buildings sector, a strong uptake of heat pumps along with high renovation rates and ambitious energy efficiency standards for both renovations and new buildings allow to phase out fossil fuels by 2050. CO_2 generated in the industry sector can partly be reduced by the application of CCS technologies, allowing the industry sector to reach even lower emission levels compared to the EUSupreme scenario despite higher production figures. In the agricultural sector, the limited effectiveness of technological measures becomes apparent**,** resulting in remaining emission levels of close to **300 Mt** CO_{2e} by 2050. Although the LULUCF sink shows a strong increase compared to the EUBase scenario from close to 300 Mt CO_2 to more than 400 Mt CO_2 in 2050, it is not sufficient to reach GHG-neutrality. **Around 30 Mt technical CDR** would be needed in 2050.
3. Behavioral measures and stronger sustainability measures allow for a substantial reduction in GHG emissions in the **EUSupreme scenario**. Lower demand for electricity as well as non-fossil fuels disburdens the renewable energy system (allowing for higher renewable energy

shares in 2050) as well as carbon imports. Despite CCS not being available in industry, the slightly lower production figures due to increased circular economy and recycling assumptions allow for a slight decrease in GHG emissions compared to generated emissions in the EUTarget scenario. Nevertheless, the omission of CCS in industry – a key aspect of the narrative for this scenario - leads to significant gross emission levels from **industry of more than 150 Mt** CO_{2e}. Large differences can be found for the **agriculture sector**. The introduction of strong sufficiency assumptions in diets allows for GHG **emissions in this sector to be almost cut in half in 2050 compared to the EUTarget scenario** (almost 140 Mt CO_2e less). In combination with a further strengthening of the LULUCF sink, which increases to almost 500 Mt CO_2 in 2050, the scenario allows to overfulfill the net-zero GHG emissions target by 2050. **Net emissions in 2050 are consequently around -115 Mt** CO_{2e}.

4. Both target scenarios require strong transformations building on **technology development, technology implementation, infrastructure build up and behavioral changes**. Moreover, interlinkages between the sectors of the economy become stronger: use of electricity for heat pumps, road transport and industry are key pieces for defossilization of those sectors. Pressure on the electricity sector is increasingly high, to provide increasing amounts of electricity from renewable energy sources or – at least – non-fossil sources. Availability of land becomes a relevant factor for electricity generation, agricultural production and development of GHG emission sinks in the LULUCF sector. Circular economy can reduce industry emissions by reducing production, at the same time helping in reducing emissions from waste. Similarly, reduced consumption of protein consumption helps to effectively reduce emissions from the agricultural sector, but also from waste and wastewater. Extensification, possible due to the reduced demand for animal products, allows to reduce nitrogen input into soil, helping to further reduce emissions from land.
5. While the EUBase scenario is strongly based on existing policies and measures or targets defined in MS's NECPs, the target scenarios are mainly built on meeting the 2050 target for GHGs. As the analysis shows, current policies, as implemented in the EUBase scenario, are not in line with meeting the 2030 or 2050 targets. **Strong supporting policies are needed in all sectors** to realize the transformation towards net-zero GHG emissions. Those measures need to address different challenges in the different sectors.
   In **industry**, policies need to drive a complete process shift in primary steel production and need to incentivize fuel switch towards electricity in all major industries including the chemical industry. Further hydrogen needs to be developed. CCS - if politically and socially acceptable – as modelled in the case of EUTarget, can further help to reduce emissions from industry and energy sector and enables technical CDR. Fossil feedstock – not addressed at all with current policies – need to be replaced by non-fossil alternatives such as green naphtha or MTO/MTA production routes. As the EUSupreme scenario shows a systemic change moving away from volume-driven growth toward resource efficiency, circularity and new business models allows for further emission reductions. It allows to reduce pressure and costs in the energy system at the supply side by reducing demand for secondary energy carriers and hydrocarbon feedstocks. However, it requires well-coordinated policies to address different steps in the production and use chain of a product (material efficiency, substitution, reuse, repair, remanufacturing). Ultimately, for the EUSupreme scenario to become fossil free by 2050, a ban on fossil fuels needs to be implemented.
   In the **transport** sector, the implemented quota is found to be an adequate instrument to electrify road transport over time. Due to its size, it dominates the results for the transport sector. However, a complete defossilization of aviation and navigation requires a strengthening of quotas currently defined for those sectors. Ultimately, again a ban on fossil fuels was implemented in 2050. Sufficiency measures as implemented in the EUSupreme scenario help to lower overall energy demand, in particular demand for non-fossil fuels

which play a strong role for the defossilization of international aviation and mitigation. Ultimately that also helps to reduce non-CO_2 effects from aviation, which is a major part of the climate impact from aviation.

For the **buildings** sector, current policies as translated in the EUBase scenario only allow to reach a reduction in GHG emissions of 50% compared to 2020. The two target scenarios in contrast show that complete defossilization of the sector is possible. High energy efficiency gains in combination with a strict and fast phasing out of fossil fuels are the key. Additional behavioral measures allow to lower the pressure on the supply sector, both for district heating as well as for electricity.

The **supply sector** is characterized by an increasing demand for both electricity and hydrogen, the key secondary energy carriers in all scenarios. The effect is particularly pronounced in the EUTarget scenario, while EUBase due to the lower ambition level and EUSupreme due to the additional efficiency and sufficiency measures. Despite strong differences in the demand for electricity, all scenarios manage to reduce emissions from electricity to close to zero by 2050. The decline in coal and gas generation is a critical element in order to reduce GHG emissions in the supply sector across all scenarios. The EUBase scenario reflects a gradual reduction in coal and gas, while the target scenarios demonstrate a more aggressive phase-out. This transition is influenced not only by political measures but also by decreasing costs of renewable energy and rising CO_2 prices, which render fossil fuel generation less economically viable.

In the **agricultural** sector, significant differences exist between all three scenarios. The lack of adequate instruments in place results in limited emission reductions in the EUBase scenario. Livestock numbers see a modest decline, meat and milk production decrease slightly despite the assumption of yield improvements. The EUTarget scenario shows that implementation of technical mitigation measures – assuming conservative effectiveness of measures - has limited effects on GHG emissions: an additional reduction of 50 Mt CO_2e. Significant differences in GHG emissions are found in the EUSupreme scenario, where strong dietary assumptions are included. An alignment of consumption with nutritional recommendations of the Planetary Health Diet allows to more than half the EU's agricultural emissions and at the same time allows for continued export of milk (10% of production). The reduction is achieved by significant reductions in livestock numbers by 67% by 2050 compared to 2020 levels. To realize those dietary changes, strong and robust instruments and an ample supply of attractive plant-based foods are essential.

