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POTEnCIA CETO 2024 Scenario

ENERGY SYSTEM MODELLING FOR CLEAN ENERGY TECHNOLOGY SCENARIOS

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Contents

Abstract 3

Foreword on the Clean Energy Technology Observatory 4

Acknowledgements 5

1 Introduction 6

1.1 Motivation 6

1.2 The Policy-Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA)......7

2 Model and Scenario Assumptions 9

2.1 Key Policies 9

2.2 Key Data Inputs 14

2.2.1 Techno-economics and technology dynamics 14

2.2.2 Demographics and Macroeconomics 14

2.2.3 Fuel prices 16

2.3 Interlinkages with other models 17

2.4 Drivers of Economic Decisions 19

3 Trends of the EU Energy System 22

3.1 Emissions and Energy System Overview 22

3.2 Carbon values and Energy system costs 25

3.3 Energy Demand Sectors 28

3.3.1 Industry 29

3.3.1.1 Non-metallic Mineral Products 33

3.3.1.2 Iron and Steel 35

3.3.1.3 Chemicals 37

3.3.1.4 Non-ferrous Metals 39

3.3.1.5 Pulp and Paper 41

3.3.1.6 Non-energy-intensive Industries 43

3.3.2 Transport 45

3.3.2.1 Passenger Cars 48

3.3.2.2 Buses and Coaches 49

3.3.2.3 Powered 2-Wheelers 50

3.3.2.4 Road Freight Transport 51

3.3.2.5 Rail and Metro 54
3.3.2.6 Aviation 55
3.3.2.7 Shipping 56
3.3.3 Residential and Services sectors 58
3.3.3.1 Residential sector 60
3.3.3.2 Services 61
3.3.4 Agriculture 63
3.4 Energy Supply 65
3.4.1 Electricity 65
3.4.2 Distributed heat 70
3.4.3 Renewable Fuels 72
3.4.3.1 Green Hydrogen 72
3.4.3.2 Synthetic Fuels 73
3.4.3.3 Liquid Biofuels 75
3.4.3.4 Biogas and biomethane 78
3.4.3.5 Solid Biomass 78
3.5 Carbon Capture, Utilisation, and Storage 80
4 Conclusions 82
References 83
List of abbreviations and definitions 87
List of units 89
List of figures 90
List of tables 94
Annexes 95
Annex 1. Supplementary information. 95

Abstract

This report describes the *POTEnCIA CETO 2024 Scenario*, which showcases how the deep decarbonisation of the EU's energy system can be achieved from an energy technology perspective in alignment with the general objectives of the European Climate Law. The scenario has been modelled using the JRC-in-house developed POTEnCIA model in order to provide a detailed explanation of how the different technology pathways were derived for the accompanying CETO 2024 technology reports.

The report summarises the underlying methodology of the POTEnCIA model as well as the key policies and data inputs used to develop the *POTEnCIA CETO 2024 Scenario.* The results show that the deployment of clean energy technologies such as renewable energy sources, electrification, and carbon capture, utilisation and storage technologies are critical for achieving the EU's climate targets.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-facetted character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission's Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy technologies sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions, as well as the sustainable market uptake of both mature and innovative technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the development and implementation of the EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy systems, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web site.

Relation to the CETO project

This study is part of the "System Modelling for Clean Energy Technology Scenarios" tasks within the CETO project. The primary objective of this study is to present a deep decarbonisation scenario and the corresponding clean energy technology pathways focussing on the EU.

The complementary report "Impacts of enhanced learning for clean energy technologies on global energy system scenarios" [1] investigates the role of clean energy technologies for the global energy system.

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1 Introduction

1.1 Motivation

Standing at the current juncture of significant technological innovation and increasing deployment of clean energy solutions, the landscape of energy generation, distribution, and consumption is rapidly transforming. The EU’s energy and climate policy framework requires a holistic approach to address the associated challenges, in which advanced technologies and innovation play a pivotal role in facilitating a successful transition to a decarbonised economy. The Policy-Oriented Tool for Energy and Climate change Impact Assessment (POTEnCIA model) allows developing highly detailed scenarios for the EU energy system, including the assessment of a broad range of related policies. In the context of the CETO initiative, POTEnCIA has been employed to model a technology-driven deep decarbonisation scenario: the *POTEnCIA CETO 2024 scenario*.

The *POTEnCIA CETO 2024 scenario* showcases from an energy technology perspective the contribution of different technologies, including emerging ones, to the decarbonisation of the EU economy. This scenario follows a deep decarbonisation pathway that aligns with the European Climate Law's (ECL) overarching objectives for EU's net greenhouse gas (GHG) emissions, while considering the different characteristics of each individual Member State. As a technology-oriented scenario, its principal aim is to explore the potential role of clean energy technologies in the achievement of the general decarbonisation objectives of the ECL, rather than to analyse in detail the climate and energy policy framework of the EU and its Member States.

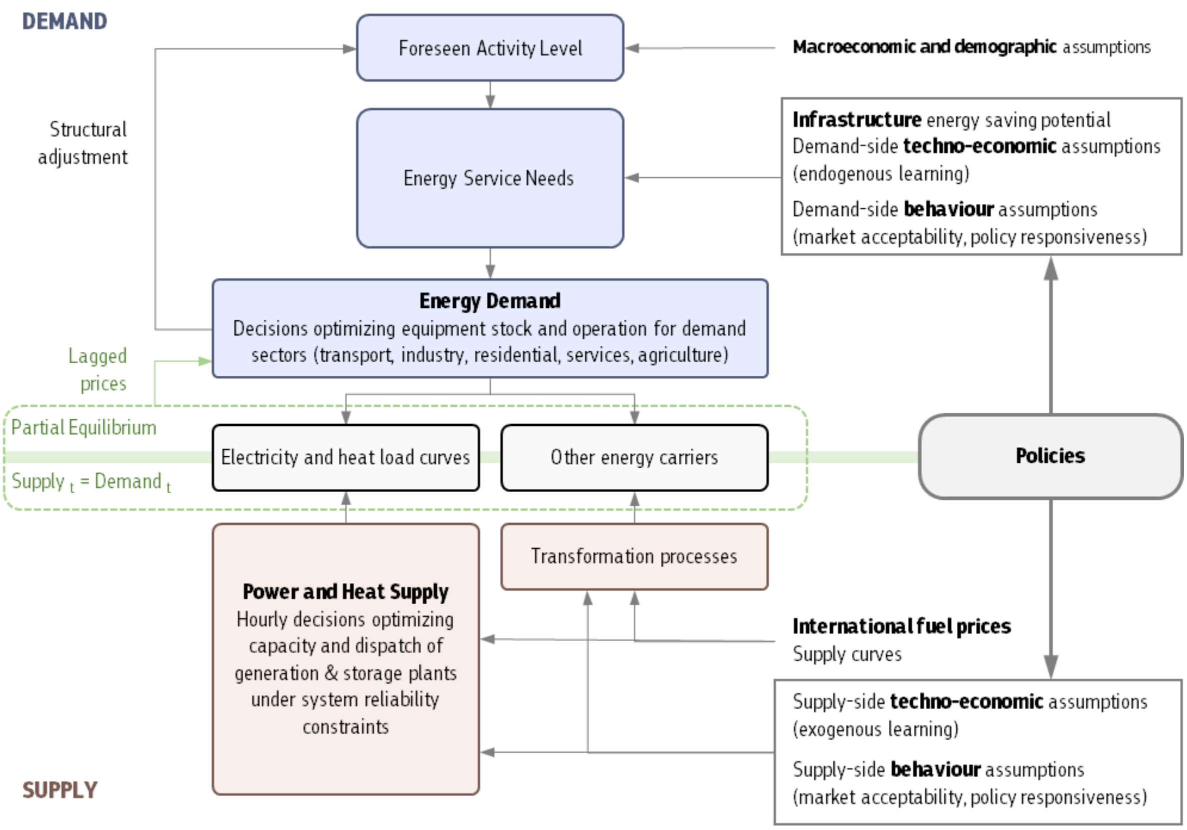
From the perspective of the CETO project, this technical report on the *POTEnCIA CETO 2024 scenario* explains how the overall scenario trajectory translates into pathways for the diffusion of different technologies, many of which are presented in more detail in the accompanying technology-specific CETO reports. Firstly, by summarising the underlying model methodology, the key data inputs used, as well as the key policies considered in the *POTEnCIA CETO 2024 scenario*. Secondly, by providing detailed information on the projections for other sectors and technologies that, although not the primary focus of the specific CETO technology reports themselves, exert a significant influence on the development of the specific technologies being assessed.

1.2 The Policy-Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA)

The POTEnCIA energy system model, developed and maintained by the European Commission's Joint Research Centre (JRC), constitutes a comprehensive, mathematical representation of the European energy system. The general working principles of earlier versions of POTEnCIA have been described by Mantzos et al. [2,3]. POTEnCIA is specifically designed to facilitate the evaluation and comparison of alternative energy system and associated CO2 emission pathways within the EU policy context. The model's scope encompasses the entire energy demand spectrum, including residential, services, industrial, transport, and agricultural sectors, as well as the corresponding energy supply chains such as the power and heat sector, and the supply and transformation of fuels. The model enables analyses both at country level and aggregated EU level. The overarching POTEnCIA model logic follows a hybrid partial equilibrium approach, where energy demand has to be met energy supply across all vectors.

POTEnCIA integrates behavioural decision-making with imperfect optimisation based on the incorporation of detailed techno-economic data. This approach enables the model to assess both technology-oriented policies and behavioural changes, thereby providing a comprehensive evaluation of energy-related policies and developments. A simplified overview of the model is presented in Figure 1.

Figure 1. Overview of the POTEnCIA model



Source: POTEnCIA - Own illustration

To accurately represent the transformation of the current and future energy system and energy policy measures, POTEnCIA incorporates several specific features and mechanisms. A key aspect of the model is its reliance on the concept of representative agents, which implicitly seek to minimise costs and/or maximise benefits subject to constraints related to behavioural preferences, technological availability, activity levels, comfort requirements, equipment vintages, fuel prices, and environmental considerations. Investment decisions made by energy actors are modelled using discrete choice theory, which allows for a nuanced representation of the decision-making processes. The behaviour of representative agents within the model is captured by a system of causal equations, which account for the interdependencies between various factors influencing energy demand and supply.

At the aggregate energy system level, the model calculates for each sector the equilibrium by solving for the prices of scarce resources, including traditional energy carriers and renewable energy sources. These prices are determined in relation to the available resource potentials and their cost curves. In this process, various agents interact as price-takers, price-makers, or both. POTEnCIA iteratively determines this equilibrium in each year of the projection period, taking into account previous decisions made by the various economic agents. The model employs a dynamic recursive approach using equilibrium prices with a one-year lag. This lagged price mechanism on the one hand facilitates computational tractability, on the other hand is also a reflection of the observed delays in the transmission of price signals to economic agents.

Based on the energy service needs, the historical and future energy demand across vectors and sectors is calculated taking into account the efficiency of the equipment already installed in comparison to available alternative options. For each time step, demand side agents re-evaluate their current stock and may choose to prematurely retire stock if considered economically favourable. Illustrative examples for such equipment options, energy demand, and corresponding energy service needs in POTEnCIA are: Residential boilers consuming natural gas to provide thermal energy for a discrete household, steel plants consuming coke to produce steel, electric cars consuming electricity to provide passenger transportation.

On the supply side, POTEnCIA's power module uses deterministic linear optimization with an hourly resolution representing all 8760 hours of the year. The power module allows for optimization not just of the investment pattern of electricity generation and storage units, but also of their dispatch. Thus, the power module computes with high resolution and high detail the complex dynamics of the electricity sector. Apart from electricity generation, the power module also addresses the generation of high temperature steam, mostly to satisfy industrial demand. Additionally, POTEnCIA models an extensive variety of energy transformation processes (e.g. biofuel processes) with a high level of detail, which is crucial for a realistic representation of future EU decarbonisation pathways.

2 Model and Scenario Assumptions

This chapter describes, along several subsections, the key assumptions and drivers that underpin the *POTEnCIA CETO 2024 Scenario*. Even though all results are presented for the EU level, POTEnCIA models each MS individually and hence requires for each MS an individual set of historical data and assumptions. These assumptions range from national demographic and macro-economic projections, over national and EU policies, to international fuel and technology prices.

Unless explicitly stated otherwise, the data and model results presented in this report refer to aggregate values for the EU (27 Member States).

The time scope of the *POTEnCIA CETO 2024 scenario* ranges from 2000-2050.

All monetary figures in this report and in all graphs are expressed in constant € of the year 2015.

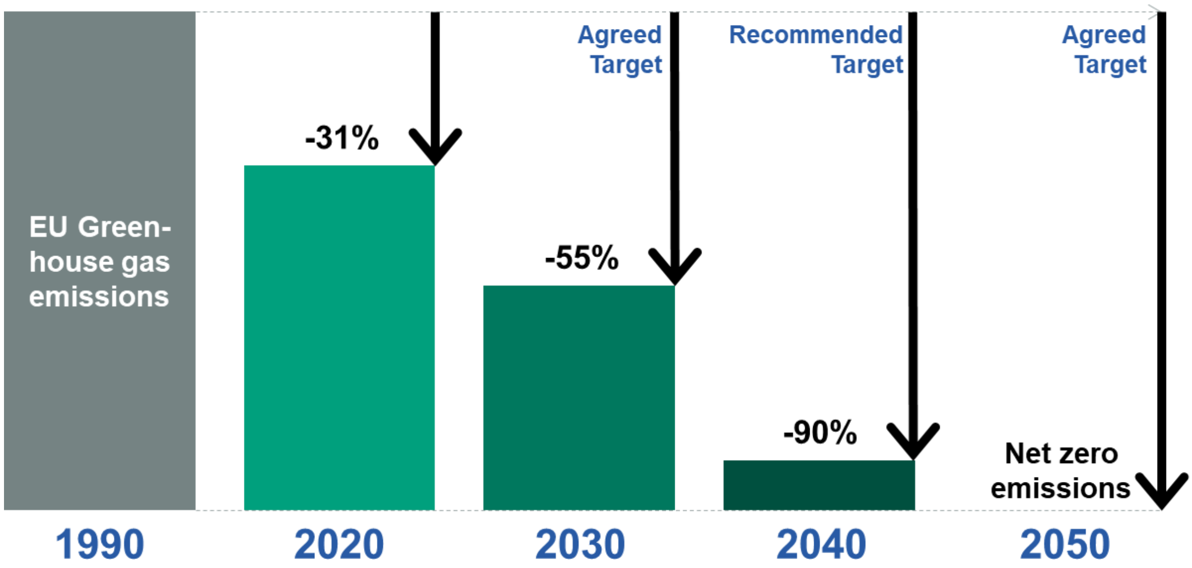
For many visualizations, values and text descriptions have been indexed to a base year. This base year is generally 2021, being the last year entirely based on historical data. However, because of the distortionary effects of the COVID pandemic on 2020 and 2021, results for the residential and transport sectors have been indexed to 2019 instead.

2.1 Key Policies

The *POTEnCIA CETO 2024 scenario* follows a trajectory for EU's net GHG emissions aligned with the general objectives of the European Climate Law (ECL). The ECL sets the objective to achieve net-zero GHG emissions by 2050, as well as a binding interim objective for 2030 to reduce GHG emissions by at least 55% compared to the 1990 benchmark. The 2030 interim objective is supported by a comprehensive package of climate and energy legislative instruments: the Fit-for-55 (FF55) policy package. Furthermore, the European Commission, acting on the obligation described in Article 4.3 of the ECL, in February 2024 proposed as interim target for 2040 a 90% reduction of GHG emissions below the 1990 level. The resulting target trajectory for net GHG emissions aimed by the *POTEnCIA CETO 2024 scenario* is displayed in Figure 2.

Although POTEnCIA CETO 2024 is a technology-driven scenario, it is important to represent at an appropriate level of detail the comprehensive set of policies that constitute the 2030 legislative framework for climate and energy (the FF55 package), for several reasons. Firstly, the FF55 package sets a number of interlinked targets that - while leaving open a broad set of technology options- pose constraints on the choices of technology mix that can deliver on all targets. Secondly, the technology choices adopted to fulfil the 2030 targets are highly consequential in determining investments in energy-related equipment: there is a path dependency. Further, the policies that jointly make up the FF55 package do not cease in 2030, and many of them become more stringent after 2030. In other words, the FF55 package will not only determine the EU's energy system in 2030 but also significantly shape its post-2030 transition to a climate-neutral Union.

Figure 2. EU emission targets in the *POTEnCIA CETO 2024 scenario*



Source: Adaption from the factsheet on Europe's 2050 climate pathway [4]

The 2030 policy framework as modelled in the *POTEnCIA CETO 2024 scenario* includes:

- EU **Emissions Trading System** (ETS): Emissions from the sectors covered by the EU ETS are limited by an annual cap subject to a linear reduction factor increasing to up to 4.4% of the emission allowances in 2010, resulting in a 62% reduction by 2030 compared to 2005. The EU ETS comprises most of the power sector, large energy-intensive industries, and -since more recent revisions- aviation and international shipping

- **Effort Sharing Regulation** (ESR): The ESR, covering emissions from sectors not covered by the EU ETS, sets national targets through annual emissions allocations that lead to an EU-wide 40% reduction of emissions in the ESR sectors compared to 2005. Individual MS contribute to the overall EU reduction with differentiated targets ranging from -10% to -50% below 2005 level in 2030.