Similarly to the agricultural sector, the **waste** sector also shows significant differences in scenario design: from compliance (EUBase) to optimization (EUTarget) to transformation (EUSupreme). Effects on GHG emissions are, however, less pronounced. While EUBase achieves a 41% reduction, EUSupreme reaches a reduction of 60% compared to 2020. Hence, a complete systemic change towards circular economy and assuming strong behavioral change allows to generate another 50% reduction compared to current policies. It requires strong waste prevention measures, high recycling rates, a ban on landfilling of untreated biowaste and – in line with assumptions in the agricultural sector – a reduction in protein consumption due to lower consumption of animal products.

Finally, the **LULUCF** sector, the main CDR option in all three scenarios, shows significant differences between scenarios as well. In the EUBase scenario, a slow reduction of emissions, a mere stabilization of the forest sink and relatively small areas available for afforestation and SRC plantations limit the sector's possibility to increase its carbon sink. Nevertheless, the sink increases from -224 Mt in 2020 to -290 Mt in 2050 (+30%). The target scenarios show significantly higher carbon sinks from LULUCF of -420 Mt in 2050 in EUTarget and even -500 Mt in 2050 in EUSupreme. The additional removals in the EUSupreme scenario can be realized with additional land becoming available from the agricultural sector.

However, there are also adverse effects in the EUSupreme scenario: the reduction in wood supply from waste streams leads to more demand for wood from the forest.

6. One relevant aspect here is that the EU ETS1, 2 and the ESR are not implemented as binding quantity-based tools, but via a CO_2-price. This partly reflects the assumption that too high CO_2 prices would not be politically acceptable and would result in political activities that lower the CO_2 prices. Social justice and competitiveness of EU industry are two aspects that are key to policy makers and make such developments likely. The gaps to the binding caps of ETS 1, ETS 2 and ESR can be interpreted as missing additional measures and policy efforts to keep the CO_2 prices at the assumed trajectories.
7. A key factor for the illustrated transformation towards GHG-neutrality – independent of the chosen pathway – is the availability of financial resources. The **EU taxonomy is one central element of EU energy and climate policy** which shall help to provide the much-needed private money for the transformation. Hence, gaining an understanding of the role of the taxonomy for financial flows and its effects on the decarbonization of the economy is essential. The analyses in this project show that the **modeling suite applied for the scenario analysis is not suited to adequately reflect this policy element**. A proper integration into techno-economic models could be a step forward to assessing the speed possible for decarbonization of the economy. However, currently financial flows are not part of most models applied in this context and deriving suitable assumptions to estimate the effects can be tricky.

6 List of references

ACEA (Ed.) (2022). Fuel types of new cars: battery electric 9.1%, hybrid 19.6% and petrol 40.0% market share full-year 2021. Available at https://www.acea.auto/files/20220202_PRPC-fuel_Q4-2021_FINAL.pdf.

ACEA (Ed.) (2023). Fuel types of new cars: battery electric 12.1%, hybrid 22.6% and petrol 36.4% market share full-year 2022. Available at https://www.acea.auto/files/20230201_PRPC-fuel_Q4-2022_FINAL-1.pdf.

ACEA (Ed.) (2024). New car registrations: +13.9% in 2023; battery electric 14.6% market share. Available at https://www.acea.auto/files/Press_release_car_registrations_full_year_2023.pdf.

Agora Agriculture (2024): Agriculture, forestry and food in a climate neutral EU. The land use sectors as part of a sustainable food system and bioeconomy.

Airbus (2024): ZEROe. Towards the world's first hydrogen-powered commercial aircraft. Available at https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe.

Biewald, A. et. al. (2025): Urease- und Nitrifikationsinhibitoren für Klima- und Umweltschutz: Chance oder Risiko? In: Texte, (76).

Copernicus Land Monitoring Service (2018): Impervious Built-up. Available at https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness/status-maps/impervious-built-up-2018, accessed 20.07.2023.

Dahlmann, K., Matthes, S., Plohr, M., Niklaß, M., Scheelhaase, J. D., Wozny, F. (2023): Klimawirkung des Luftverkehrs. Wissenschaftlicher Kenntnisstand, Entwicklungen und Maßnahmen. Dessau-Roßlau: Umweltbundesamt

DENA (2022): E-Kerosene for Commercial Aviation. Study. Available at https://www.dena.de/newsroom/publikationsdetailansicht/pub/studie-e-kerosene-for-commercial-aviation/, accessed 06.11.2023.

Duscha, V.; Wachsmuth, J.; Eckstein, J.; Pfluger, B. (2019): GHG-neutral EU2050 - a scenario fo an EU with net-zero greenhouse gas emissions and its implications. Dessau-Roßlau: Umweltbundesamt

Eckstein, J.; Al-Dabbas, K.; Alexander-Haw, A.; Deac, G.; Duscha, V.; Frank, F.; Böttcher, H.; Hennenberg, K.; Hesse, T.; Ludig, S.; Scheffler, M.; Wiegmann, K. (2025, forthcoming): The EU Taxonomy in modeling. Quantifying the effect of the EU Taxonomy by modeling and an evaluation of scenarios for their EU Taxonomy alignment. UBA.

EEA (Ed.) (2022): Annual European Union greenhouse gas inventory 1990–2020 and inventory report 2022. Submission to the UNFCCC Secretariat. Available at Online available at https://unfccc.int/documents/461931.

European Commission: Global Human Settlement. Available at https://ghsl.jrc.ec.europa.eu/download.php?ds=bu, accessed 21.07.2023.

European Commission (2016): EU reference scenario 2016. Energy, transport and GHG emissions: trends to 2050. Luxembourg: Publications Office. https://doi.org/10.2833/9127.

European Commission (Ed.) (2020): Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 (Text with EEA relevance). Taxonomy Regulation. Available at https://eur-lex.europa.eu/eli/reg/2020/852/oj.

European Commission (2022): Overview of existing EU Ecodesign, Energy Labelling and Tyre Labelling measures. Brussels.

European Commission (2024): EU transport in figures – Statistical pocketbook 2024. Publications Office of the European Union. https://doi.org/10.2832/16593.

European Commission: Directorate-General for Agriculture and Rural Development (2021): EU agricultural outlook for markets, income and environment 2021-2031. https://doi.org/10.2762/753688.

European Commission: Directorate-General for Climate Action, Fraunhofer ISI, ICF, Herbst, A., Langkau, S. et al. (2024): Role of the circular economy as a contributor to industry decarbonization beyond 2030 Final report. https://doi.org/10.2834/261758.

European Environment Agency (2023a): Trends and projections in Europe 2023.

European Environment Agency (2023b): Waterbase - UWWTD: Urban Waste Water Treatment Directive – reported data. Available at https://www.eea.europa.eu/en/datahub/datahubitem-view/6244937d-1c2c-47f5-bdf1-33ca01ff1715, accessed 16.05.2024.

European Environment Agency (2024): Greenhouse gas emissions under the EU Emissions Trading System.

Eurostat (2021): Applying the Degree of Urbanisation.

Eurostat (2023a): Food waste and food waste prevention by NACE Rev. 2 activity - tonnes of fresh mass. [env_wasfw]. Available at https://ec.europa.eu/eurostat/databrowser/view/env_wasfw/default/table?lang=en, accessed 16.05.2024.

Eurostat (2023b): Treatment of waste by waste category, hazardousness and waste management operations. Available at https://ec.europa.eu/eurostat/databrowser/view/env_wastrt/default/table?lang=en, accessed 16.05.2024.

Eurostat (2024a): Complete energy balances. https://doi.org/10.2908/NRG_BAL_C.

Eurostat (2024b): Municipal waste by waste management operations. Available at https://ec.europa.eu/eurostat/databrowser/view/env_wasmun/default/table, accessed 16.05.2024.

Fleiter, T.; Rehfeldt, M.; Herbst, A.; Elsland, R.; Klingler, A.-L.; Manz, P.; Eideloth, S. (2018): A methodology for bottom-up modeling of energy transitions in the industry sector. The FORECAST model. In: Energy Strategy Reviews, (22), pp. 237–254. https://doi.org/10.1016/j.esr.2018.09.005.

Förster, H.; Repenning, J.; Braungardt, S.; Bürger, V.; Görz, W. K.; Harthan, R.; Hermann, H.; Jörß, W.; Kasten, P.; Ludig, S.; Matthes, F. C.; Mendelevitch, R.; Scheffler, M.; Bei der Wieden, M.; Wiegmann, K.; Blömer, R.; Brugger, H.; Eckstein, J.; Fleiter, T.; Fritz, M.; Krail, M.; Mandel, T.; Rehfeldt, M.; Lütz, L.; Rohde, C.; Deurer, J.; Steinbach, J.; Osterburg, B.; Rieger, J.; Rock, J.; Kemmler, A.; Kreidelmeyer, S.; Thamling, N.; Schade, W.; Haug, I.; Streif, M.; Walther, C.; Gocht, A.; Stepanyan, D. (2024): Instrumente für die Treibhausgas-Projektionen 2025. Dessau-Roßlau: Öko-Institut; Fraunhofer ISI; IREES; Thünen-Institut; Prognos; M-Five. https://doi.org/10.60810/openumwelt-7632.

Frank, F.; Gnann, T. (2022): Alternative Antriebe im Schienenverkehr. https://doi.org/10.24406/publica-fhg-416708.

Gnann, T.; Speth, D.; Krail, M.; Wietschel, M. (2024): Langfristszenarien für die Transformation des Energiesystems in Deutschland 3. T45-Szenarien. Modul Verkehr. Karlsruhe. Available at https://langfristszenarien.de/enertile-explorer-wAssets/docs/LFS3_Langbericht_Verkehr_final.pdf.

Gnann, T.; Wietschel, M.; Kühn, A.; Thielmann, A.; Sauer, A.; Plötz, P.; Moll, C.; Stütz, S.; Schellert, M.; Rüdiger, D.; Waßmuth, V.; Paufler-Mann, D. (2017): Brennstoffzellen-LKW: kritische Entwicklungshemmnisse, Forschungsbedar und Marktpotential. Studie im Rahmen der wissenschaftlichen Beratung des MBVI zur Mobilitäts- und Kraftstoffstrategie der Bodesregierung. Fraunhofer ISI Karlsruhe, Fraunhofer IML Dortmund, PTV Transport Consulat GmbH.

Gschrey, Barbara, Behringer, David, Kleinschmidt, Jlia; Jörß, W.; Liste, V.; Ludig, S.; Wissner, N.; Birchby, D.; Dubey, J.; Hekman, J. (2022): Support contract for an Evaluation and Impact Assessment for amending Regulation (EU) No 517/2014 on fluorinated greenhouse gases. Impact Assessment Final Report.

Höck, A.; Klein, C.; Landau, A.; Zwergel, B. (2020): The effect of environmental sustainability on credit risk. In: Journal of Asset Management, 21 (2), pp. 85–93. https://doi.org/10.1057/s41260-020-00155-4.

Intergovernmental Panel on Climate Change (2006a): 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste. Available at https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html, accessed 04.06.2025.

IPCC (2006b): Guidelines for National Greenhouse Gas Inventories. Volume 4 Agriculture, Forestry and Other Land Use. Available at https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html, accessed 22.11.2021.

Jochum, P. et. al. (2017): Ableitung eines Korridors für den Ausbau der erneuerbaren Wärme im Gebäudebereich. Anlagenpotenzial. Endbericht.

Kluschke, P.; Gnann, T.; Plötz, P.; Wietschel, M. (2019): Market diffusion of alternative fuels and powertrains in heavy-duty vehicles: A literature review. In: Energy Reports, 5, pp. 1010–1024.

Kölbel, J. F.; Heeb, F.; Paetzold, F.; Busch, T. (2020): Can Sustainable Investing Save the World? Reviewing the Mechanisms of Investor Impact. In: Organization & Environment, 33 (4), pp. 554–574. https://doi.org/10.1177/1086026620919202.

Krail, M.; Hellekes, J.; Schneider, U.; Dütschke, E.; Schellert, M.; Rüdiger, D.; Steindl, A.; Luchmann, I.; Waßmuth, V.; Flämig, H.; Schade, W.; Mader, S. (2019): Energie- und Treibhausgaswirkungen des automatisierten und vernetzten Fahrens im Straßenverkehr. https://doi.org/10.24406/publica-fhg-299467.

Kranzl, Lukas; Forthuber, Sebastian; Fallahnejad, Mostafa; Büchele, Richard; Müller, Andreas; Hummel, Marcus et al. (2022): ENER/C1/2018-494 - Renewable Space Heating under the Revised Renewable Energy Directive. Final report.

Kuhla, B. (2025): Wirksamkeit und Kontrolle der Methanminderung nach Fütterung von 3-Nitrooxypropanol an Milchkühe. Vortrag im Rahmen der Webinar Serie: Agrarforschungzum Klimawandel. Available at https://www.dafa.de/wp-content/uploads/DAFA-Webinar-THG-Bilanzierung-20250515-Kuhla.pdf.

Lotz, M. T.; Al-Dabbas, K.; Rehfeldt, M.; Herbst, A.; Fleiter, T.; Worrell, E. (2025): Quantifying the impact of a circular economy in buildings on industry decarbonization: Integrating material flow and industry modeling. In: Resources, Conservation and Recycling, 219, p. 108306. https://doi.org/10.1016/j.resconrec.2025.108306.