- New **ETS 2**, designed to help the MS achieve the objectives of the ESR through an EU-wide cap-and-trade instrument covering the emissions from the combustion of fuels in buildings, road transport and industrial uses not part of the EU ETS. The associated emission cap decreases with a LRF of up to 5.43%, resulting in emissions at least 42% below the 2005 level by 2030.

- **Energy Efficiency Directive** (EED), requiring for the MS to collectively reduce its energy consumption by 11.7% by 2030 compared to the projections of the EU Reference Scenario 2020, resulting in an overall EU primary energy consumption not exceeding 992.5 Mtoe and final energy consumption (FEC) not exceeding 763 Mtoe.

- **Renewable Energy Directive** (RED III) requiring for the MS to collectively achieve 42.5% of renewable energy share in the Union's gross FEC in 2030. Sector specific targets and regulations are also imposed at the MS level, among which the main ones are:

- **Transport:** At least 29% of renewable energy share in transport FEC in 2030 or a greenhouse gas (GHG) intensity reduction of 14.5% by 2030. Minimum penetration of advanced biofuels[1] and biogas (Annex IX part A) and Renewable Fuels of Non-Biological Origin (RFNBOs[2]) in transport FEC of 1% in 2025 and 5.5% in 2030, of which 1% is from RFNBOs in 2030
- **Industries:** Annual average increase of at least 1.6% in renewable energy use for final energy and non-energy purposes over the period 2021-2030. Renewable hydrogen should cover 42% of hydrogen consumption (for energy and non-energy purposes) by 2030 and 60% by 2035 in industries (excluding refineries)
- **Heating and cooling:** With the aim of achieving 49% of renewable energy share in heating and cooling FEC by 2030, MS must increase the annual average renewable energy share by at least 0.8% and 1.1 %, in the periods 2021-2025 and 2026-2030, respectively, and by 2.2% in district heating and cooling in the period 2021-2030. Waste heat, waste cold and renewable electricity can be accounted towards these targets, albeit with additional rules.

- **Energy Performance of Buildings** Directive (EPBD) setting a framework for EU Member States to improve the energy efficiency of buildings. MS must establish minimum energy performance requirements for new buildings, existing buildings undergoing major renovation, and non-residential buildings.
- **Ecodesign Requirements**, setting minimum energy efficiency standards (among other requirements) for appliances and other energy-related products. Implemented standards are aligned to the values reported in the Ecodesign Impact Accounting Annual Report 2021 [5]
- **CO_2 Emission Standards for new vehicles**, imposing EU fleet-wide percentage reduction targets for tail-pipe CO_2 emissions per km driven for new vehicles (s. Table 1). For cars and light commercial vehicles, the percentage reductions refer to 2021, while for heavy-duty vehicles to 2019. Different manufacturers can act jointly to meet the targets (known as “pooling”).

[1] Biofuels in this report are all fuels using biogenic sources as primary feedstock. If biogas has not been separated as an individual fuel, it has been grouped together with biofuels.

[2] RFNBOs (Renewable Fuels of Non-Biological Origin) refers to hydrogen and hydrogen-derivatives as defined in At. 2.36 of the RED III. Inputs for RFNBOs must be green hydrogen and carbon from biogenic sources or DAC

Table 1. CO2 Emission Standards for New Vehicles

VEHICLE TYPE	2025-2029	2030-2034	2035-2039	2040- ONWARDS
CARS	-25%	-55%	-100%	-100%
LIGHT COMMERCIAL VEHICLES	-17%	-50%	-100%	-100%
HEAVY-DUTY VEHICLES[3]	-15%	-45%	-65%	-90%

Source: EU Regulation **[6,7]**

- **FuelEU Maritime** Regulation sets minimum well-to-wake GHG emission intensity reduction on energy use on vessels above 5,000 gross tonnage operating in the EU (including 50% of voyages between an EU port and a non-EU port). The targets get more stringent over the years, starting with a 2% reduction in the period 2025-2029 and reaching 80% by 2050[4]. Compliance towards the target are not required at the single vessel level, ship owners can do pooling to comply with the regulation
- **ReFuelEU Aviation** Regulation imposing to fuel suppliers an increasing minimum share of Sustainable Aviation Fuels (SAFs) supplied to EU airports, starting with 2% in 2025, with a share target of 1.2% RFNBOs by 2030, and reaching 70% in 2050 (of which 35% RFNBOs)[5]. SAFs include only specific categories of biofuels and synthetic fuels, e.g. food and feed crops based biofuels are excluded
- **Alternative Fuels Infrastructure** Regulation (AFIR), supporting the uptake of alternative fuel options across transport modes by ensuring minimum infrastructure requirements in all MS

For the post-2030 period, aside from the extension of specific source-control legislation (e.g. the further tightening of CO2 standards for vehicles and of decarbonisation requirements of international transport activities), the POTEnCIA CETO 2024 decarbonisation scenario does not seek to make specific hypotheses on the policy framework in place and simply applies a common carbon value to all sectors of the energy system as a driver for decarbonisation[6]. The carbon value is not set a priori but determined as the "shadow value" of the emissions constraint, i.e. the incentive necessary to reduce GHG emissions along the set decarbonisation trajectory. For non-CO2 GHG emission reductions and LULUCF (Land-Use, Land-Use Change and Forestry) emissions and sinks, as well as for industrial carbon removals, no incentive (equal to a carbon value of zero) is applied until 2030; for the post-2030 period the carbon value converges to the common one applied in the energy system.

Additional legislative and non-legislative policy initiatives that are taken into account at different levels and with different degrees in the scenario definition include: **Net-Zero Industry Act (NZIA)**, supporting the availability of investment goods necessary for the energy transition; **Industrial**

[3] New city buses are mandated to be 90% zero-emissions by 2030 and 100% by 2035

[4] The reduction should be calculated with respect to a reference value of 91.16 grams of CO2_equivalent per MJ.

[5] ReFuelEU Aviation Regulation defines RFNBOs in aviation sector as the synthetic aviation fuels.

[6] While the ETS directive is applicable beyond 2030, the methodology would lead to infeasibility for modelling purposes, as removal credits are currently not taken into account in the regulation

carbon management strategy (ICMS), supporting the development of the technologies, investment framework and infrastructure to enable the large scale capture, transport, storage, and utilisation of CO2 from industrial facilities and from the atmosphere; **Carbon Border Adjustment Mechanism (CBAM)**, contributing to level the playfield between EU's suppliers of energy intensive goods and international competitors; **Social Climate Fund**, helping vulnerable income groups shoulder energy transition costs; **Trans-European Transport Network** (**TEN-T)** legislation aiming to develop a comprehensive, interconnected, and efficient trans-European transport network; **Energy taxation** directive and MS-specific energy tax rates; **key national energy policies and plans**, such as fossil fuel phase-out plans, nuclear energy plans, and major renewable energy projects; **Energy Efficiency Design Index (EEDI)** of **the International Maritime Organization's (IMO),** setting a minimum energy efficiency standard for new ships and requiring them to meet a specific CO2 emission reduction target.

2.2 Key Data Inputs

The fundament for historical data of the *POTEnCIA CETO 2024 Scenario* is the Joint Research Centre's Integrated Database of the European Energy System (JRC-IDEES) [8,9]. Covering each EU MS and all sectors of the energy system for the 2000-2021 period, this database offers a comprehensive and detailed set of energy-economy-emissions data for energy system modelling and policy analysis. JRC-IDEES harmonizes primary statistics with sector-specific technical assumptions to break down historical energy supply and consumption into individual end uses. This disaggregation matches the POTEnCIA model structure, and uses a vintage-specific approach to capture the evolution of energy equipment and account for structural differences between countries. JRC-IDEES uses a wide set of statistical data sources, with key primary statistics being:

- Eurostat historical data related to energy balances [10–14], to climate [15], to macroeconomics [16,17], and to demographics [18–20]
- IPCC [21], UNFCC [22], and EC [23] related to CO2 emission data

2.2.1 Techno-economics and technology dynamics

The techno-economic assumptions for the *POTEnCIA CETO 2024 scenario* are based on the technology assumptions used in the modelling underpinning the European Commission's communication on a 2040 climate target (CT2040) and its Impact Assessment [24]. In the context of the CETO joint initiative, techno-economic assumptions for the reported key clean energy technologies have been aligned to latest findings presented in the individual reports [25–41]. For other technologies, especially in the demand sectors, additional recent literature has been reviewed and relevant findings evaluated in order to reassess the techno-economics.

For most demand-side technologies, POTEnCIA incorporates endogenous technology learning. For supply-side technologies and some specific demand-side ones (e.g. batteries), technology development is set exogenously in POTEnCIA, on the grounds that the price dynamics of those technologies are primarily determined by global markets rather than by the EU market within the scope of the model. Existing and planned electricity grid interconnections among EU countries (internal and external) are taken from ENTSO-E databases [42,43] until the early 2030s. For the period beyond, additional investment in interconnection capacities is endogenously determined taking into account the cost-benefit ratio.

2.2.2 Demographics and Macroeconomics

Figure 3 visualizes projected EU population and household numbers. Population projections are taken from EUROPOP23 [44]. Following the logic of JRC-IDEES, historical average household size values are used to project future average household size and then the total count of households is calculated by dividing the population over the average household size. Number of households and household size are the key variables for demand projections of the residential and service sectors.

Figure 4 shows EU GDP projections, where short-term values are based on DG ECFIN's Spring Forecast 2024 [45], while long-term growth is based on DG ECFIN's 2024 Ageing Report [46]. Activity projections for the industry sector are generally based on S2 of the CT 2040 report [24], which are described as a "continuation of trends of sector-specific material demand and associated production". However, as IDEES2021 provides more recent data and hence the base year has shifted, the precise values of the projections have been adjusted. In order to project the sector activities, gross value added (GVA) projections are used as a proxy, which are then translated into physical production volumes driving energy demand calculations. Value added intensity, measured as value added per unit of output, is assumed to evolve over time based on factors such as wages, material costs, and sectoral growth rates, with limited convergence across countries to reflect prevailing product diversification and specialization. Specifically for the POTEnCIA CETO 2024 scenarios, the projections assume no notable long-term growth of total steel production (primary and secondary) from 2021 to 2050, but a growth rate of 10-32% for other energy intensive sectors like chemicals, non-metallic minerals, and non-ferrous metals.

Activities for all transport sectors are projected to grow between 2019 and 2050, but to varying degrees. While for example the aviation and rail sectors experience growth rates of over 90%, the passenger cars sector grows by only 23%. Similarly, S2 activities of the CT2040 build the basis for these transport sector projections, but are adjusted to the more recent GDP and population projections of DG ECFIN's 2024 Ageing Report [46].

Figure 3. EU population & number of households projections

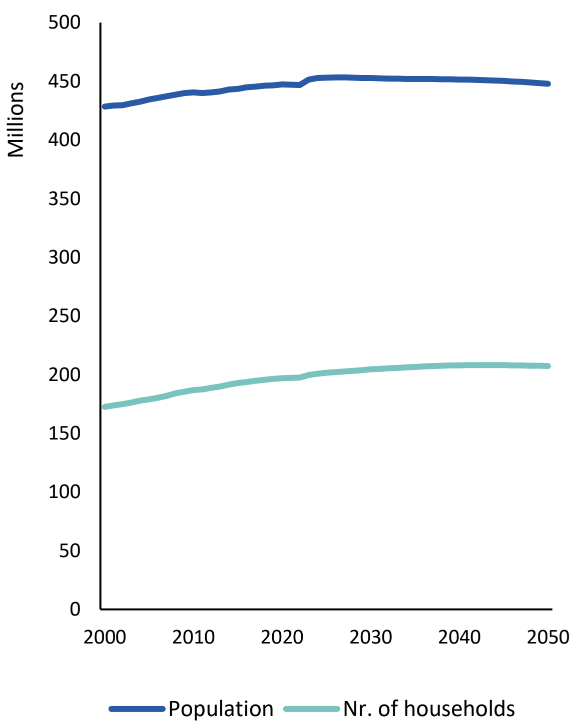
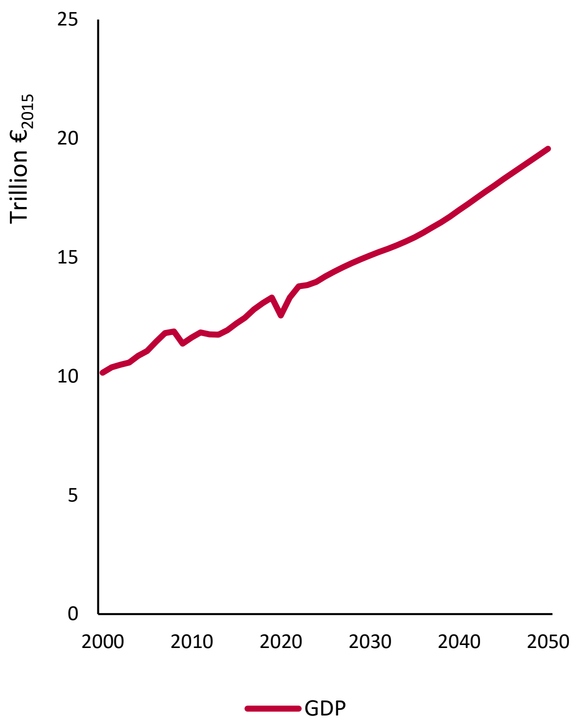


Figure 4. EU GDP projections

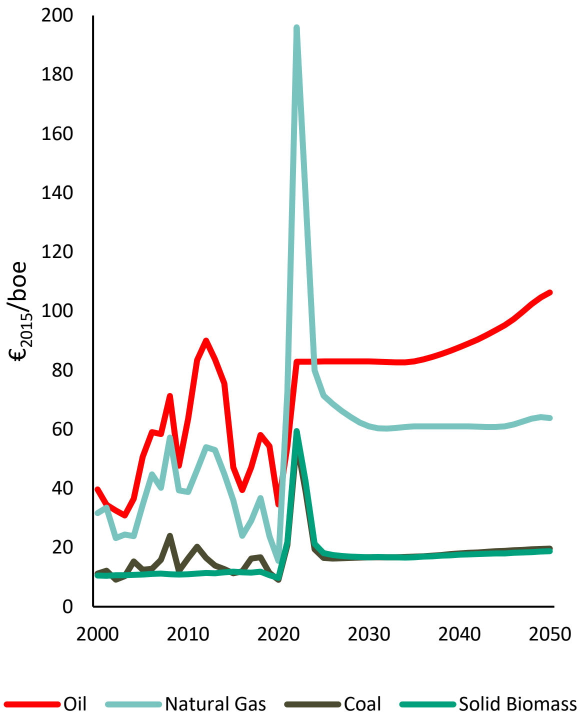


Source: Eurostat, CT2040 Impact Assessment Report

2.2.3 Fuel prices

The price trajectories for oil, natural gas, coal, and solid biomass are presented in Figure 5 and are aligned to projections from the European Commission's impact assessment of the 2040 climate target (CT2040) [24], in turn based on projections from the Global Energy and Climate Outlook 2023 (GECO 2023) [47]. Fossil fuel prices exhibit a rising trend over the long term, mainly because of the depletion of conventional resources being substituted with more expensive unconventional alternatives. Furthermore, these price trajectories consider structural shifts in both supply and demand, with the Russian invasion of Ukraine expected to have lasting impacts on gas prices, as pipeline supply is replaced by more costly liquefied natural gas (LNG). Hydrogen import price curves are based on POLES-JRC model outputs for the GECO 2023 scenario [47].

Figure 5. International fuel prices



Source: POTEnCIA, CT2040 Impact Assessment Report

The prices of EU-internally produced electricity, green hydrogen, synthetic fuels, and biofuels are determined endogenously in POTEnCIA based on electricity market simulations, transformation costs, and the cost of biogenic resources of various types. End-use fuel prices are derived based on international fuel prices and sector-specific tax rates.

2.3 Interlinkages with other models

In order to provide more holistic assessments of EU energy-related scenarios, POTEnCIA, as a dedicated energy system model, has been interlinked with various other models, which enable the assessment and integration of developments in other areas such as land-use, agriculture, international trade, and non-CO2 emissions:

The **Global Biosphere Management Model (GLOBIOM)** and **the Global Forest Model (G4M),** which form part of the integrated model cluster of the International Institute for Applied Systems Analysis (IIASA) [48]. GLOBIOM is a bottom-up partial-equilibrium model developed and operated by IIASA, which "is used to analyse the competition for land use between agriculture, forestry, and bioenergy, which are the main land-based production sectors". G4M is a dedicated silviculture model allowing for detailed estimates of land cover, productivity, emissions, and costs of different forest types. For the interlinkage, baseline scenarios are modelled in GLOBIOM/G4M using preliminary POTEnCIA base line inputs. For each MS, two key data sets are then obtained from GLOBIOM/G4M and used as exogenous inputs for POTEnCIA:

1. Annual lignocellulosic feedstock supply cost curves, which determine solid biomass availability and costs in relationship to energy system demand
2. Marginal Abatement Cost (MAC) curves for LULUCF emissions, which allow for scenario-specific projections of released and captured emissions related to silvi- and agricultural activities

The **Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)** model, also developed and managed by IIASA [49]. It allows for the estimation of current and future non-CO2 GHG emissions[7] by utilising externally generated scenario inputs on macroeconomic, energy, and agricultural sector developments. A key data output of the GAINS model specifically created for utilisation in POTEnCIA is a set of activity-specific MAC curves for non-CO2 GHG emissions. Hence, by applying scenario-specific carbon values in POTEnCIA, the abated (and the non-abated) non-CO2 GHG emissions can be calculated.