Lotz, M. T.; Herbst, A.; Müller, A.; Kranzl, L.; Rosales Carreon, J.; Worrell, E. (2024a): A material flow model of steel and concrete in EU buildings: National differences of the service-stock-flow nexus. In: Cleaner Waste Systems, 8, p. 100153. https://doi.org/10.1016/j.clwas.2024.100153.

Lotz, M. T.; Rosales Carreón, J.; Worrell, E.; Herbst, A.; Kochański, M.; Korczak, K. (2024b): Estimating the impact range of circular economy actions for buildings on basic material demand in the European Union: A combination of qualitative and quantitative approaches. In: Sustainable Production and Consumption, 51, pp. 532–544. https://doi.org/10.1016/j.spc.2024.10.002.

Lütkehermöller, K.; Mooldijk, S.; Roelfsema, M.; Höhne, N.; Kuramochi, T. (2020): Unpacking the finance sector's climate-related investment commitments. NewClimate Institute. Available at https://newclimate.org/sites/default/files/2020/09/NewClimate_Unpacking_Finance_Sector_Sept20.pdf, accessed 30.06.2025.

Müller, A.; Hummel, M.; Kranzl, L., Fallahnejad, M. and Büchele, R. (2019): Open-source data for gross floor area and heat demand density on the hectare level for EU 28. In: Energies, 12 (24). https://doi.org/10.3390/en12244789.

Münzel, C.; Plötz, P.; Sprei, F.; Gnann, T. (2019): How large is the effect of financial incentives on electric vehicle sales? – A global review and European analysis. In: Energy Economics, 84, p. 104493. https://doi.org/10.1016/j.eneco.2019.104493.

NOW (2023): FuelEU Maritime Regulation – How does it affect the maritime sector? Available at https://www.now-gmbh.de/wp-content/uploads/2023/10/NOW_Factsheet_FuelEuMaritime_Oktober-2023.pdf.

Pérez Domínguez, I., Fellmann, T., Witzke, P., Weiss, F., Hristov, J. et al. (2020): Economic assessment of GHG mitigation policy options for EU agriculture – A closer look at mitigation options and regional mitigation costs - EcAMPA 3. Luxembourg. https://doi.org/10.2760/4668.

Plötz, P.; Gnann, T.; Kühn, A.; Wietschel, M. (2013): Markthochlaufszenarien für Elektrofahrzeuge. https://doi.org/10.24406/publica-fhg-296519.

Plötz, P.; Gnann, T.; Wietschel, M. (2014): Modeling market diffusion of electric vehicles with real world driving data — Part I: Model structure and validation. In: Ecological Economics, 107, pp. 411–421. https://doi.org/10.1016/j.ecolecon.2014.09.021.

Rehfeldt, M.; Fleiter, T.; Herbst, A.; Eidelloth, S. (2020): Fuel switching as an option for medium-term emission reduction - A model-based analysis of reactions to price signals and regulatory action in Germanys. In: Energy Policy, 147. https://doi.org/10.1016/j.enpol.2020.111889.

Research Data Centre of the Federal Statistical Office and the Research Data Centre of the Statistical Offices of the Federal States (2021): Building: Heating Type. Survey.

Rohde, C.; Arnold-Keifer, S.; Hirzel, S.; Schlomann, B.; Brugger, H.; Reinfandt, N. (2022): Erhebung des Endenergieverbrauchs im Sektor Gewerbe, Handel, Dienstleistungen (GHD). Endbericht mit Sonderauswertung Digitalisierung. Karlsruhe.

Rostek, L.; Lotz, M. T.; Wittig, S.; Herbst, A.; Loibl, A.; Tercero Espinoza, L. (2022): A dynamic material flow model for the European steel cycle. Karlsruhe.

Rozsai, M.; Jaxa-Rozen, M.; Salvucci, R.; Sikora, P.; Tattini, J.; Neuwahl, F. (2024): JRC-IDEES-2021. European Commission, Joint Research Centre (JRC) [Dataset]. Available at http://data.europa.eu/89h/82322924-506a-4c9a-8532-2bdd30d69bf5.

SYSTEMIQ (2022): ReShaping Plastics: Pathways to a Circular, Climate Neutral Plastics System in Europe. ReShaping Plastics. Available at https://plasticseurope.org/wp-content/uploads/2022/04/SYSTEMIQ-ReShapingPlastics-April2022.pdf.

Timmerberg, S.; Bullerdiek, N.; Kaltschmitt, M.; Gnann, T.; Neumann, F.; Wietschel, M. (2018). Import von Stromkraftstoffen für den Verkehr - Lkw, Binnen-/Seeschiffe, Flugzeuge. Studie im Rahmen der wissenschaftlichen Beratung des BMVI zur Mobilitäts- und Kraftstoffstrategie. Unveröffentlichte Studie, Karlsruhe.

Truckscout24 (2016): Verkaufsportal für gebrauchte Nutzfahrzeuge. Available at http://www.truckscout24.de, accessed 13.02.2017.

UBA (2022): Rahmendaten für den Projektionsbericht 2023. Stand: 20. Dezember 2022. Available at https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/factsheet_rahmendaten_fuer_den_projektionsbericht_2023_fuer_deutschland.pdf

UNFCCC (2022): National Inventory Submissions 2022. Available at https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/submissions/national-inventory-submissions-2022, accessed 16.05.2024.

Wermuth, M. (2012): Kraftfahrzeugverkehr in Deutschland 2010 (KiD 2010).

Wietschel, M.; Gnann, T.; Kühn, A.; Plötz, P.; Moll, C.; Speth, D.; Buch, J.; Boßmann, T.; Stütz, S.; Schellert, M.; Rüdiger, D.; Balz, W.; Frik, H.; Waßmuth, V.; Paufler-Mann, D.; Rödl, A.; Schade, W.; Mader, S. (2017):

Machbarkeitsstudie zur Ermittlung des Potentials des Hybrid-Oberleitungs-LKW. Studie im Rahmen der wissenschaftlichen Beratung des BMVI zur Mobilitäts- und Kraftstoffstrategie.

Willett, W. et al. (2019): Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. In: Lancet (London, England), 393 (10170), pp. 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Xavier Le Den et al. (2020): Quantification methodology for, and analysis of, the decarbonization benefits of sectoral circular economy actions: Final Report on behalf of the EEA.

A Modeling details

A.1 Role of prices in the different sector models

A.1.1 Energy carrier prices

Table 37: Sectors and how energy prices are being used in the modeling

Sector	Role of energy carrier price in the model	What prices do you use? (end-consumer/global market/with taxes and levies/large consumer prices/etc.)	What is your data source? By which method and data do you derive the values the model uses in the end in the different countries?
Appliances	Investment decisions for efficient equipment as function of total cost of ownership and thus consumer prices	Household consumer prices for average load band incl. all relevant taxes and charges	For electricity & gas: prices based on Eurostat [NRG_PC_204_C; NRG_PC_202_C]. Constant taxes and network charges; supply component scaled based on wholesale trend
Tertiary	Investment decisions for efficient equipment as function of total cost of ownership and thus consumer prices	Non-household consumer prices for average load band incl. all relevant taxes and charges	For electricity & gas: prices based on Eurostat [NRG_PC_205_C; NRG_PC_203_C]. Constant taxes and network charges; supply component scaled based on wholesale trend. Other fuels: dedicated assumptions needed
Transport	Energy prices for Germany are one element in the TCO to determine investment decisions in trucks. Furthermore, the ratio of electricity and diesel price is used to calculate the slope of market diffusion curves for electric passenger cars in EU27+UK.	As they determine the investment decision of the user, end prices finally go into the model (incl. Taxes etc.)	**Fuel prices Europe**: Eurostat-Oil Bulletin Prices History: https://ec.europa.eu/energy/data-analysis/weekly-oil-bulletin_en **Electricity prices Europe for households**: Statistics | Eurostat (europa.eu) **Energy carrier prices ALADIN DE**: https://www.bdew.de/media/documents/190723_BDEW-Gaspreisanalyse_Juli-2019.pdf https://www.bdew.de/media/documents/190723_BDEW-Strompreisanalyse_Juli-2019.pdf MVV.de
Buildings	None at	None	n/a
Industry	Energy prices are one element in the TCO to determine investment decisions in process, heating technologies like for example, electric boilers or gas-based CHP. They also influence the	Average industry consumer prices incl. all relevant taxes and levies.	Eurostat for electricity and gas.

Sector	Role of energy carrier price in the model	What prices do you use? (end-consumer/global market/with taxes and levies/large consumer prices/etc.)	What is your data source? By which method and data do you derive the values the model uses in the end in the different countries?
	diffusion speed of energy-efficiency measures and fuel switching in existing installations.		
Enertile	Invest and Dispatch decisions in power and district heat generation	Global market prices	EU Ref 2020

A.2 CO_2 prices

Table 38: Sectors and how CO_2 prices are being used in the modeling

Sector model	Role of CO_2 price in the model	CO_2 price used in the model
Industry (Forecast)	CO_2 prices are one element in the TCO to determine investment decisions in process heating technologies, e.g. for electric boilers or gas-based CHP.	The EU ETS price is used. Can distinguish between EU ETS and non-ETS CO_2 prices based on sectors or processes Can include foresight on future CO_2 price or myopic investment decisions with today's CO_2 price
Transport (ALADIN)	CO_2 prices are one element in the TCO to determine investment decisions for trucks.	EU-ETS2 CO_2 price acc. to Table B.1 is used, reflecting the implementation of CO_2 pricing that includes road transport.
Energy supply (Enertile)	CO_2 prices are one element to determine invest and dispatch decisions in power and district heat generation.	The EU ETS price is used.

A.3 NIR emissions coverage of modeling suite

Table 39: GHG emissions according to NIR 2020 (submission 2022) and modelled 2020 GHG emissions

Category	NIR 2020	Modeling 2020	Difference (% of NIR)	Comments
Industry - energy-related	445.0	421.0	24.0 (5%)	Model calibrated to 2019 inventory data due to special effects in the year 2020

Category	**NIR 2020**	**Modeling 2020**	**Difference** (% of NIR)	**Comments**
Industry - process-related	239.1	228.9	10.2 (4%)	Model calibrated to 2019 inventory data due to special effects in the year 2020
Industry CCS	---	0	0	
Product uses (2.D-H)	109.1	97.2	11.8 (11%)	
Transport	1,019.6	1,004.0	15.6 (2%)	Calibrated to NIR 2019
Buildings	600.0	600.6	-0.6 (0%)	Calibrated to NIR
Supply	856.8	821.1	35.7 (4%)	No calibration possible
Agriculture	422.8	388.2	34.6 (8%)	Calibrated on 2023 submission
LULUCF	-225.9	-224.1	1.8 (-1%)	
Waste	130.0	123.5	6.5 (5%)	
Total exc. fugitive emissions	3,596.5	3,460.4	136.1 (4%)	
Fugitive emissions	70.1	---	70.1 (--)	No coverage
Total	3,666.6	3,460.4	206.2 (4%)	

B Table of modeling assumptions

B.1 General modeling assumptions

Table 40: Macroeconomic drivers and prices

Variable	Year	EU Pathways Base Scenario (EUBase)	Sources	EU Pathways Target Scenario (EUTarget)	Sources	EU Pathways Supreme Scenario (EUSupreme)	Sources
GDP [bn€15]	2020	12.272	Ref 2020	As EUBase		As EUBase	
	2030	14.814	Ref 2020	As EUBase		As EUBase	
	2040	16.898	Ref 2020	As EUBase		As EUBase	
	2050	19.466	Ref 2020	As EUBase		As EUBase	
Population [m]	2020	447.67	Ref 2020	As EUBase		As EUBase	
	2030	449.12	Ref 2020	As EUBase		As EUBase	
	2040	446.75	Ref 2020	As EUBase		As EUBase	
	2050	441.22	Ref 2020	As EUBase		As EUBase	
CO_2 price EU ETS 1 [€15 per t]	2020	24.7	Projektionsbericht 2023 (UBA 2022)	24.7	Projektionsbericht 2023 (UBA 2022)	24.7	CARE[71]
	2030	108.8	Projektionsbericht 2023 (UBA 2022)	110	Determined via iterative model runs	120	CARE

[71] CARE is a project financed by UBA, which builds around different scenarios for a GHG-neutral Germany and includes a CARESupreme scenario. We use initial assumptions from the CARE project, CARESupreme scenario, (from 2022) for CO_2 prices in our EUSupreme scenario.