The **Common Agricultural Policy Regionalised Impact (CAPRI)** model, managed by various research groups as a result of various EU-funded research projects [50]. It is a quantitative economic model that analyses the impacts of agricultural and trade policies on European agriculture and forestry at the regional and farm type level. CAPRI cost curves are used in POTEnCIA for the modelling of food- and feed-crop based biofuel production.

The **Prospective Outlook on Long-term Energy Systems (POLES-JRC)** model, a JRC in-house development. It is a global energy system model that simulates energy demand, supply, and emissions to 2050 and beyond, taking into account various economic, technological, and policy scenarios. Crucially, it captures international price dynamics of fuel trading across 66 countries and regions including all EU and all G-20 countries. As mentioned in chapter 0, international prices of fossil fuels and hydrogen used in the *POTEnCIA CETO 2024 scenario* are based on the GECO23 scenario [47] modelled in POLES-JRC.

For the road transport sector, the **DIONE Fleet Impact Model** has been employed [51]. It allows for the assessment of the impact of various factors on the European vehicle fleet, including CO2

[7] The non-CO2 GHG emissions modelled in GAINS include methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6).

emissions, fuel efficiency, and air pollution, to inform policy and regulatory decisions. DIONE provides investment curves for fuel efficiency improvements for the different vehicle categories modelled in POTEnCIA

2.4 Drivers of Economic Decisions

With the general POTEnCIA model logic laid out in Chapter 1.2, this chapter aims to elaborate on specific drivers of economic decisions on the supply and demand side:

Subjective financing: In an ideal scenario with unlimited financing and no risk aversion, an energy agent's discount rate for investment decisions should equal the real financing cost of capital. However, due to budgetary constraints, risk factors, and asymmetric information, the actual cost of capital for energy consumers may be higher, leading to a "perceived discount rate" that includes a risk premium. In the POTEnCIA model, this perceived discount rate varies across sectors and EU MS, with larger industrial investors less affected by budgetary constraints, while individual households and private transport are more impacted and show significant differences linked to income level. Assuming the EU will experience economic convergence, these differences are expected to gradually narrow over time.

Economic vs. technical lifetime: POTEnCIA distinguishes between the economic and technical lifespans of equipment to more accurately reflect the cost considerations that drive investment decisions. It assumes that the economic lifespan, used to calculate the annual repayments of the capital investment, may be shorter than the technical lifespan, during which no further capital costs are incurred after the initial loan period has ended.

Endogenous technology dynamics and cost elasticity: In the POTEnCIA model, economic agents have the option to invest in one of three technology types: "almost ordinary" (T1), "advanced" (T2), or "state of the art" (T3), each with dynamically evolving techno-economic characteristics over time. The characteristics of these technologies are determined endogenously, with the "ordinary" technology representing the average country-specific technological characteristics of the existing stock, and the "state of the art" technology representing the best technology that can be obtained in a given year with maximum investment. The technology improvements are limited by the "backstop" technology representing the technical optimum that a technology can converge towards in the future. The model captures endogenous learning effects and allows for a gradual convergence of available technologies across the EU MS, with costs varying across countries to reflect the efficiency of their existing equipment. A sector-specific elasticity factor allows for individually controlling the pace of the technology evolution.

Market acceptability: The POTEnCIA model captures changes in consumer behaviour through an endogenously defined market acceptance factor, which reflects shifts in consumer preferences, economic conditions, and policy introductions. This approach allows for a nuanced representation of consumer behaviour, including differences in technology adoption across Member States based on e.g. income per capita, and can also be used to simulate the impact of specific policies on consumer preferences.

Market attractiveness: The final investment decision of each agent is defined by the market attractiveness, which itself is a function of the market acceptability (see above) and the total annual costs of a given technology option (which themselves are defined by e.g. the endogenous technology dynamics, the economic lifetime).

Carbon capture, utilization, and storage pathways: To suitably depict plausible pathways for CCUS, POTEnCIA models four categories of CO2 capture applications: thermal power generation, energy-intensive industries, biogas upgrading, and direct air capture. The first three categories are modelled assuming the use of amine solvent-based chemical absorption technology, which is commercially mature and technically versatile; within each category, technology assumptions are tailored to individual capture applications (e.g. specific industry sectors) based on a review of current literature [52–54] . Direct air capture is modelled assuming the deployment of solid adsorption technology, given its higher TRL compared to high-temperature coupled liquid solvent/calcium looping technology [55].

Power module: While a hybrid partial equilibrium approach is suitable for representing the entire energy sector dynamics, the decision complexities of the power sector require a different modelling logic. The POTEnCIA power module employs a deterministic linear optimization approach, which allows to capture these complex dynamics within the wider POTEnCIA model environment. The power module computes cost-optimal investment decisions with hourly electricity and steam unit dispatch proceeding along the following steps:

1. Decomposition of the annual demand of all stock types of the demand sector into hourly load profiles. While in the historical period most electricity demand follows inflexible load patterns, future technology options allow for higher shares of flexible demand (e.g. hydrogen electrolysers, vehicle-to-grid, heat pumps).
2. Computation of unplanned and planned outages of different types of power plants. A Monte Carlo approach[8] [56] and power-plant-specific outage data [53] are used for this purpose.
3. Optimization of investment decisions for generation and storage capacities with the objective of minimizing system costs while respecting the system constraints (e.g. CO2 capture limits, annual and total technology capacity limits). The model includes daily and seasonal storage. Investment decision take into account CO2 price expectations, which are estimated based on historical CO2 price growth rates.
4. Full year hourly dispatch of steam and electricity generation units. The hourly electricity dispatch simulation in the POTEnCIA model involves a sequential series of optimization steps, including inflexible hourly generation dispatch, long-term operational decision optimization, day-ahead market optimization, close-to-real-time market optimization, and additional investments to avoid loss-of-load. These optimizations determine the dispatch of electricity generators, storage loading, flexible demand, and electricity trade between countries, while accounting for system constraints and uncertainty.
5. Investment optimisation of interconnector capacities. Based on the day-ahead market price of the previous step, the model may identify options to expand interconnector capacities within the annual capacity expansion restrictions.
6. Calculation of steam and electricity prices. The model distinguishes between average annual electricity prices, long-term contract prices, and distributed steam industrial prices. Sector- and country-specific taxes and grid tariffs to be paid by the end consumer are also taken into account. The calculated prices then impact the agent's investment choices of the demand side sectors. The modelling of electricity network costs (used to derive grid tariffs) use as starting point historical network tariff data.

[8] Reproducibility of results is ensured as the outputs derived from the deterministic computation can be used for reproduction of the model scenario

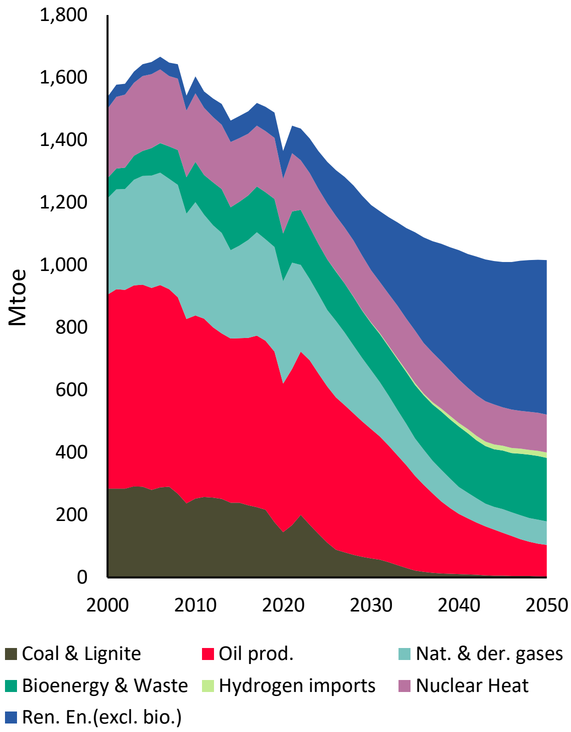
The evolution of the costs in projection years considers the increase of demand, the change of the load pattern, and the penetration of distributed energy resources.

3 Trends of the EU Energy System

3.1 Emissions and Energy System Overview

Figure 6 shows that since 2006, when gross available energy[9] (GAE) peaked in the EU at 1667 Mtoe, GAE has been falling steadily down to 1447 Mtoe in 2021. This demand reduction of 13% is contrasted by a population increase of 3% and a GDP increase of 16% in the same time period, signalling that GDP growth is decoupling from energy demand. Within this overall energy consumption, coal shares have reduced significantly, whereas the GAE shares of natural gas and oil products have seen only slight decreases, as the pace of the energy transition has been uneven across sectors and their specific fuel demand.

Figure 6. GAE by fuel type[10]



Source: POTEnCIA

The transition towards a more sustainable energy system led to emission reductions of almost 1 Gt CO2, equivalent to 22%, from 2006 to 2021, as illustrated in Figure 7. In parallel, non-CO2 emissions reduced by 15% from 2005 to 2020, see Figure 8. Most of the coal reduction can be traced back to shifts towards renewable energy and natural gas in the power and heat sector, which resulted in this sector's emission reductions of 517 Mt CO2 (or 39%) between 2006 and 2021. The 2020 COVID crisis led to a sudden drop in GAE and total CO2 emissions, although the impact varies widely across the different sectors, with some sectors having experienced unprecedented activity drops (e.g. transport), while others (e.g. residential) were only marginally affected.

In the *POTEnCIA CETO 2024* scenario, the downwards trend of coal demand within the EU accelerates further, so that by the late 2030s coal is virtually phased out, not just from the power sector but from the entire energy system. Additionally, the demand for oil products and natural gas reduces rapidly as a consequence of policies in place. Oil demand from road transport drops sharply, primarily due to swift electrification of vehicles, but remains sustained in other sectors (e.g. as feedstock for chemicals). Similarly, the demand for natural gas is significantly reduced, most notably in the industry as well as in the residential and services sectors. In both sectors, energy efficiency measures and electrification are the main drivers, complemented by the substitution of fossil natural gas by

[9] Excluding ambient heat

[10] See annex for a detailed breakdown of fuel categories into specific fuels. Oil prod. = Oil products, Ren. En. (excl. biom.) = Renewable Energy (excluding biomass), Nat. & der. gases = Natural & derived gases:
Ren. En. includes electric import & exports

biomethane. In other sectors hydrogen and hydrogen-based fuels further substitute oil products (e.g. in aviation) and natural gas (e.g. in chemicals production), as well as solid fuels in steelmaking. Although natural gas use remains significant in the power sector and in some industries, the associated emissions are increasingly abated through the deployment of carbon capture coupled with the development of an associated CO2 storage infrastructure. Carbon capture and storage also plays an important role in the decarbonisation of industrial process emissions, such as those originating from the chemical transformation of mineral raw materials into cement clinker, which are not driven by combustion and hence cannot be abated by fuel switching.

Figure 7. EU emissions overview[11]

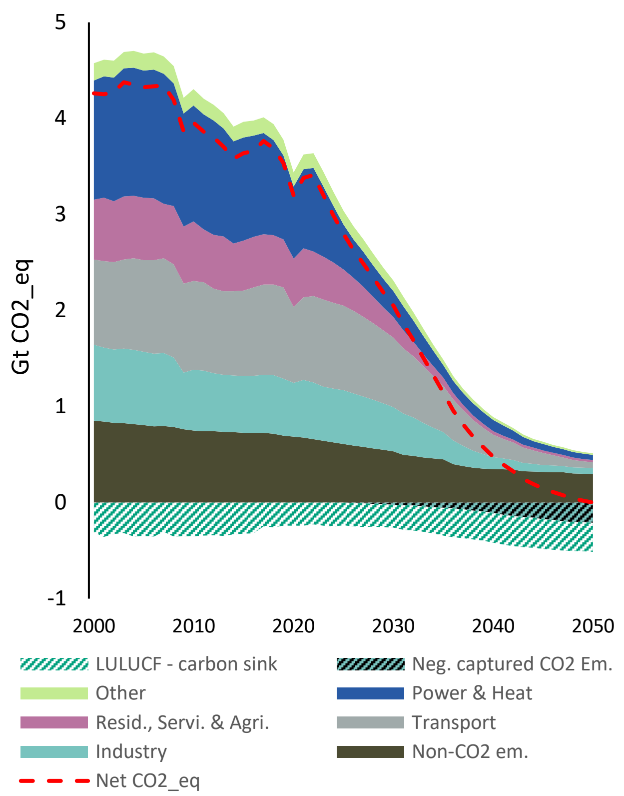
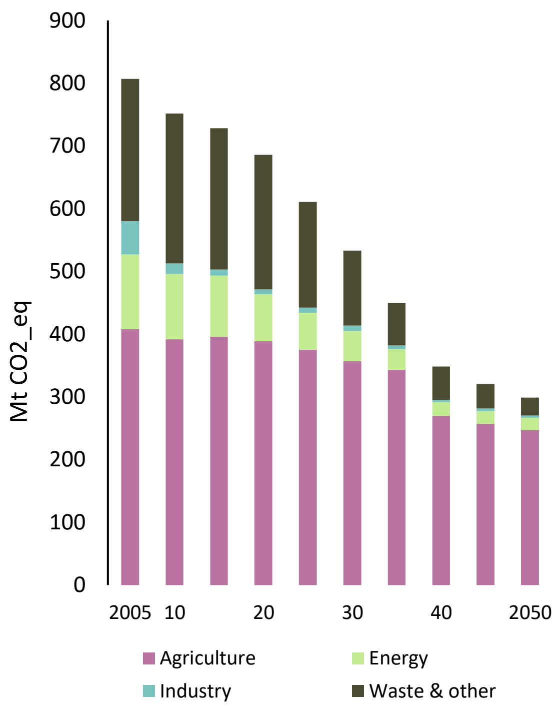


Figure 8. Non-CO2 GHG emissions by sector in the EU



Source: POTEnCIA, GLOBIOM, GAINS

By 2050, total GAE amounts to 1015 Mtoe, a 30% reduction relative to 2021. Demand for oil products and natural gas is reduced to 101 Mtoe and 75 Mtoe, respectively, indicating that over 82% of GAE comes from carbon-neutral sources. Half of GAE is sourced from non-biogenic renewable energies, primarily wind and solar energy, while bioenergy contributes 20% followed by nuclear energy with 12%. Hydrogen and hydrogen-derived fuels play an increasingly important role, with the majority

[11] Other includes emissions from petroleum refineries, primary energy production sectors, other energy branches, fugitive emissions from fuels, and waste management;

Transport emissions include 50% of Extra-EEA international navigation emissions following the methodology of the MRV maritime regulations and Intra-EEAwUK aviation emissions;

Neg. CO2 emissions includes equivalent negative CO2 emissions due to biogenic carbon being stored in chemicals being produced domestically, although almost 2% of GAE corresponds to externally sourced hydrogen. As a consequence, all sectors reduce their CO_2 emissions rapidly in order to meet EU emission targets, but no final demand sector achieves absolute zero emissions by 2050. Non-CO_2 emissions, which include hard-to-abate emissions such as methane from animal production, are reduced proportionally much less, by 56%, and hence constitute by mid-century a high share of the residual GHG emissions with 299 Mt CO2_eq by 2050, equivalent to 58% of the remaining unabated emissions. In order to mitigate the remaining CO2_eq emissions from all sectors to meet the 2050 net-zero target, net negative emissions from land-use, land-use change and forestry emissions (LULUCF) are supplemented by Bioenergy Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC), reaching together 512 Mt CO2_eq.

This transformative energy transition, in which fossil fuels drop from 71%[12] of GAE today to only 18% in 2050, is marked by a profound transformation across many dimensions. The following general trends can be identified:

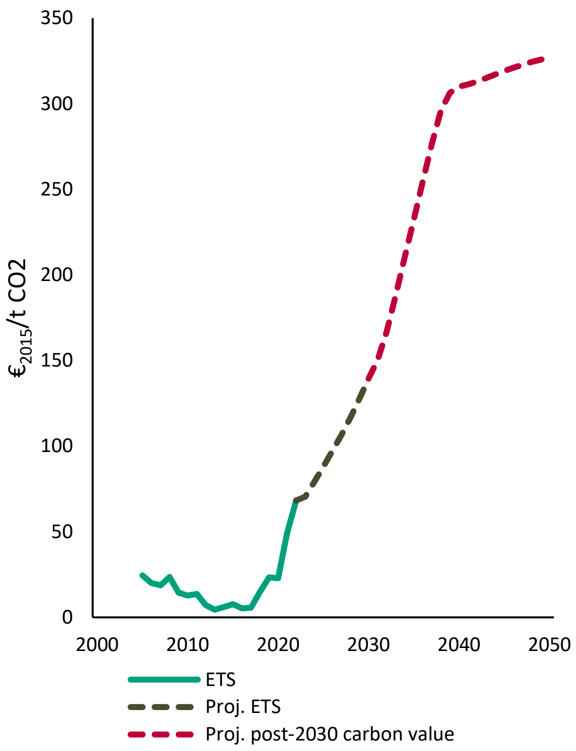
- Electricity consumption, after remaining rather stable over the past decades, surges to 17% more in 2030 to 40% in 2040 and 49% in 2050, pushed by emerging demand in road transport and for the production of green hydrogen and hydrogen-derived fuels, as well as by increased electrification across all end-use sectors.
- In order to enable the power sector to shift to 77% of electricity being generated by variable non-dispatchable sources (solar photovoltaic and wind), electricity storage, demand flexibility, and reinforced transmission and distribution grids, including interconnectors, become crucially important. The role of gas-fired generators changes radically, from combined-cycle gas turbines optimised for high efficiency at baseload regime to peaking plants operated only for a limited number of hours per year but providing essential services for grid stability and the security of electricity supply in cases of prolonged absence of wind and sun resources (Dunkelflaute).
- With tightening emission constraints, even hard-to-abate sectors undergo deep transformations, shifting from traditional carbon-intensive processes to emerging carbon-free options. Energy-intensive industries progressively shift from traditional fossil-fuel-based processes to directly or indirectly (via hydrogen) electrified production routes. International aviation and shipping replace vast amounts of fossil kerosene and fuel oil with renewable fuels of biogenic or synthetic origin.
- Carbon capture takes up a prominent role, as it fulfils several functions: as a solution to decarbonise industrial processes and the remaining fossil-fuel-fired capacities in the power and heat sector, as a source of CO_2 for the production of synthetic fuels, and to offset remaining unabated GHG emissions by sequestering CO_2 of biogenic origin, or directly from the air. A new infrastructure for the transport and injection in geological storage sites of CO_2 is developed.