Variable	Year	EU Pathways Base Scenario (EUBase)	Sources	EU Pathways Target Scenario (EUTarget)	Sources	EU Pathways Supreme Scenario (EUSupreme)	Sources
	2040	141.3	Projektionsbericht 2023 (UBA 2022)	340	Determined via iterative model runs	220	CARE
	2050	161.1	Projektionsbericht 2023 (UBA 2022)	390	Determined via iterative model runs	320	CARE
CO_2 price EU ETS 2[€15 per t]	2020	---	Projektionsbericht 2023 (UBA 2022)	---		----	CARE
	2030	95	Projektionsbericht 2023 (UBA 2022)	300	Determined via iterative model runs	220	CARE
	2040	171	Projektionsbericht 2023 (UBA 2022)	340	Determined via iterative model runs	270	CARE
	2050	216	Projektionsbericht 2023 (UBA 2022)	500	Determined via iterative model runs	320	CARE
Int. oil price [€15 per MWh]	2020	22.0	Projektionsbericht 2023 (UBA 2022)	As EUBase		22.0	WEO22 NZE
	2030	27.5	Projektionsbericht 2023 (UBA 2022)	As EUBase		16.9	WEO22 NZE
	2040	26.8	Projektionsbericht 2023 (UBA 2022)	As EUBase		14.2	WEO22 NZE
	2050	25.8	Projektionsbericht 2023 (UBA 2022)	As EUBase		11.6	WEO22 NZE

Variable	Year	EU Pathways Base Scenario (EUBase)	Sources	EU Pathways Target Scenario (EUTarget)	Sources	EU Pathways Supreme Scenario (EUSupreme)	Sources
Int. gas price [€15 per MWh]	2020	12.7	Projektionsbericht 2023 (UBA 2022)	As EUBase		12.7	WEO22 NZE
	2030	23.0	Projektionsbericht 2023 (UBA 2022)	As EUBase		12.3	WEO22 NZE
	2040	20.6	Projektionsbericht 2023 (UBA 2022)	As EUBase		11.2	WEO22 NZE
	2050	18.2	Projektionsbericht 2023 (UBA 2022)	As EUBase		10.2	WEO22 NZE
Int. coal price [€15 per MWh]	2020	6.9	Projektionsbericht 2023 (UBA 2022)	As EUBase		6.9	WEO22 NZE
	2030	10.6	Projektionsbericht 2023 (UBA 2022)	As EUBase		5.0	WEO22 NZE
	2040	9.6	Projektionsbericht 2023 (UBA 2022)	As EUBase		4.5	WEO22 NZE
	2050	8.9	Projektionsbericht 2023 (UBA 2022)	As EUBase		4.0	WEO22 NZE
Hydrogen price [€19 per MWh]	2020	207.7	Projektionsbericht 2023 (UBA 2022)	As EUBase		207.7	Own assumptions based on scenario narrative
	2030	100.3	Projektionsbericht 2023 (UBA 2022)	As EUBase		95.3	Own assumptions based on scenario narrative

Variable	Year	EU Pathways Base Scenario (EUBase)	Sources	EU Pathways Target Scenario (EUTarget)	Sources	EU Pathways Supreme Scenario (EUSupreme)	Sources
	2040	82.4	Projektionsbericht 2023 (UBA 2022)	As EUBase		74.4	Own assumptions based on scenario narrative
	2050	64.5	Projektionsbericht 2023 (UBA 2022)	As EUBase		55.3	Own assumptions based on scenario narrative

B.2 Sector-specific modeling assumptions – an overview

Table 41: Sector-specific key assumptions

	EUBase	EUTarget	EUSupreme
Industry general			
average annual growth rate in gross value added	1.6% p.a. until 2030, 0.8% p.a. from 2031-2050 Higher growth in equipment goods industry compared to energy-intensive basic industry; moderate decoupling of physical production from GVA in the long-run	As EUBase	Faster decoupling between economic growth and physical production; delivery of resource-efficient, longer-lasting solutions, optimized processes to minimize resource input, supported by enhanced recycling and reuse of materials; shift to service-oriented models such as repair, reuse and remanufacturing
CCS	Limited uptake of CCS in cement and lime industry until 2030 based on already planned and started projects	Uptake of CCS in cement and lime industry	No use of CCS in industry
Iron & Steel			

	EUBase	EUTarget	EUSupreme
production [Mt p.a., 2020/ 2030/ 2040/ 2050]	BOF: 82/70/68/53 EAF: 57/67/67/67 H_2-DRI: 0/20/21/33	BOF: 82/69/49/0 EAF: 57/66/68/69 H_2-DRI: 0/22/40/83	BOF: 82/70/0/0 EAF: 57/67/73/76 H_2-DRI: 0/20/64/46
material efficiency	More efficient steel use and substitution result in decreasing production by about 8% (13 Mt) in 2050 compared to 2015	More efficient steel use and substitution result in decreasing production by about 14% (23 Mt) in 2050 compared to 2015	Further increase in material efficiency reaching a reduction of 27% (45 Mt) in 2050 compared to 2015
circular economy	Increased secondary steel share from 39% (65 Mt) by 2015 to 44% (67 Mt) by 2050	Increased secondary steel share from 39% (65 Mt) by 2015 to 45% (69 Mt) by 2050	Further increase in secondary steel share by 10% to 76 Mt (63%) by 2050
process switch	19,5 Mt direct reduction route by 2030 and 33 Mt by 2050	Full replacement of BOF production route by 2050	Full replacement of BOF production route by 2040
(Petro-)chemical industry			
Production [Mt p.a., 2020/ 2030/ 2040/ 2050]	Conv steam cracker: 23/23/19/17 MTO: 0/0/0/0 Elect. Steam cracker: 0/0/4/4	Conv steam cracker: 23/22/12/0 MTO: 0/0/5/11 Elect. Steam cracker: 0/0/5/11	Conv steam cracker: 23/21/6/0 MTO: 0/1/8/9 Elect. Steam cracker: 0/1/7/9
Material efficiency	Slow increase in plastic recycling	Slow increase in plastic recycling	Ambitious increase in plastics recycling along entire value chain and new consumption models; reduces demand for feedstocks by 15% by 2050 compared to 2015
Process switch Ammonia	33% feedstock H_2 for ammonia in 2050	100% feedstock H_2 for ammonia in 2050	100% feedstock H_2 for ammonia in 2050
Process switch HVC	20% electrical steam cracker with synthetic naphtha, no switch to methanol-to-olefins/methanol-to-aromatics (MtO/MtA) in 2050	50% electrical steam cracker with synthetic naphtha, 50% MtO/MtA in 2050	50% electrical steam cracker with synthetic naphtha, 50% MtO/MtA in 2050
Primary feedstock	Fossil-based and 20% imported green Naphtha	Synthetic Naphtha + H_2 + CO_2 (CCUS and DACCS)	Synthetic Naphtha + H_2 + CO_2 + plastic waste
Feedstock availability	Crude oil imports	Import	Import

	EUBase	EUTarget	EUSupreme
Non-metallic minerals			
Production [Mt p.a., 2020/ 2030/ 2040/ 2050]	Clinker, primary: 184/202/207/205 Clinke, secondary: 0/0/0/0	Clinker, primary: 184/202/207/205 Clinker, secondary: 0/0/0/0	Clinker, primary: 184/196/185/166 Clinker, secondary: 0/0/12/21
Material efficiency	18% increase in total cement production by 2050 compared to 2018	18% increase in total cement production by 2050 compared to 2018	9% lower primary cement production in 2050 compared to EUBase and EUTarget
Clinker factor [%, 2020/ 2030/ 2040/ 2050]	76/75/73/71	76/75/73/71	76/76/72/67
Process switch	No low-carbon types of cement	No low-carbon types of cement	Low-carbon types of cement substitute around 10% by 2050
CCUS	CO_2 capture at limited sites,	CO_2 capture at most cement and lime plants by 2050	No CCS
Transport			
Cars	Continuous electrification - growth of PEV market shares in car registrations endogenously determined in model	Complete electrification of stock until 2050 via electric vehicle diffusion: Until 2034: PEV market shares endogenously determined in model From 2035: 100% BEV registrations	Electrification as in EUTarget 25% reduction in car stock and thus 25% reduction in total driving performance, compared to EUBase/EUTarget
Trucks	Technology costs: €70/kW fuel cell costs in 2050 €80/kW battery costs in 2050 Energy carrier prices and EU-ETS2 CO_2 prices acc. to Table B.1	Lower technology costs compared to EUBase: €55/kW fuel cell costs €70/kWh battery costs Energy carrier prices acc. to Table B.1 Higher EU-ETS2 CO_2 price, reaching €500 in 2050	Energy carrier prices and EU-ETS2 CO_2 prices acc. to Table B.1 Reduction in development of truck stocks until 2050 compared to EUBase/EUTarget scenarios depending on truck size: light-duty: -11% medium-duty: 0% heavy-duty: -21%

	EUBase	EUTarget	EUSupreme
Rail	Electrification of 80% of non-electrified routes until 2050 (via track electrification or battery electric trains)	Full electrification until 2050 (via track electrification or battery electric trains)	Electrification as in EUTarget Additional increase of freight and passenger rail transport performance
Aviation	Increasing shares of non-fossil jet fuel: Domestic: 100% H2 reached in 2050 International: 70% non-fossil fuel reached in 2050	Complete phase-out of fossil aviation fuel until 2050 Domestic: 100% H2 reached in 2050 International: 100% e-kerosene reached in 2050	Complete phase-out of fossil fuel as in EUTarget Decreasing transport performances: Domestic: –50% between 2019 and 2050 International flights: -10% between 2019 and 2050
Navigation	Increasing shares of non-fossil fuels: 75% e-fuel until 2050	Complete phase-out of fossil fuel until 2050: Domestic: 70% e-fuel, 30% H2 reached in 2050 International: 100% e-fuel reached in 2050	Complete phase-out of fossil fuel as in EUTarget Decreasing international transport performance: -10% between 2020 and 2050 Increasing domestic transport performance: +20% between 2020 and 2050.
Buildings			
Space Heating and Cooling:			
Demolition rate	Increasing demolition rates starting with 0.2-0.4% per year in the 2020s and rising linearly to 0.5-1.0% per year by 2050 (lower values are for residential buildings, higher values for non-residential buildings)	Slightly steeper rise in demolition rates reaching 0.6-1.3% per year by 2050	Same as EUTarget scenario
New construction rate	Linear regression depending on change in population (RES) or GDP (NRES)	same as EUBase scenario	New construction rate reduced by 25%

	EUBase	EUTarget	EUSupreme
New construction standard	Constant at 60 kWh/(m²a)	Starting with an average of 60 kWh/(m²a) in the 2020s, linearly decreasing to 15 kWh/(m²a) by 2040	Same as EUTarget scenario
Renovation rate	Starting with 0.8-1.1% per year in the 2020s, reaching 1.2-2.3% per year by 2050	Starting with 1.0-1.4% per year in the 2020s, reaching 2.75% per year by 2050	Starting with 1.2-1.7% per year in the 2020s, reaching 3.0% per year by 2050
Renovation standard	Constant at 80 kWh/(m²a)	Starting with an average of 80 kWh/(m²a) in the 2020s, linearly decreasing to 30 kWh/(m²a) by 2050	Same as EUTarget scenario
Energy carriers	Distribution per country for the latest available year (2017) and linear change to country cluster averages by 2050	Faster shift away from gas and oil in particular compared to EUBase; heat pumps as main beneficiary; fossil fuels completely phased out by 2050	Same as EUTarget, but even faster shift away from fossil energy carriers and more restrictive use of biomass: linear reduction to zero in 2050
Sufficiency	No assumptions regarding sufficiency	Same as EUBase	Lower per capita floor area: minus 2 m² per person per decade starting in 2030
Appliances and processes			
Energy efficiency of appliances and processes	Business-as-usual (see xxx)	2020: Default 2030: Remove +1 worst performing class 2040: Remove +1 worst performing classes	2020: Default 2030: Remove +1 worst performing class 2040: Remove +2 worst performing classes
Electrification	Business-as-usual trends	From 2040: All new processes/appliances are electricity-based	From 2030: All new processes/appliances are electricity-based
Usage intensity	Business-as-usual trends	Business-as-usual trends	From 2025 to 2050: Gradual reduction of 10% for ICT (e.g. TVs); 20% for non-essential large appliances (e.g. dryers)
Product lifetime	Business-as-usual trends	Business-as-usual trends	Increase in average product lifetime by 20% from 2030 to 2050
Ownership rate	Business-as-usual trends	Business-as-usual trends	No increase in the rate of ownership, e.g. households continue to have an average of 1.1 washing machines per household, but no more.

	EUBase	EUTarget	EUSupreme
LULUCF			
Reduction of deforestation emissions	Stabilizing annual emissions reported in 2020	Reducing 50% of annual emissions reported in 2020	Reducing 75% of annual emissions reported in 2020
Afforestation	Increase forest area through new forest plantations by 1%, i.e. 1.6 Mha by 2050 compared to 2020	Increase forest area through new forest plantations by 5%, i.e. 7 Mha by 2050 compared to 2020	Increase forest area through new forest plantations by 6%, i.e. 10 Mha by 2050 compared to 2020
Increase carbon stocks in existing forest	Maintain the forest sink compared to 2020 by stabilizing the harvest rate at about 70% of increment	Increasing the forest sink compared to 2020 by reducing the harvest rate to about 67% of increment	Increasing the forest sink compared to 2020 by reducing the harvest rate to about 67% of increment (same EUTarget)
Increase the share of longer-living wood products and increased cascade use of wood	Measures to stabilize HWP pool	Measures to stabilize HWP pool despite decreased harvest rate, e.g. by increasing lifespan of products/carbon stored in products	Increase residence time of carbon in HWP by 25%, increase share of long-living products
Rewetting of organic soils	Rewetting of 20% of cropland, 33% of grassland and 30% of forests on organic soils to wetlands by 2050	Rewetting of 50% of cropland, 60% of grassland and 30% of forests on organic soils to wetlands by 2050	Rewetting of 67% of cropland, 78% of grassland and 70% of forests on organic soils to wetlands by 2050
Reduction of grassland conversion	Reduction of grassland conversion to zero	Same as EUBase	Same as EUBase
Short rotation coppice and agroforestry	Establish 0.3 Mha of coppice/agroforestry area	Establish 6.9 Mha of coppice/agroforestry area	Establish 13.6 Mha of coppice/agroforestry area
Reduction of emissions from peat extraction	Peat extraction is reduced until 2050 by 50% compared to 2020	A peat extraction ban is implemented until 2050	A peat extraction ban is implemented until 2050 (same EUTarget)
Reduction of land consumption due to increase of area used for settlements	Net land take of infrastructure and settlements is reduced by 50% until 2050 compared to 2020	No net land take of infrastructure and settlements by 2050	No net land take of infrastructure and settlements by 2050 (same EUTarget)
Agriculture			
Protein consumption	Constant, based on population trends	Constant, based on population trends	Coupled with changes in consumption
UAA	-3% (-4.9 Mio. ha) until 2050 compared to 2020	-6% (-8.7 Mio. ha) until 2050 compared to 2020	-7% (- 10.2 Mio. ha) until 2050 compared to 2020