[12] including non-renewable waste

3.2 Carbon values and Energy system costs

Historical and projected annual EU ETS price and carbon values applying to the *POTEnCIA CETO 2024* scenario are shown in Figure 9. The yearly-average ETS price, modelled until the year 2030 as the shadow price of the reducing number of emission allowances in the sectors covered by the EU ETS, is projected to increase roughly linearly from current level to 140 €/t CO2 in 2030. After 2030, a more universal carbon value is applied to all sectors. This carbon value is derived endogenously as the shadow price of the progressively tightening emission constraint covering the entire economy on its course towards climate neutrality. The carbon value roughly doubles from the 2030 level to above 300 €/t CO2 in 2040, and then stabilises, with only a modest further increase up to 2050, largely owing to cost reductions in key decarbonisation technologies.

Figure 9. EU ETS price & carbon value



Source: POTEnCIA

Figure 10 shows the evolution of total investment expenditure for energy equipment and efficiency improvements, aggregating by decade and comparing to total GDP during the same periods to assess the relative economic effort required. Total investments are dominated by transport and reach their peak relative to GDP in 2031-2040 in all energy sectors, except residential and services; economic efforts in these sectors instead peak in 2041-2050 (at 1.5% of GDP for the residential sector) due to greater efficiency investments later in the modelled period. Figure 11 compares these residential investment needs with total household consumption expenditure and the investment needs in the industrial sector relative to total industry value added. In the power and heat sector, relative Investment expenditure for power plants drops by 2041-2050, as the bulk of the supply-side transformation is achieved by 2040. Investment efforts required in industry are similarly lower in the last decade whether comparing to GDP or total industry value added.

As with investment expenditure, the total energy-related costs (including the annuities of energy equipment and efficiency improvements, maintenance and fuel costs) as a share of GDP[13] (see Figure 12) also peak in 2031-2040. However, this is largely driven by the transport sector, whereas relative costs in the other sectors tend to decrease throughout the projection period. This trend also holds when comparing residential and industry´s energy costs against household expenditure and industry value added (see Figure 13), and reflects among other things the benefits of investing in efficiency measures.

[13] Total costs include annuities of capital costs

Figure 10. Total investment expenditure by energy sector and by decade relative to GDP[14]

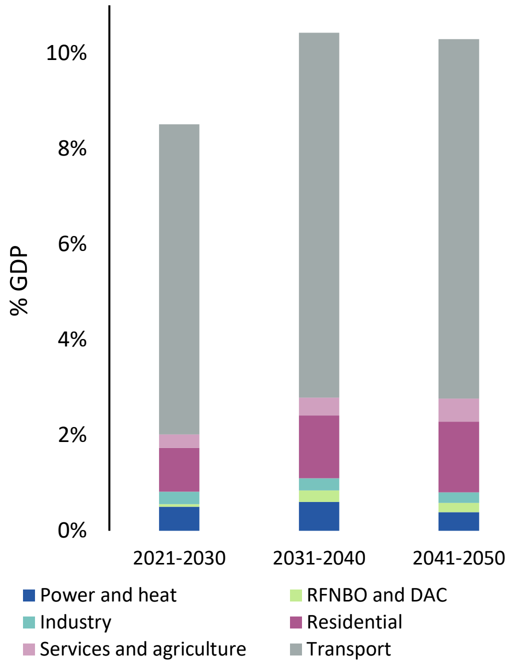
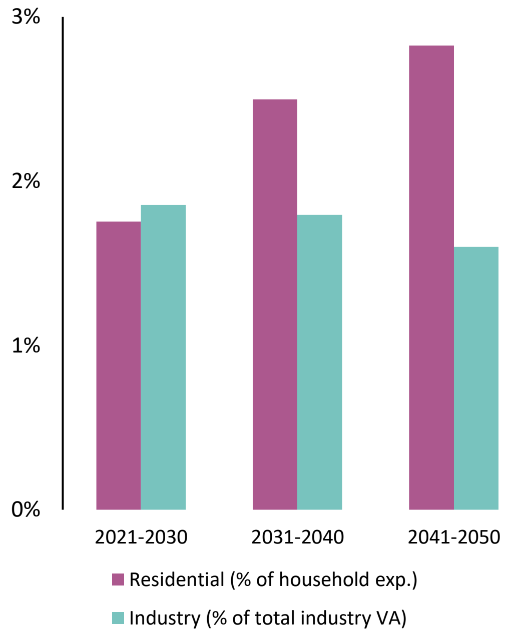


Figure 11. Total investment expenditure by decade for residential and industry sectors, relative to total household expenditure and value added[14]



Source: POTEnCIA

The cost of power and heat generation is generally stable relative to GDP through the modelled period, but relative network costs peak in 2031-2040 – following the expansion of cross-border transmission capacity and the connection of new renewable capacity to the grid (see Figure 14). This relative increase in network costs is consistent with expectations from electricity network studies [57] and ultimately supports a more efficient integration of national markets. This integration in turn contributes to decreasing the unit costs of generation over time (see Figure 15), alongside the lower operating costs associated with new variable renewable capacities.

[14] Only costs related to thermal uses are reported: purchase costs of electric appliances in the residential and services sectors are excluded

Figure 12. Total energy-related cost by energy sector and by decade, relative to GDP[14]

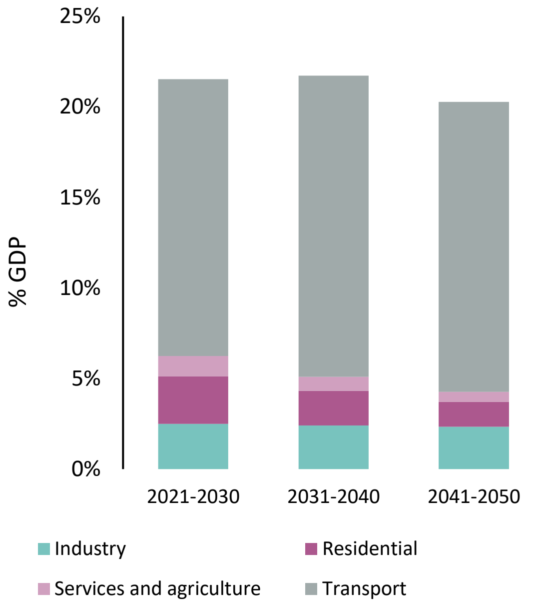
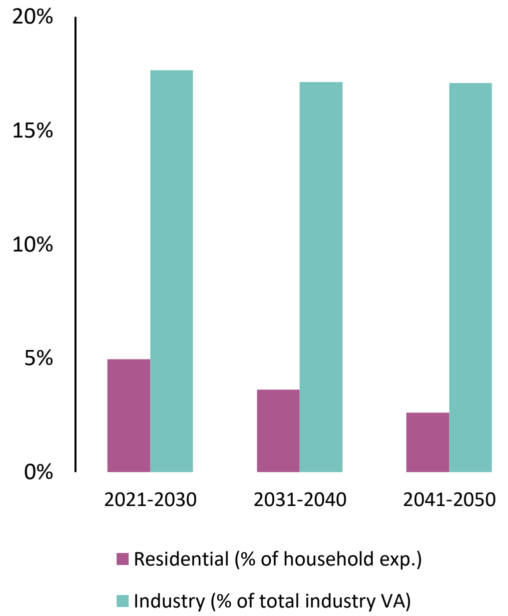


Figure 13. Total energy-related cost by decade for residential and industry sectors, relative to total household expenditure and value added[14]



Source: POTEnCIA

Figure 14. Total power and heat system costs relative to GDP

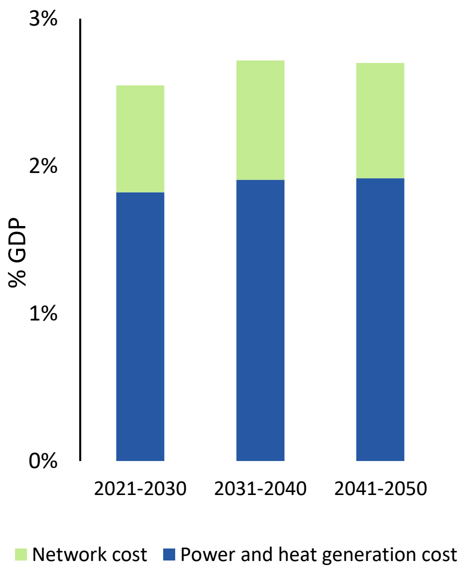
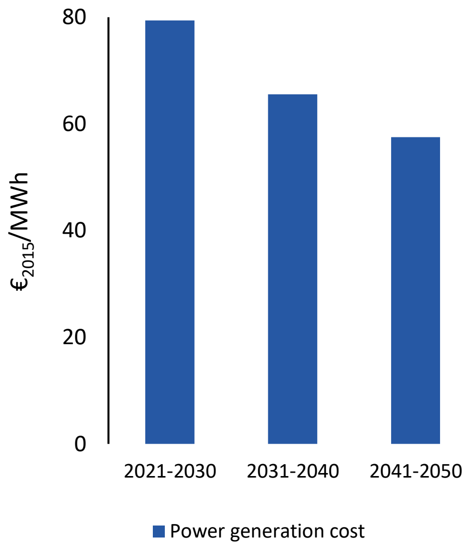


Figure 15. Average electricity generation cost



Source: POTEnCIA

3.3 Energy Demand Sectors

The total energy available for final consumption by end-users is the sum of all final energy consumption (FEC) and final non-energy consumption (FNEC). The FEC is defined as the total amount of energy used by end-users, such as households, industry, and businesses, to perform various activities, like heating, cooling, lighting, and powering appliances and machinery [58][15]. The FNEC includes fuels that are used as raw materials and are not consumed as fuel or transformed into another fuel (for example, natural gas used in fertilizers). In 2021, the combined final energy and non-energy consumption amounted to almost 72% of the EU's gross available energy, while the remaining 28% represent losses and self-consumption in transformation and distribution processes. The latter value decreased by 3% since 2000, where it stood at over 31%, indicating an overall trend towards a more efficient energy transformation system, primarily driven by a more efficient power sector.

Figure 16 shows that in 2021 the energy[16] and non-energy consumption is roughly evenly split between the transport, the industry, and the buildings (residential and services) sectors, making up 30%, 32%, and 34%, respectively. The energy consumption of the agriculture, forestry and fishing sector[17] is limited to around 3%. In the projection years, upward pressure on energy service demand due to increasing activity is offset in all aggregate sectors by efficiency gains, so that total energy and non-energy consumption decreases from 1100 Mtoe in 2021 down to 937 Mtoe by 2030 and 714 Mtoe by 2050. The projected evolution of energy consumption across the sectors from 2021 to 2050 is very heterogeneous: The building sector decreases energy consumption by 62%, compared to 33% in the transport sector, and 15% in the industry sector. In contrast, FNEC rises by 12%.

Figure 17 visualizes how energy and non-energy consumption changes across all sectors. A large part of the afore-mentioned efficiency gains is caused by the wide-ranging electrification of many energy uses and processes (notably including the pervasive electrification of road transport and of the heating demand of buildings through heat pumps), determining an increase in electricity demand of 41%, reaching 302 Mtoe (or around 3500 TWh), between 2021 and 2050. Starting from the 2030s, biofuels, hydrogen, and hydrogen-based synthetic fuels further substitute the remaining fossil fuels, predominantly oil products in transport and all types of fossil fuels in the industrial sectors. As a consequence, coal consumption is phased out entirely, while the use of natural gas and oil products diminishes rapidly, accounting together for only 17% of total fuel consumption compared to 67% in 2021. However, the demand of petroleum products remains sustained especially for non-energy consumption purposes in chemicals, and also to smaller degrees in international transport (aviation and maritime shipping).

[15] International aviation is included in FEC while ambient heat is excluded in this report's definition, matching the Eurostat category "Final energy consumption (Europe 2020-2030)

[16] Referring here to the sum of FEC, energy demand of marine bunkers (which is attributed to transport), and transformation losses and auto-consumption of blast furnaces (which are attributed to Industry).

[17] Unless specified, the sector is abbreviated as agriculture in the remaining part of the report

Figure 16. Energy consumption by demand sector[18]

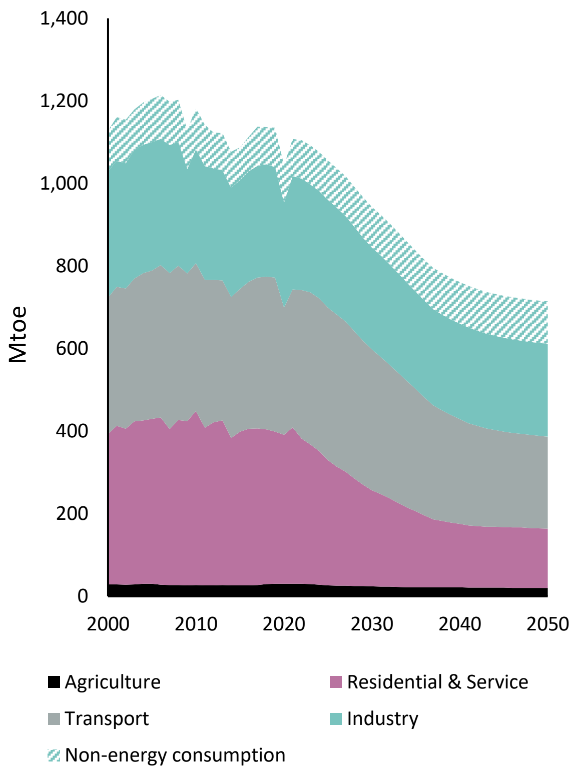
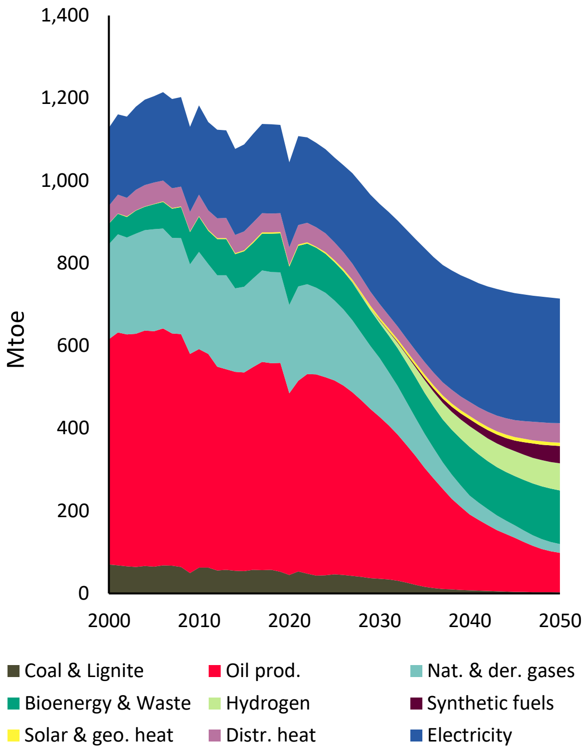


Figure 17. Fuel consumption by demand sector[19]



Source: POTEnCIA

3.3.1 Industry

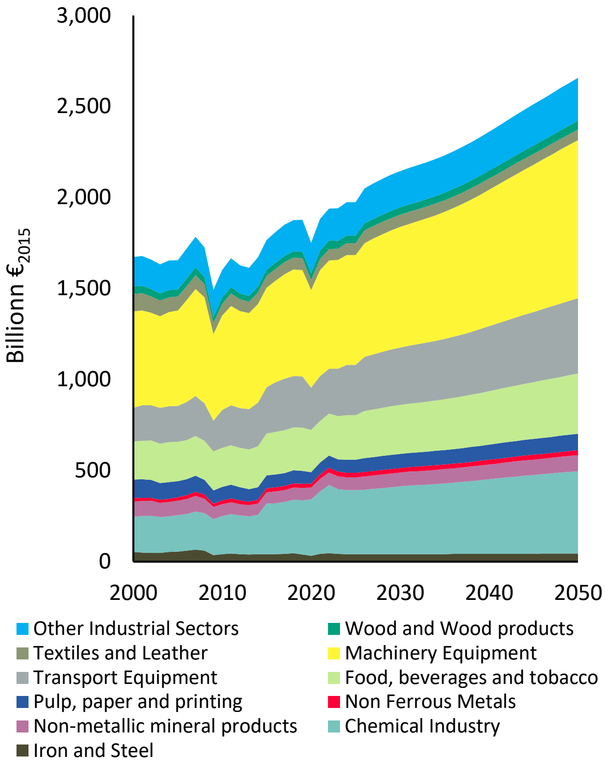
Despite the various crises of the last decades, value added in the industry sector has risen by 12.5% from 2000 to 2021, as shown in Figure 18. The value added of the industry sector is projected to continue to grow by 41% by 2050. Historically, the industry sector has relied heavily on fossil fuels, leading to substantial emissions. Figure 19 shows that the sector has reduced its emissions some 25% from 829 Mt CO2_eq in 2005 down to 625 Mt CO2_eq in 2021, representing 17% of total EU GHG emissions in the latter year. Most of these emissions are concentrated in energy-intensive industries, with the three largest emitters (non-metallic minerals, iron and steel, chemicals) making up over 75% of the emissions[20].

[18] Energy consumption in this visualization includes FEC, energy demand of marine bunkers, which is attributed to transport, and transformation losses and auto-consumption of blast furnaces, which are attributed to Industry and final non-energy consumption (FNEC)

[19] Fuel consumption in this visualization includes FEC, final non-energy consumption (FNEC), energy demand of marine bunkers, and energy demand for transformation losses and auto-consumption of blast furnaces

[20] This value includes emissions from energy transformation processes and auto-consumption in blast furnaces, primarily used for processes related to iron & steel production

Figure 18. Value added for the industry sector[21]



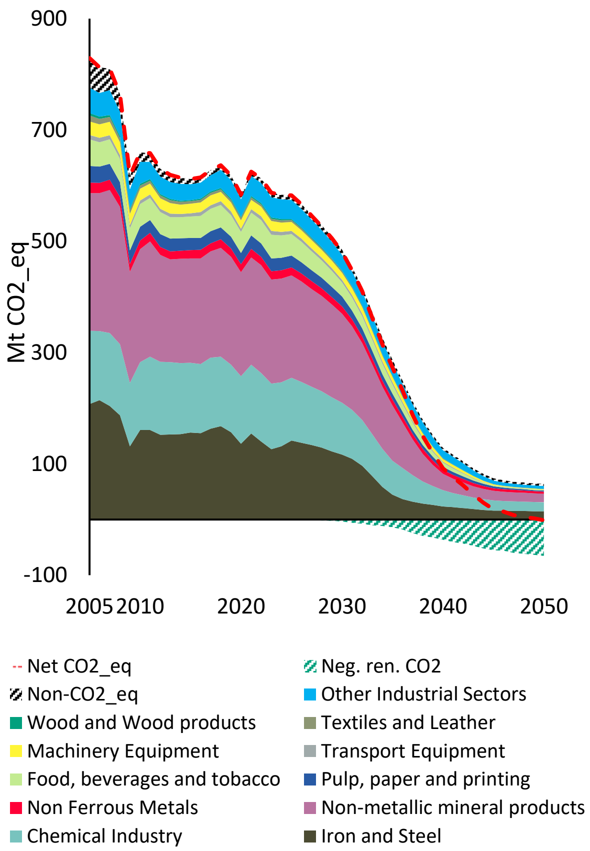
Source: POTEnCIA

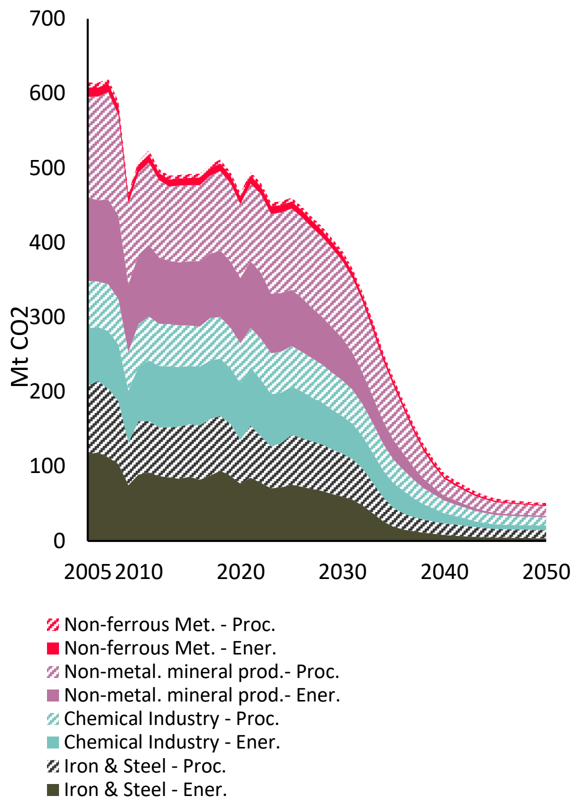
Over the past two decades the EU's industrial emissions have seen a progressive reduction, albeit at a pace slower than some other sectors such as power generation. With the renewed stringency of the EU's decarbonisation objectives under the Climate Law, the industrial sector now faces critical challenges in reducing its carbon footprint and must speed up a pervasive energy transition towards cleaner production, more renewable energy sources, optimised energy efficiency, and carbon capture for the processes that are hardest to decarbonise. Regarding the latter, the following EU policy levers outlined in chapter 2.1 are especially impactful: the ETS, the ESR, NZIA, the ICMS, and the CBAM.

[21] For visualization purposes, the added value of the construction sector has been omitted. In all other graphs, the construction sector is included in the "Other Industrial sectors" category.

Figure 19. GHG emissions for the industry sector[22]

Figure 20. Unabated energy & process emissions for selected sectors[23]





Source: POTEnCIA

Figure 21 indicates how energy consumption[24] in industry is reduced from 265 Mtoe in 2021 down to 241 Mtoe in 2030 and to 225 Mtoe in 2050. In parallel, final non-energy consumption rises marginally from 92 Mtoe in 2021 to 103 Mtoe in 2050. The strongest energy consumption reductions occur in the iron and steel (I&S) sector, driven by a switch from blast furnace process towards less energy-intensive direct reduced iron (DRI) making and an increased share of recycled steel in the overall production, as well as in the non-energy-intensive sectors, where more efficient electricity-based technologies take up increasing shares of the FEC. All industrial sectors undergo a progressive electrification of their processes, albeit with varying degrees. Moreover, in various sectors biofuels as well as hydrogen and hydrogen-based fuels (primarily as chemical feedstock) reduce reliance on fossil fuels. In some sectors, distributed heat, coming from either Combined Heat and Power (CHP) plants or large-scale heat pumps via district heating, satisfies increasing shares of the demand.

[22] Includes emissions from blast furnaces; Negative emissions include bio-energy carbon capture and storage (BECCS) and the storage of biogenic carbon in materials (e.g. biomethanol in chemicals); excludes process emissions from solvent use and other process emissions

[23] Includes emissions from energy transformation and auto-consumption in blast furnaces

[24] The numbers mentioned here for energy consumption include FEC of all industry sectors plus transformation losses and auto-consumption of blast furnaces

Consequently, by 2050, the energy consumption share of fossil fuels (incl. non-renewable waste) falls down to 5%, while electricity accounts for 50%, see Figure 22. Apart from the residual fossil fuel use, which remains concentrated in combination with CCUS in energy-intensive processes where fossil fuels are particularly challenging and/or costly to replace, the non-energy use of fossil fuels remains sustained as feedstock for chemicals. Specifically, oil products remain with 62% the dominant choice for FNEC purposes in 2050.

Figure 21. Energy demand in industry by sector[25]

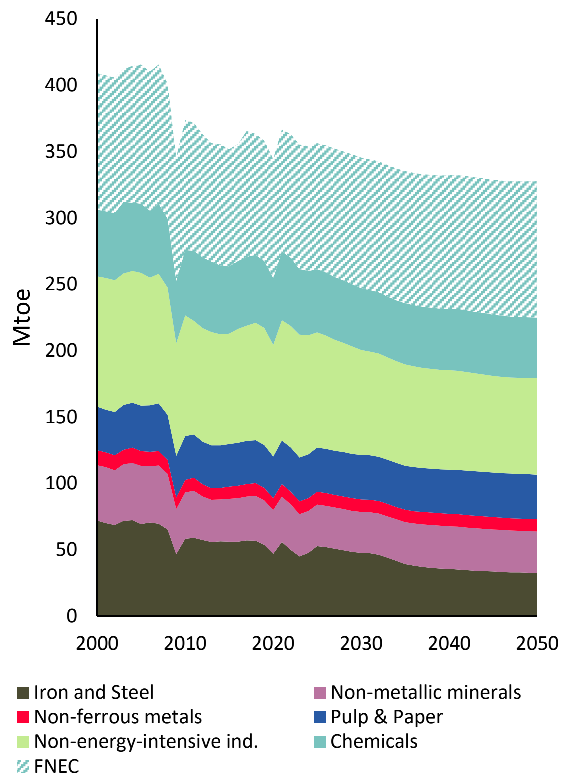
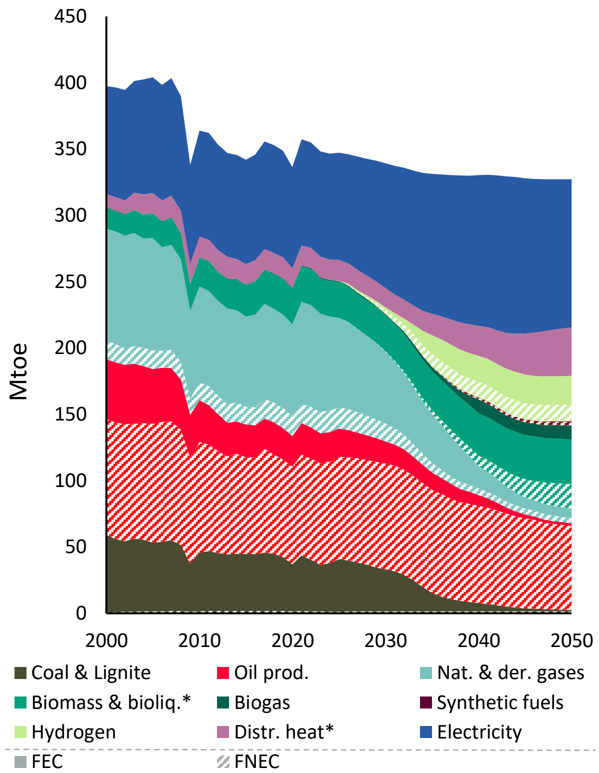


Figure 22. Energy demand in industry by fuel[26]



Source: POTEnCIA

[25] Includes transformation losses and auto-consumption of blast furnaces, which are attributed to I&S

[26] Includes transformation losses and auto-consumption of blast furnaces; Distr. heat includes geothermal and solar heat; Biomass & bioliquids includes waste

3.3.1.1 Non-metallic Mineral Products

Within the EU, the processing of non-metallic mineral (NMM) products caused 193 Mt of CO2 emissions in 2021, making it the most significant industry sector in terms of climate impact. Unlike in other industry sectors, where fuel combustion emissions dominate, NMM processing emissions released during mineral transformation accounted for 104 Mt CO2 (54% of the total), while fuel combustion caused 89 Mt CO2 (46%). Consequently, in order to decarbonise, the NMMs industry must address both fuel decarbonisation and process emission reduction. These challenges are amplified by projected sustained demand, resulting in a physical output growth of 13-16% for cement as well as ceramics and other NMMs from 2021 to 2050, as visualized in Figure 23.

In order to meet these challenges, thermal kilns using fossil fuels are to a large extent replaced by electric kilns by 2050, so that 69% of FEC is covered by electricity and 17% by biomass and waste, as shown in Figure 24. For the reduction of process emissions, traditional clinker substitution options (e.g. with coal fly ashes, blast furnace slag, ground limestone) become with time insufficient to meet the decarbonisation targets, in part because of projected lesser availability of alternative pozzolans (as coal combustion withdraws from the energy system), but mainly because only a certain share of the clinker can be substituted while maintaining the structural characteristics of cement. Alternative options include for instance CO2 curing of concrete but are not ubiquitously applicable, making the cement sector a prominent target for the deployment of carbon capture devices, which see rapid growth in the 2030s, leading to a capture amount of 114 Mt CO2 by 2040 already, equivalent to 58% of the emissions of 2021. Overall, emissions from NMM products fall by 85% in 2040 and over 92% in 2050 compared to 2021 (see Figure 25).

Figure 23. Physical output of NMM products

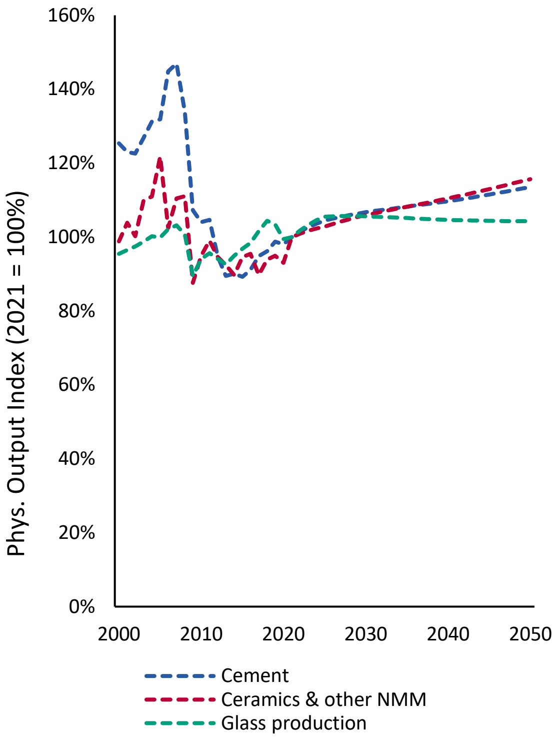
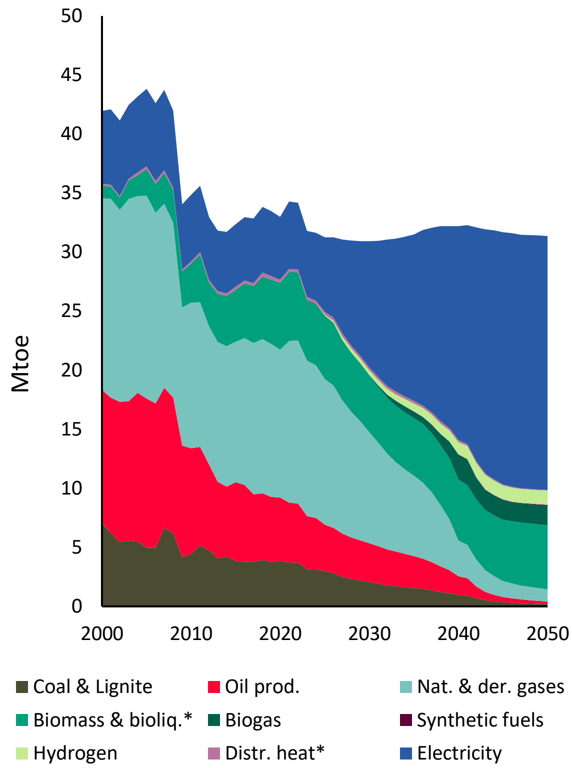
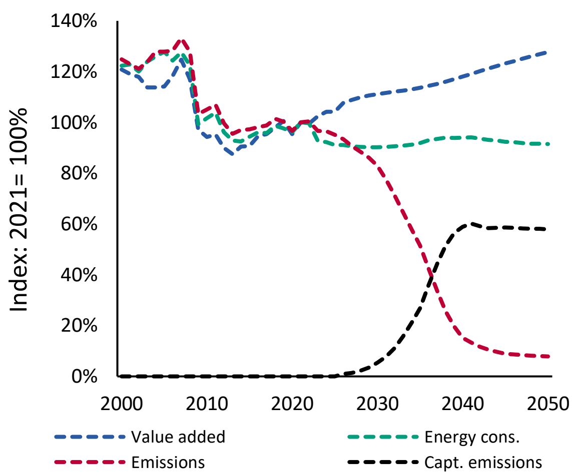


Figure 24. FEC for NMMs products[27]



Source: POTEnCIA

Figure 25. Key indicators for NMMs[28]



Source: POTEnCIA

3.3.1.2 Iron and Steel

The EU production of iron and steel was in 2021 associated with the emission of 155 Mt CO2, some 25% of all industrial GHG emissions in the Union. Transition to net-zero requires accordingly significant efforts. Figure 26 shows the historical and projected EU output of I&S products, stabilising to around 145 Mt of steel over the entire time horizon, with a modest reduction of energy-intensive primary steel and a corresponding increase of recycled electric arc steel, the latter being far less energy-intensive but supply-limited. Figure 27 shows the associated evolution of energy consumption, driven mostly by the shift of primary production from traditional blast furnace + basic oxygen furnace (BF+BOF) to direct reduced iron (DRI) operating initially in part with natural gas and progressively being replaced by hydrogen, coupled with electric arc steelmaking. BF+BOF, mostly coupled with CCS, remains as an alternative, and makes up 3% of the total 76 Mt primary production in 2050, compared to 97% produced with DRI fuelled by hydrogen. As a consequence, solid fuels strongly withdraw from the sector. Overall energy consumption reduces by 31% compared to 2021, driven by incremental energy efficiency improvements, the marginal shift to secondary production, and the lower specific energy consumption of the DRI+EAF route compared to BF+BOF.