	EUBase	EUTarget	EUSupreme
Animal yield and animal efficiency	Based on EU Agricultural outlook, slight difference due to own assumptions on development of organic farming with lower yields	Same as EUBase for animal production, slight increase for plant-based production	Same as EUTarget for plant-based production, decrease in milk yield due to increase of grassland-based milk production
Increase organic farming	13% of UAA in 2030 and up to 19% in 2050	Same as in EUBase	25% of UAA in 2030 based on target of farm to forck strategy. Until 2050 further increase up to 30%
Increase biodiversity area	5% of UAA on MS level until 2030 (constant if already higher)	Same as in EUBase	10% of UAA until 2030
Increase in legumes cultivation	3% in total cropland area until 2030, 5% until 2050	3% in total cropland area until 2030, 6% until 2050	Necessary amount for Planetary Health Diet-consumption[72]
Expansion of agroforestry	0,25% of total UAA until 2030, 1% until 2050	1% cropland, 0.5% grassland in 2030, 5% cropland, 2.5% grassland until 2050	2.5% of total UAA, 10% until 2050
Increase in N efficiency – increase in the imputation of the minimum nitrogen content of agricultural fertilizers	55% in 2030 (increase of 5% compared to 2020) and increase to 65% in 2050	Faster and higher increase, due to high gas and fertilizer prices: 60% in 2030, up to 70% in 2050	Same as EUTarget
Increase in N efficiency in lifestock feeding*	+1,5% in 2030 and +5% in 2050	+3% in 2030 and +5% in 2050	Same as EUTarget
Increase in anaerobic digestion of animal manure	10% of manure in stable until 2030 and 22% in 2050	15% of manure in stable until 2030 and 70% in 2050	15% of manure in stable until 2030 and 50% in 2050[73]
Development of animal numbers	Livestock units: -5% until 2030 and -14% until 2050	Same as in EUBase	Production levels based on reduced demand (Planetary Health Diet for Europe) in 2050, linear reduction path from 2030 on.

[72] The planetary health diet includes recommendations for the consumption of pulses (75g daily) (Willet et al., 2019). Additionally, legumes remain important for animal feed. Therefore, the development of the legume cultivation area is based on the quantities needed for both human consumption and animal feed.

[73] We assume that the animals are more widely distributed across the area due to the sharp decline, therefore the capture rates decrease compared to the target scenario.

	EUBase	EUTarget	EUSupreme
Nitrification inhibitors	No use	Applied for the total amount of synthetic nitrogen input in 2050 (Reduction in emissions by total of 34%)(Pérez Domínguez, I., Fellmann, T., Witzke, P., Weiss, F., Hristov, J. et al. 2020). Applied to 50% of manure spread to soils.	No use
Feed additives	No use	100% of dairy cows and 50% of other cattle until 2050 with 15% reduction in enteric fermentation CH_4 No application in organic farming	No use
NH3 mitigation of manure/slurry (in stable, tank and application on soils)	Reduction in line with the obligation of the NEC regulation	Effect of N reduced feeding, NEC regulation and increased anaerobic digestion of manure; effect of innovative stables is not represented by the model	Same as EUTarget
Waste and wastewater			
Waste generation (except food waste) per capita	Constant compared to 2020 levels	Same as EUBase	Reduction of plastic waste and paper due to increased recycling etc.
Food waste	Reduction of -20% compared to 2020 levels until 2050	Reduction of -40% compared to 2020 levels until 2050	Reduction of -50% compared to 2020 levels until 2050
Recycling rates	Target for 2050: Organic waste: 65% Wood: 30% Paper: 85% Synthetics/Plastics: 55%	Same as EUBase	Target for 2050: Organic waste: 75% Wood: 40% Paper: 85% Synthetics/Plastics: 65%
Waste landfilled	Reduction to 10% of municipal waste for MS with waste disposal rates below 60% in 2013 until 2035, 2040 for other MS, constant until 2050	Reduction of landfilled waste to 10% in 2035 in all Member States	Reduction of landfilled waste to 10% in 2035 in all Member States No landfilling of untreated biowaste from 2040 onwards

	EUBase	EUTarget	EUSupreme
Landfill gas (CH_4) recovery rates	Increase by 0.2% per year, share in 2050 = 31% in total CH_4 emissions generated (own assumption)	Increase by 0.5% per year, share in 2050 = 45% in total CH_4 emissions generated	Increase by 0.5% per year, share in 2050 = 45% in total CH_4 emissions generated
Landfill stabilization	-	Treatment of 75% of waste landfilled in MBA before final landfilling until 2050	Strong reduction of waste with organic share by treatment in MBA before final landfilling and further reduction in landfilling until 2050
Biological treatment	Share of waste treatment in total biological waste treatment in 2050: Composted: 58% Digested: 42%	Share of waste treatment in total biological waste treatment in 2050: Composted: 40% Digested: 60%	Share of waste treatment in total biological waste treatment in 2050: Composted: 30% Digested: 70%
Wastewater treatment	Constant, based on population trends	Improvement of wastewater treatment to 80% of tertiary treatment in all MS until 2050 Incremental improvements first in countries with high EF, using countries with similar situations but better EF as EUBase Implementation of revised EU Wastewater directive (Reduction of emissions by 60% in 2040 compared to 1990)	Improvement of wastewater treatment to 90% of tertiary treatment in all MS until 2050 Incremental improvements first in countries with high EF, using countries with similar situations but better EF as reference (higher improvement rates than EUTarget) Higher emission reduction than EU Wastewater directive: -68% in 2040 compared to 1990