This pervasive transformation in the prevailing production process for primary steel results in a strong acceleration of emission reductions after 2030: compared to 2021, emissions are 24% lower in 2030, 85% lower in 2040, and 90% lower in 2050. CCS makes up 4% of these emission reductions, with a yearly captured volume of 6 Mt CO2 in year 2050, as can be seen in Figure 28.

[27] Distr. heat includes geothermal and solar heat; Biomass & bioliquids includes waste

[28] Captured emissions are indexed to 2021 released emissions

Figure 26. Physical production of iron and steel

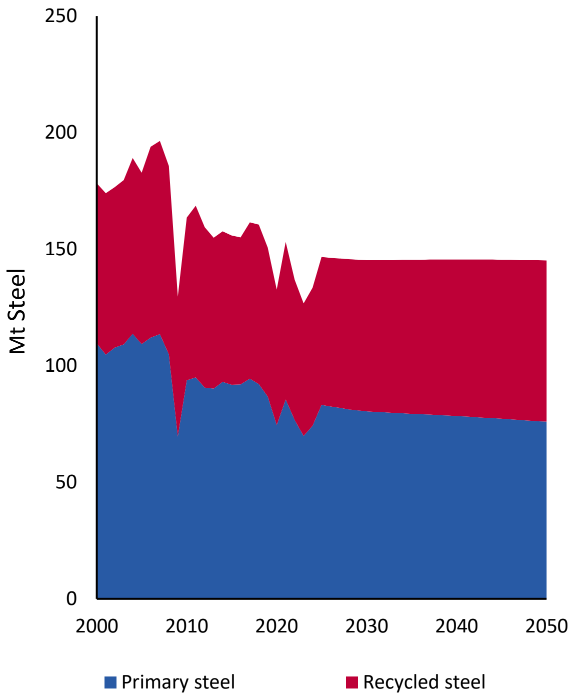
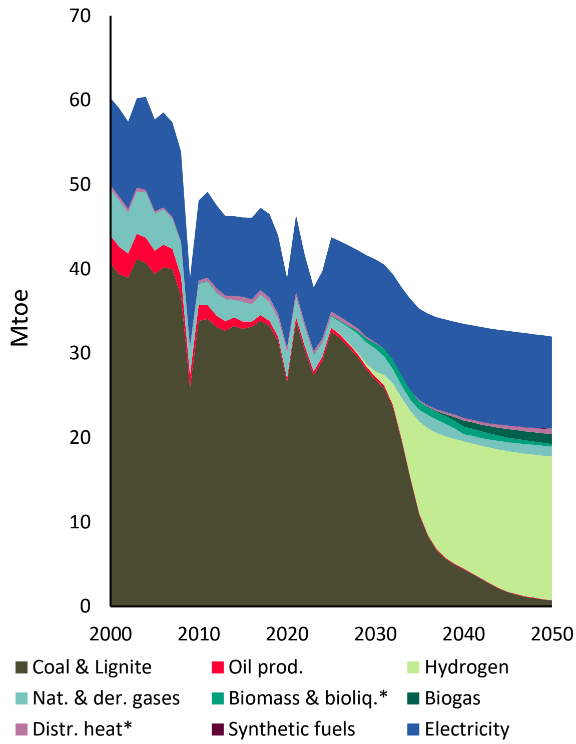
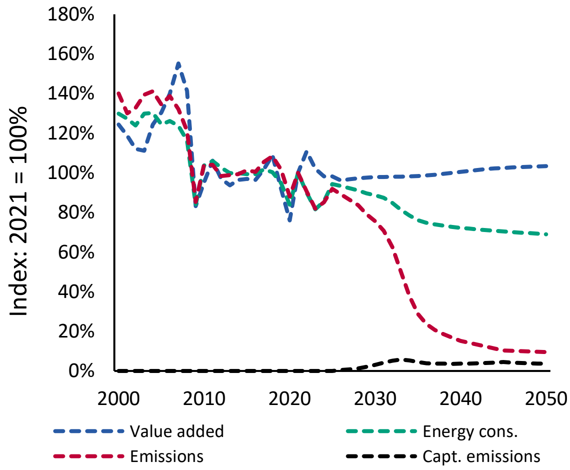


Figure 27. Energy demand of iron and steel production[29]



Source: POTEnCIA

Figure 28. Key indicators for iron and steel[30]



Source: POTEnCIA

3.3.1.3 Chemicals

In 2021, the chemicals industry, with 123 Mt of CO_2 emissions, was the third largest emitter among the industrial sectors in the EU. Combustion accounted for 63% of these emissions, while 37% were process-related emissions from various value chains including ammonia, olefins, and others. The chemical sector's heterogeneity in terms of products and processes implies that a diversification of carbon-free solutions will also be required to decarbonise the industry.

As shown in Figure 29, basic chemicals (e.g., ethylene, ammonia), which were responsible for 66% of FEC in the chemical sector in 2021, are expected to increase by 9% by 2050 relative to 2021-levels. To meet this growing demand and as a response to policy incentives, fossil FEC in the chemical industry decreases from nearly 58% in 2021 to 5% in 2050[31]. Conversely, electricity increases to 37% of FEC, distributed heat to 41%, and bioenergy combustion (predominantly biogas) to 11% (see Figure 30). Hydrogen and hydrogen-based fuels play an increasingly important role in the chemical sector, rising together to 5% of FEC and 20% of FNEC by 2050, the latter being equivalent to 15 Mtoe by then. For FNEC used as feedstock in chemical compounds, biomethanol accounts for 19 Mtoe, equivalent to 24%. However, 39 Mtoe of petroleum products and 6 Mtoe of natural gas are still used for chemicals production (when combining FEC and FNEC), highlighting the sustained reliance on fossil fuels, especially as feedstock sources. Carbon Capture, Utilisation, and Storage (CCUS) plays a significant role in reducing emissions, capturing 8.5 Mt CO_2 by 2050. As a result, emissions decrease by 87% to less than 17 Mt in 2050 compared to 2021, as visualized in Figure 31.

[29] Includes transformation losses and auto-consumption of blast furnaces; Distr. heat includes geothermal and solar heat; Biomass & bioliquids includes waste

[30] Captured emissions are indexed to 2015 released emissions: Includes emissions from energy transformation and auto-consumption in blast furnaces

[31] Both percentage numbers include non-renewable waste

Figure 29. Physical output for chemicals

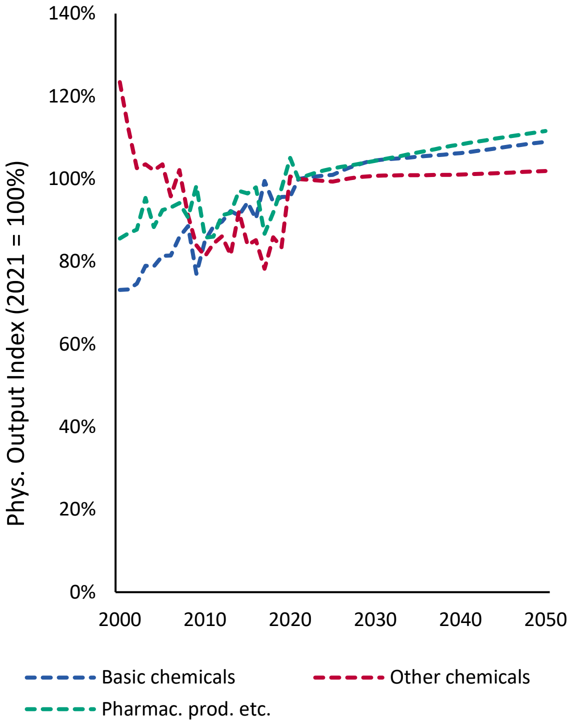
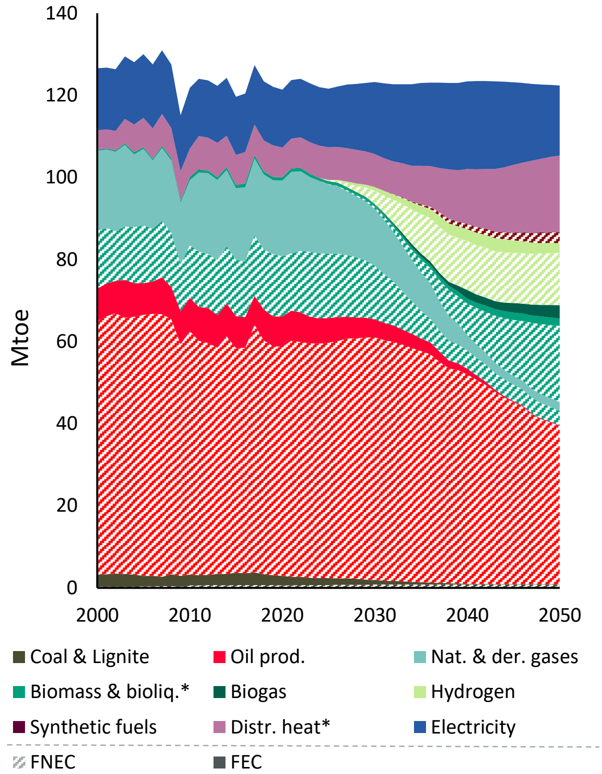
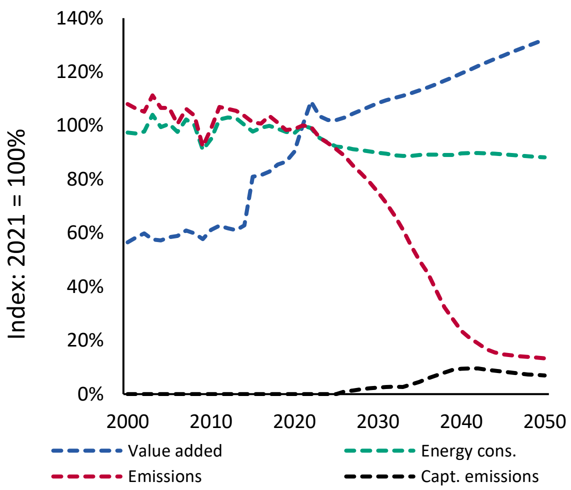


Figure 30. FEC and FNEC for chemicals[32]



Source: POTEnCIA

Figure 31. Key indicators for the chemical industry[33]



Source: POTEnCIA

3.3.1.4 Non-ferrous Metals

In 2021, the EU production of non-ferrous metals (NFM) was responsible for the emission of almost 11 Mt CO2 due to energy uses and another 5 Mt due to process emissions. The largest emitter in the non-ferrous metals sector is the production of aluminium, which including the upstream production of alumina from bauxite is responsible for 53% of the total 15.3 Mt CO2 emissions, while the remaining 47% are related to other non-ferrous metals, most notably copper, lead, and zinc. The sector faces specific decarbonisation challenges associated not only with the energy-intensity but also to the diversity of the applied production processes and to the smaller unit sizes of production facilities than in the case of integrated steelworks, which may make economies of scale more difficult to achieve than in some other sectors.

Figure 32 shows relatively stable production levels for the NFM subsectors over the projection years, with a moderate incremental growth for secondary aluminium. Figure 33 shows that already in 2021 almost 54% of FEC was electricity (strongly driven by the electricity demand of the electrolytic process of primary aluminium smelting), but increases to 79% by 2050. The remaining 46% of FEC in 2021 are primarily made up by natural gas, which by 2050 falls to only 6% mainly thanks to increased electrification, efficiency gains, and substitution of natural gas by biomethane. The latter reaches 10% by 2050 being used primarily for high temperature heat processes. Additionally, process emissions are reduced by the introduction of innovative technologies (e.g. the commercial deployment of inert anode technology for aluminium production). As a result, while total energy consumption remains rather stable over the projection period, emissions fall down to under 4 Mt in 2050, a 75% reduction compared to 2021 (see Figure 34).

[32] Distr. heat includes geothermal and solar heat; Biomass & bioliquids includes waste; Biomethanol and synthetic methanol can be used as feedstock for the production of chemicals

[33] Captured emissions are indexed to 2021 released emissions

Figure 32. Physical output for non-ferrous metals

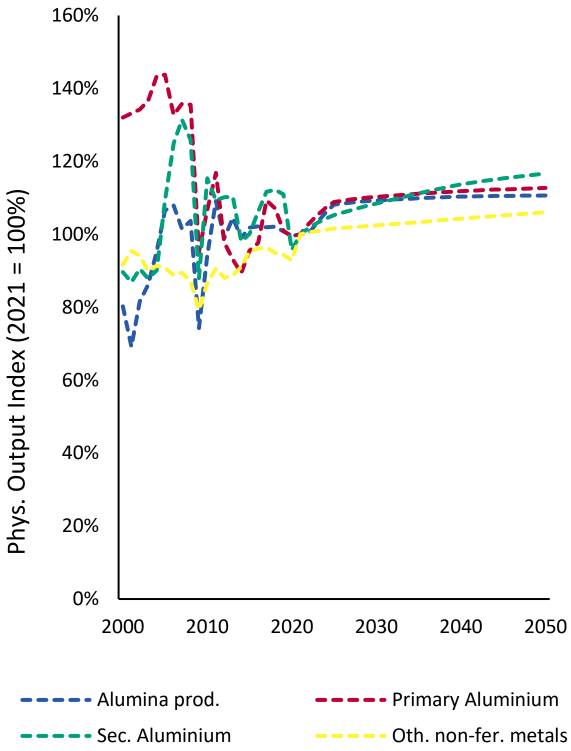
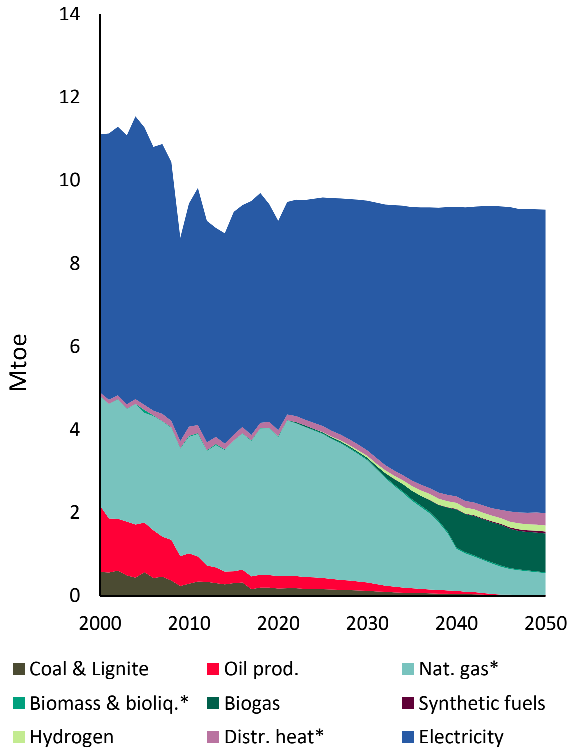


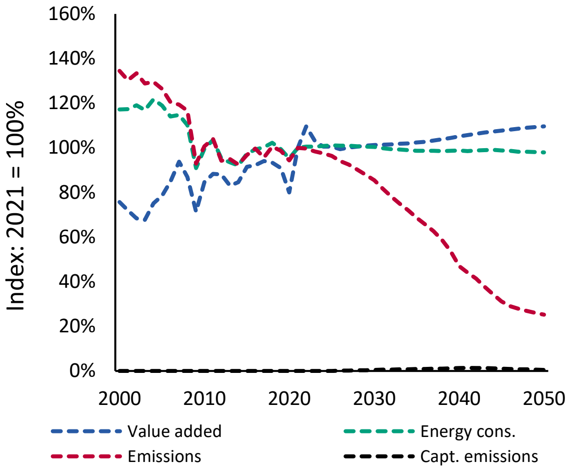
Figure 33. FEC for non-ferrous metals[34]



Source: POTEnCIA

[34] Distr. heat includes solar thermal heat (<1% of combined FEC over entire time period); Biomass & bioliquids includes waste (<1% of combined FEC over entire time period); Natural gas includes minor shares of derived gases (<2.4% of combined FEC over entire time period)

Figure 34. Key indicators for non-ferrous metals[35]



Source: POTEnCIA

3.3.1.5 Pulp and Paper

The EU produced 37 Mt of pulp and 87 Mt of paper in 2021, with the entire sector emitting 24 Mt of fossil CO2. Figure 35 shows relatively stable output of the pulp and paper industry over the projection period, with a modest reduction of pulp production compensated by an incremental increase in paper recycling efficiency. Historically, the sector has relied heavily on biomass for energy purposes, but almost equal amounts of electricity and fossil fuels have been consumed in the production processes within the EU in 2021, as shown in Figure 36. Since then, the use of solid and liquid fossil fuels has been progressively reduced and been replaced by increased consumption of electricity and biomass. Increasingly ambitious decarbonisation targets drive an intensification of this process in the coming decades, where also natural gas is substituted by non-emitting energy sources. Consequently, by 2050, 54% of the FEC is satisfied by biomass sources (including biogas) and 35% from direct electricity use, with only small amounts of natural gas use remaining, equivalent to 2%. In addition to the switch towards non-emitting fuels, 3.6 Mt of CO2 are captured in the pulp industry by 2040 and 5.7 Mt by 2050, of which 5.5 Mt (equivalent to 97%) are BECCS. The sum of all decarbonisation measures results in emissions reduction of 92% by 2050 compared to 2021, see Figure 37. When including BECCS, the entire sector emissions become net negative.

[35] Captured emissions are indexed to 2021 released emissions

Figure 35. Physical output for pulp and paper

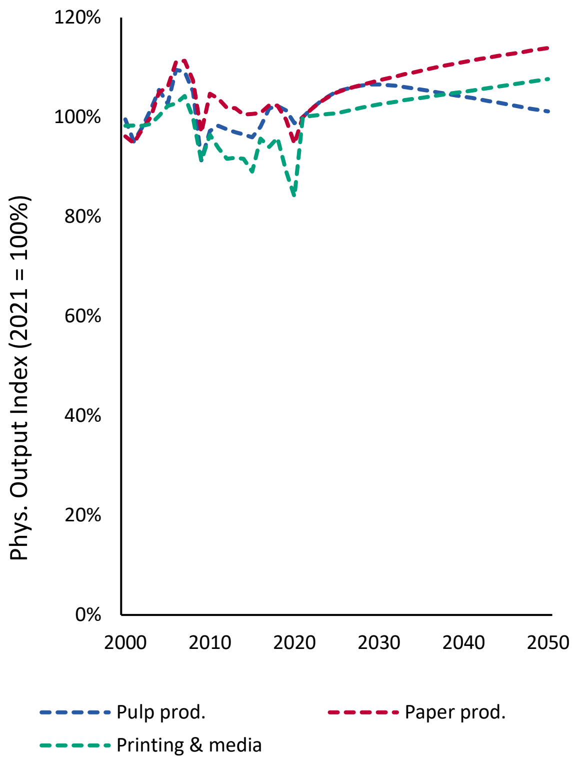
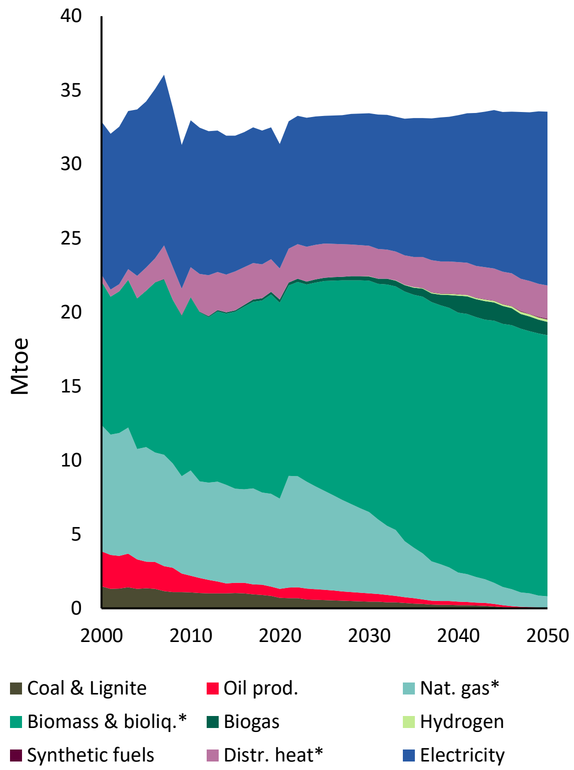
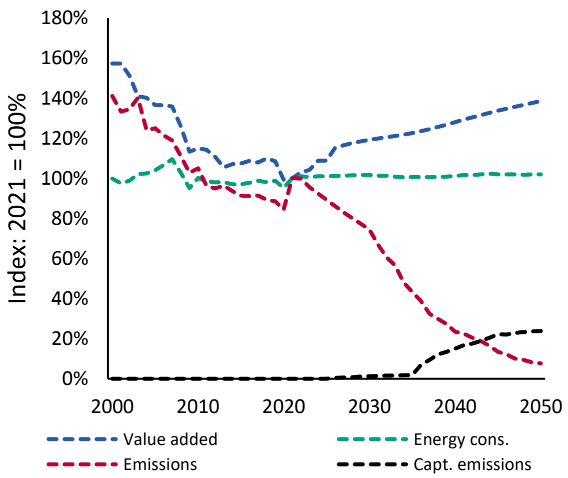


Figure 36. FEC for pulp and paper[36,37]



Source: POTEnCIA

Figure 37. Key indicators for pulp & paper[38]



Source: POTEnCIA

3.3.1.6 Non-energy-intensive Industries

Non-energy-intensive industries tend to require less energy per unit of output, and much smaller shares of high temperature process heat, than energy-intensive ones. Moreover, they are not a significant source of process emissions. But while this may suggest that the technical challenges to decarbonisation may accordingly be less critical, the sheer combined economic size of these industries makes their contribution to GHG emissions considerable. The non-energy intensive group of industries is represented by the following sector breakdown:

- Food, Beverages, and Tobacco
- Transport Equipment
- Machinery Equipment
- Textiles and Leather
- Wood and Wood products
- Other Industrial Sectors

In total, over 107 Mt CO_2 originated from these sectors in the EU in 2021. The food, beverages, and tobacco industries accounted for the most emissions with 41 Mt CO_2. The physical output across all sectors is projected to grow between 14% and 31% compared to 2021, except for wood and wood products, where output stagnates, and textiles and leather, where output follows the downwards trend experienced in the past decades (see Figure 38). Figure 39 shows that energy consumption by 2050 is 20% lower than in 2021, driven predominantly by energy efficiency improvements in various production processes. In 2021, of the total 91 Mtoe of energy consumed, 41 Mtoe (or 46%) were fossil fuels (incl. non-renewable waste), decreasing to 11 Mtoe (or 15%) by 2040 and only 3 Mtoe (or 4%) by 2050 thanks to substitution by carbon-neutral energy carriers such as solid biomass, biogas, and an increased reliance on distributed heat and direct electrification, including the intensified use of heat pumps. As a result, the non-energy-intensive sectors' emissions in 2050 shrink to 8 Mt CO_2, a 92% reduction compared to 2021 (see Figure 40).

Figure 38. Physical output for non-energy-intensive industries

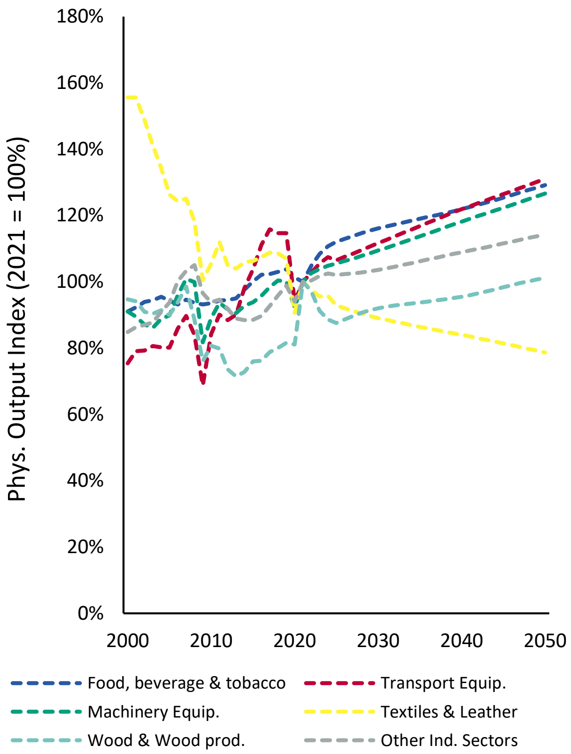
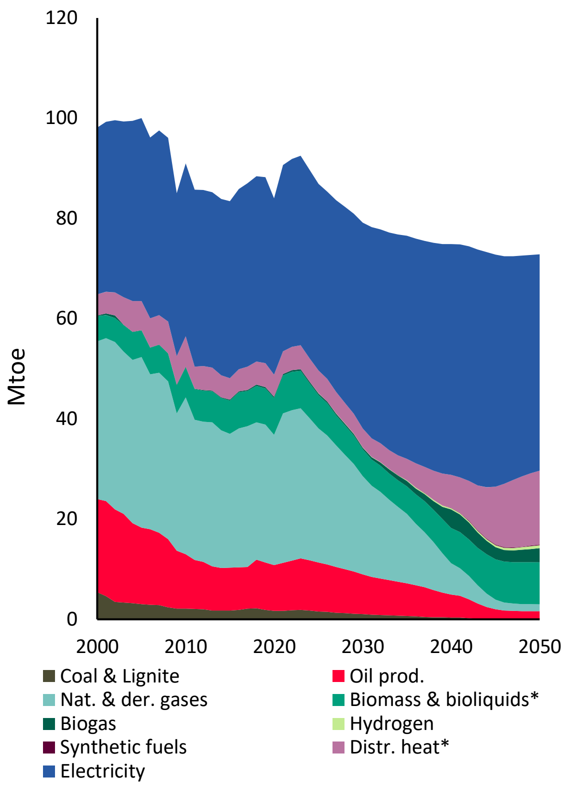
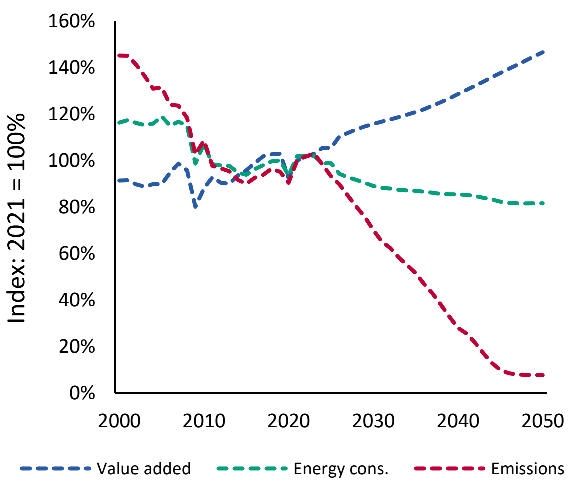


Figure 39. FEC for non-energy-intensive industries[39]



Source: POTEnCIA

Figure 40. Key indicators for non-energy-intensive sectors[40]

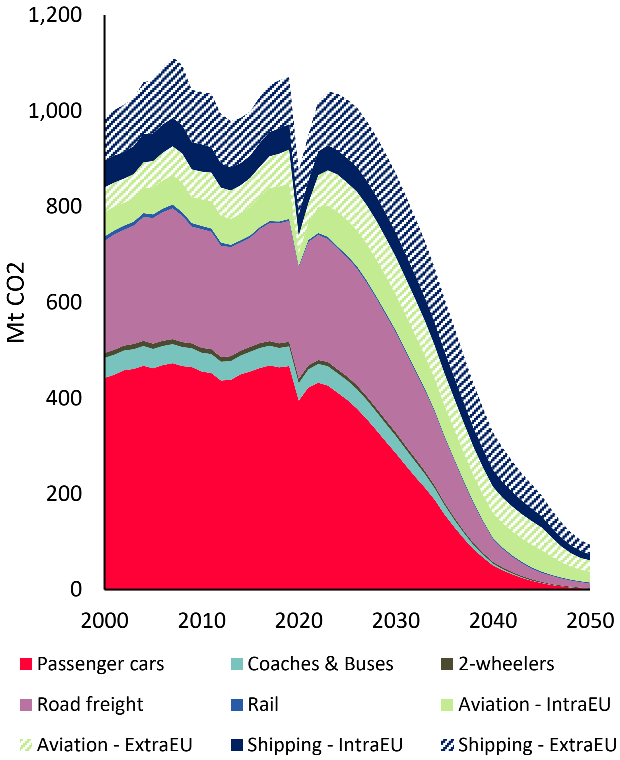


Source: POTEnCIA

3.3.2 Transport

The transport sector at large (including international transport activities) is the largest emitter among all end use sectors in the EU, with emissions ranging between 950 and 1070 Mt CO2 over the past 10 years (see Figure 41), responsible for 21-25% of all EU GHG emissions. Except for temporary events like the 2020 dip induced by the transport activity demand drop resulting from the efforts to contain the COVID pandemic, this level of emissions has been relatively stable over more than two decades. This period has seen the materialisation of incremental improvements in energy efficiency as well as the introduction of higher blending rates of biofuels, but these have been offset by the fast growth of transport demand, both to satisfy passenger mobility needs and for the transport of an increasing volume of goods over greater distances, following economic growth and the further regional and global integration of markets.

Figure 41. Emissions in the transport sector



Source: POTEnCIA

Following these trends along the projection period to 2050, both passenger and freight transport demand keep growing rapidly, as shown in Figure 42 and Figure 43. While EU freight transport sectors were less severely affected by the COVID pandemic and recovered already in 2021 to pre-COVID activity levels, most passenger sectors fully recover only between 2023 and 2025.

While all passenger transport sectors keep growing, rail and aviation experience stronger momentum than road transport sectors: Passenger car activity is projected to rise moderately by 23% in 2050 compared to pre-COVID 2019-levels, with the growth curve flattening out after 2040, as shown in Figure 44. However, in total passenger-kilometres (pkm) remain by far the dominating transport mode with 5292 bn pkm travelled in 2050. Activity in buses and coaches grows more strongly by 39% until 2050. Passenger aviation transport grows by 44% in the same time frame to reach 2095 bn pkm, being surpassed only by the rail passenger sector, which grows by 55% reaching 788 bn pkm. A stronger momentum for rail and aviation is also projected in the freight transport sectors, albeit the growth gap with the road sector is smaller. Rail freight transport is projected to almost double between 2019 and 2050, increasing by 93%, as shown in Figure 45. Activities of the other freight transport sectors follow with growth rates between 46-57%. However, when combining intra-EU and extra-EU shipping, the total sum of waterborne tonne-kilometres (tkm) grows from 8643 bn tkm to 13140 bn tkm.

Figure 42. Passenger transport activity by mode[41]

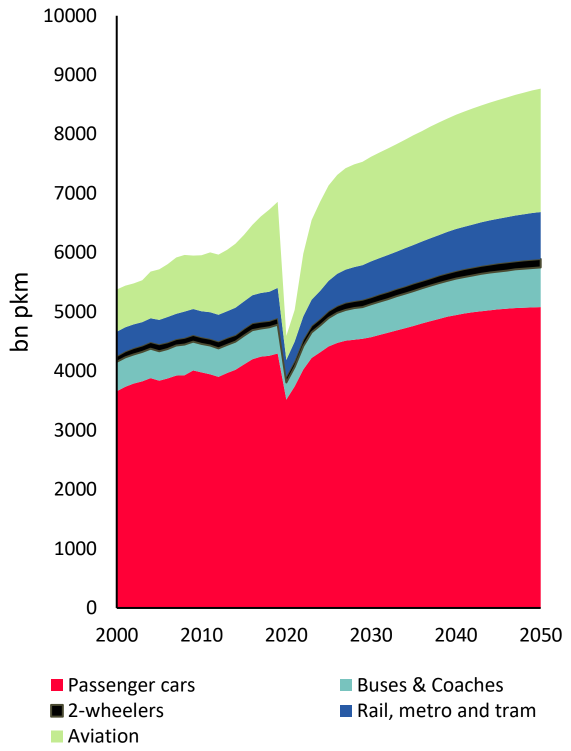
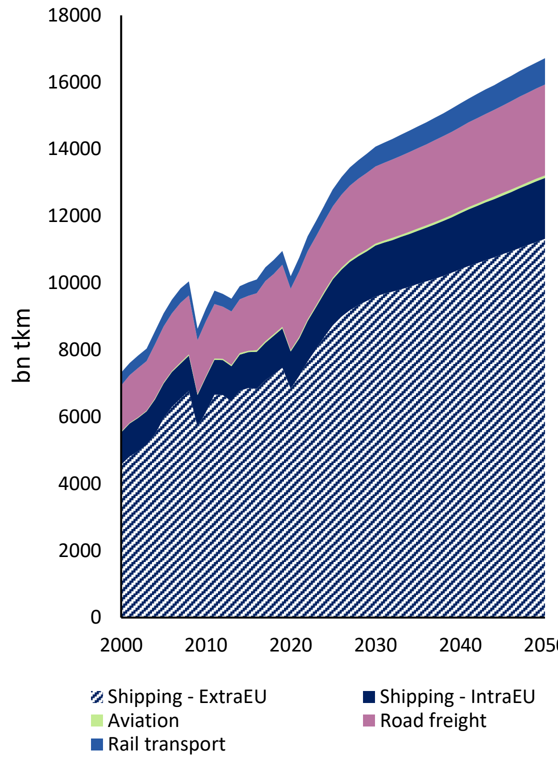


Figure 43. Freight transport activity by mode[41]



Source: POTEnCIA

To accelerate the decarbonisation of the transport sector, the EU has adopted a comprehensive policy framework that includes, in particular:

- Extension of the **EU ETS** coverage to the aviation and international shipping sectors
- **ETS2**, covering emissions from combustion of fuels in road transport (among other sectors)
- **RED III** together with **AFIR** providing a framework to incentivise the substitution of fossil fuels by renewable fuels of biological and non-biological origin, and by renewable electricity
- **CO2 standards** for new cars and vans, and for heavy-duty vehicles
- **ReFuelEU Aviation** setting low-carbon fuel targets in the corresponding sectors
- **Fuel EU Maritime** limiting GHG emissions intensities with gradually stricter reduction levels for shipping fleets

These policies drive a pervasive transformation of the transport sector's energy consumption, which are summarised by two major general trends: firstly, the rapid uptake of electric vehicles in road transport, replacing Internal Combustion Engines (ICEs) almost entirely in several sectors (e.g. passenger cars). Due to the much higher efficiency of electric motors, this shift is reflected by a

[41] Extra-EU activities for aviation are fully included

significant reduction of FEC, as can be seen in Figure 46; secondly, the replacement of fossil fuels with biofuels and RFNBOs, which emerges as the predominant means of decarbonisation in the aviation and maritime sectors. This substitution process has already started with biofuels and continues to increase, but the future composition of biofuel sources and products undergoes a profound transformation (see chapter 3.4.3.3). The uptake of hydrogen and hydrogen-based synthetic fuels starts in the late 2020s, but accelerates rapidly in the 2040s with wider availability of hydrogen. As a consequence, by 2050 renewable fuels make up for 49% of total transport energy demand, electricity 37%, and oil products and gas are reduced to a remaining 14%, as shown in Figure 47.

Figure 44. Relative passenger transport activity by mode[42]

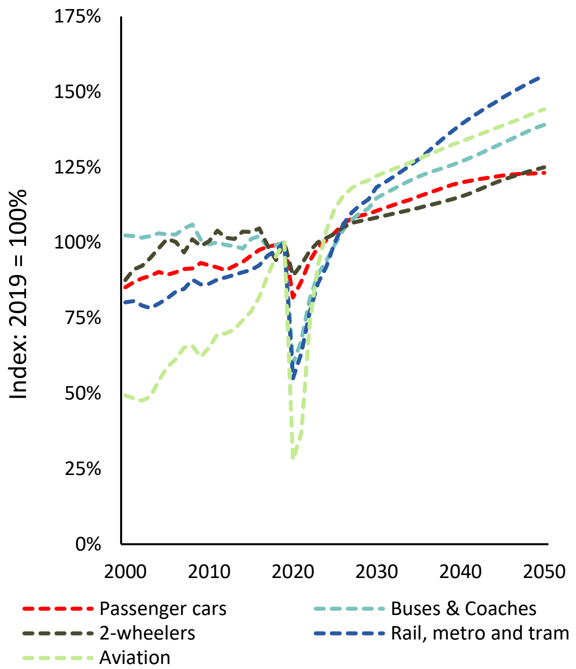
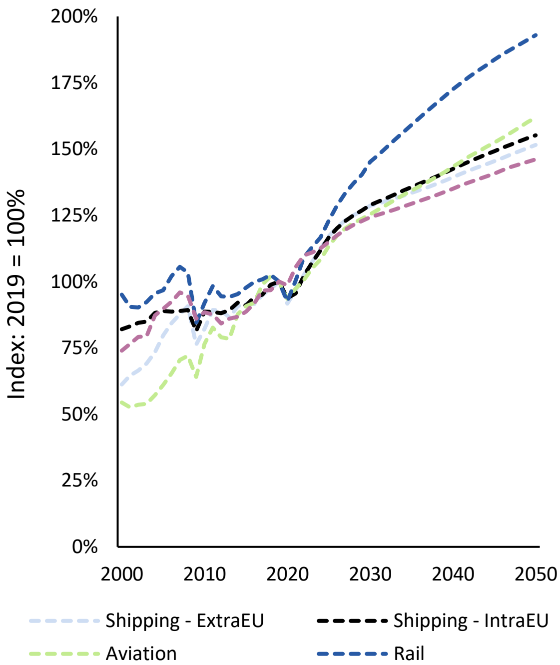


Figure 45. Relative freight transport activity by mode[42]



Source: POTEnCIA

[42] Extra-EU activities for aviation are fully included

Figure 46. Energy demand in transport by sector[43]

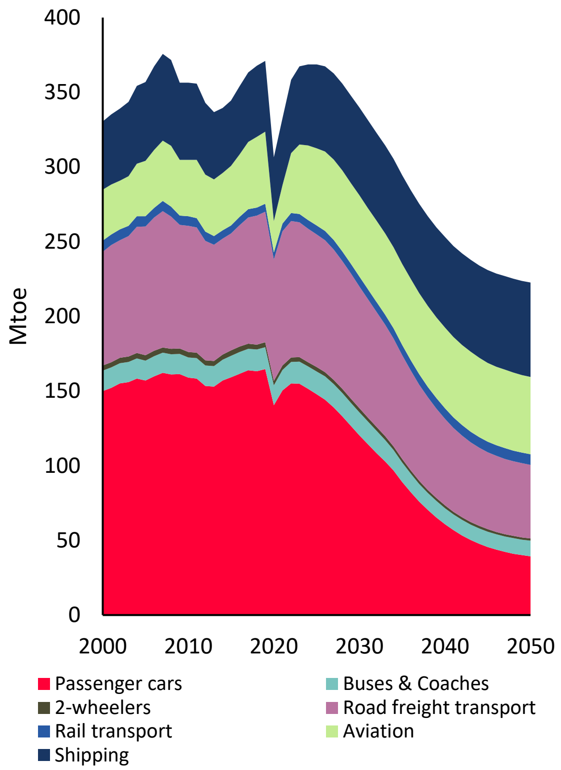
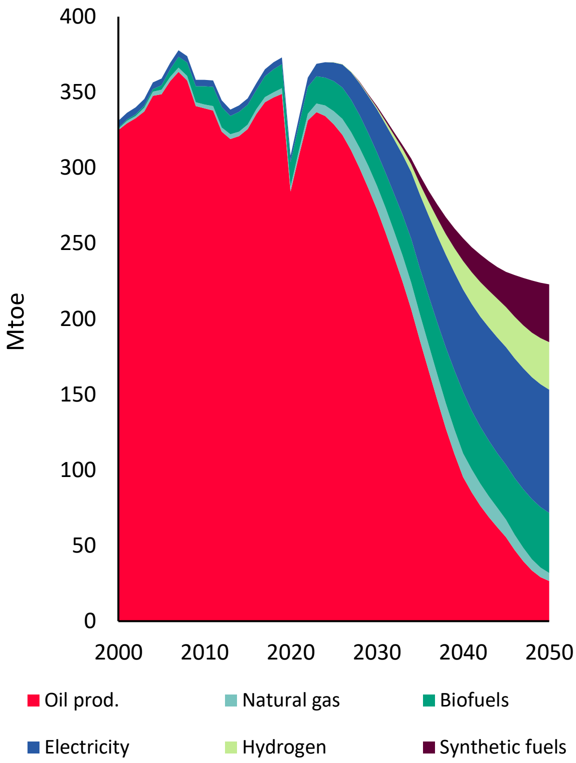


Figure 47. Energy demand in transport by fuel[44]



Source: POTEnCIA

3.3.2.1 Passenger Cars

Figure 48 shows that after an 18% reduction in 2020 due to COVID lockdowns, transport activity by passenger car quickly rebounds to pre-COVID levels in 2023, and increases by 23% towards 2050 (compared to 2019). Despite this, the associated energy consumption drops by 76% while CO2 emissions reduced to essentially zero from a 2019-level of 467 Mt CO2, with passenger cars being the largest emitters of all transport means. These striking dynamics are determined by the massive shift from ICE engines to low- and zero-emissions vehicles driven by the progressive tightening of the CO2 standards for new cars and by the stock turnover dynamics, as illustrated in Figure 49. By 2035 the CO2 standards Regulation only allows the sale of zero-emissions vehicles, so that once the fleet is completely renewed the sector is effectively decarbonised. The associated steep drop in energy demand is related to the prevailing zero-emission technology, battery electric vehicle (BEV), having a much higher energy efficiency than thermal engines. Hydrogen fuel cell cars experience a much slower penetration, mostly after 2040, until they reach a market share of around 3% of the stock by 2050.

Driven by several elements of the 2030 policy framework (especially REDIII in combination with ESR and ETS2), the further continuation of decarbonisation objectives, and by the wider availability of drop-in fuels such as Fischer-Tropsch diesel replacing first-generation biodiesel, biofuel (and RFNBO)

[43] Energy demand for international (including extra-EU) aviation and shipping is fully included

[44] Energy demand for international (including extra-EU) aviation and shipping is fully included

blending shares progressively increase from an average 6% in 2021 to 30% in 2040 onwards. However, the withdrawing share of thermal engines in the passenger cars fleet makes the overall importance of biofuels in achieving decarbonisation objectives progressively wane in the sector.

Figure 48. Key indicators for passenger cars

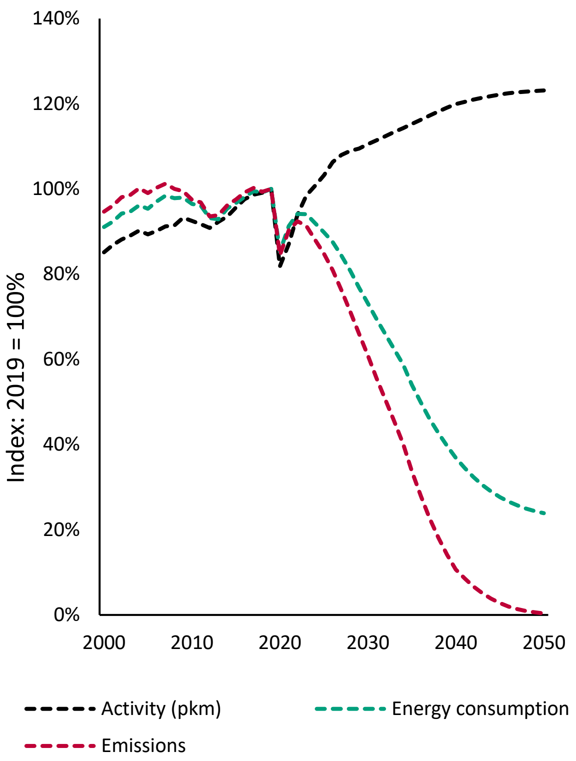
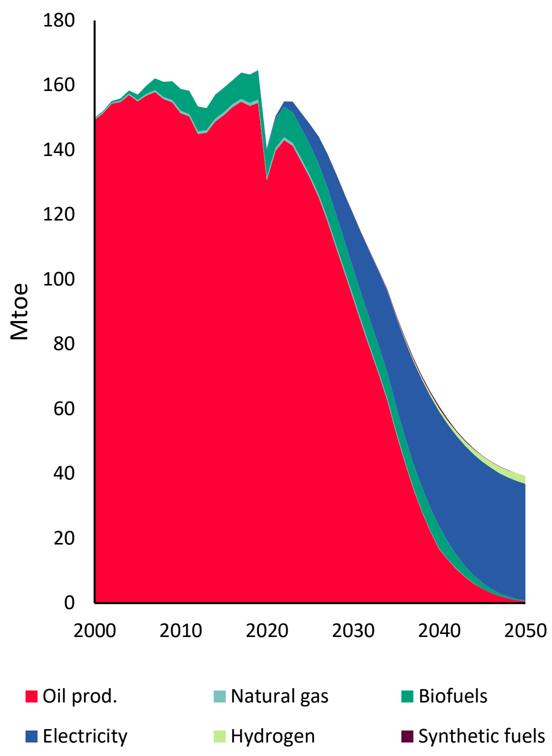


Figure 49. FEC for passenger cars



Source: POTEnCIA

3.3.2.2 Buses and Coaches

Before the COVID pandemic, passenger transport by buses and coaches caused 41 Mt CO2 in 2019. Nevertheless, the sector has been severely affected by the COVID pandemic, with an activity drop of over 40%. Since then the activity has roughly recovered to the pre-COVID level and is projected to further grow by an additional 39% until 2050 relative to 2019, as shown in Figure 48. This is aided by support policies, at local, national, and EU level, aiming to encourage the shift from private to public transport. While this activity increase implies a short-term uptake of FEC by up to 7% until 2030, a long-term transition towards more efficient technologies causes a reduction of 28% towards 2050 relative to 2019. Figure 51 shows that in the late 2020s and early 2030s, natural gas and biofuels partially replace diesel combusted in ICE vehicles. However, at the same time the shift towards BEV buses and coaches occurs, which then takes off rapidly in the 2030s, so that by 2030 already 16% of the fleet are BEV, rising steadily to 86% in 2050. Hydrogen-driven Fuel Cell Electric Vehicles (FCEV) satisfy a niche market for hard-to-electrify routes, making up 12% of the stock by 2050. Similar to the case of passenger cars, the CO2 standards regulation drives a progressive phase-out of ICE vehicles, while the renewables policy and emission caps contribute to a gradual increase of renewable fuel blending rates in the residual fuel consumption. Consequently, the buses and coaches sector achieves virtual zero emissions by 2050 with intermediate emissions reduction milestones reached of 12% by 2030 and 90% by 2040 compared to 2019-levels.

Figure 50. Key indicators for buses and coaches

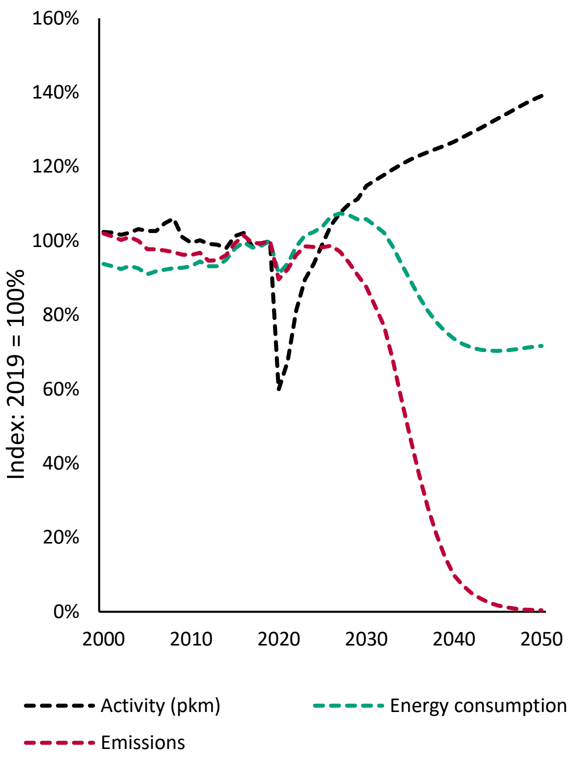
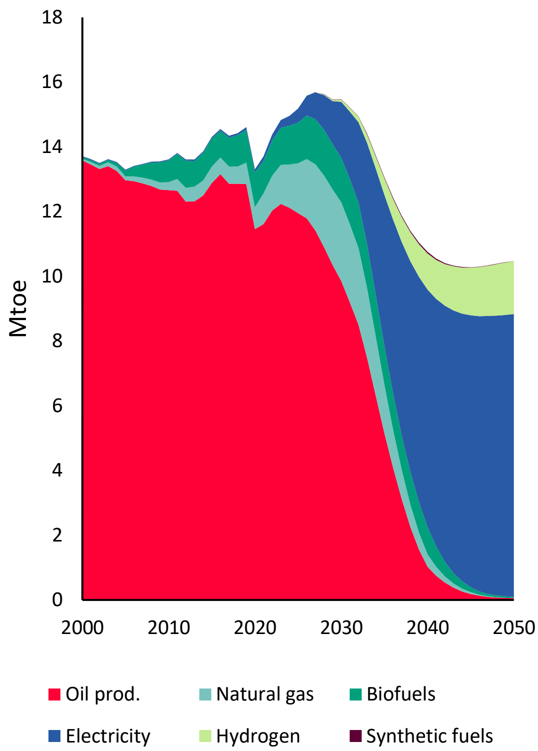


Figure 51. FEC for buses and coaches



Source: POTEnCIA

3.3.2.3 Powered 2-Wheelers[45]

Compared to other road passenger transport modes, there are no comparable CO2 emission standards are in place for powered 2-wheelers. However, the scope of the ESR, ETS2 and RED III also affect the sector. Figure 52 shows a projected activity growth of 25% until 2050 compared to pre-COVID 2019, yet during the same period energy consumption decreases by 57%. This is mostly due to a switch to more energy-efficient BEV motorcycles, while at the same time increasing blending shares of renewable fuels support the decarbonisation of ICE-powered motorcycles. The effects of this transition cause emissions to drop from 8 Mt in 2021 to 1 Mt in 2050 and FEC becoming dominated by electricity, the latter being displayed in Figure 53.

[45] Includes 3-Wheelers and quadricycles

Figure 52. Key indicators for powered 2-wheelers

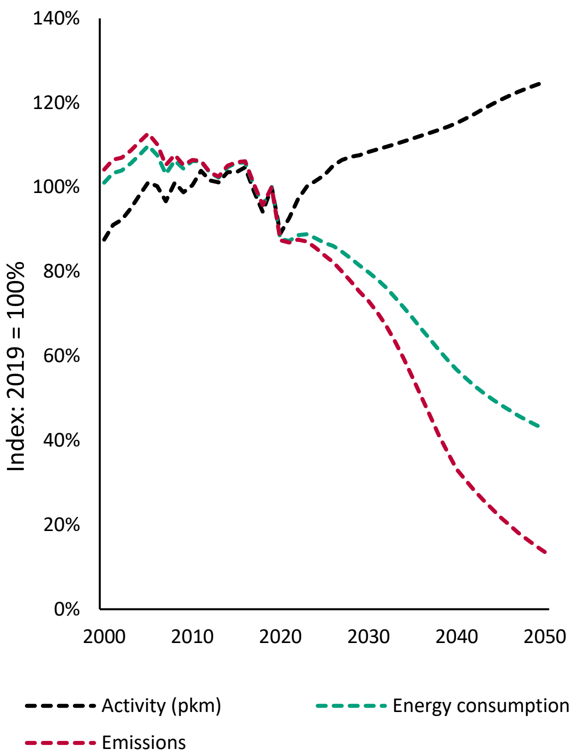
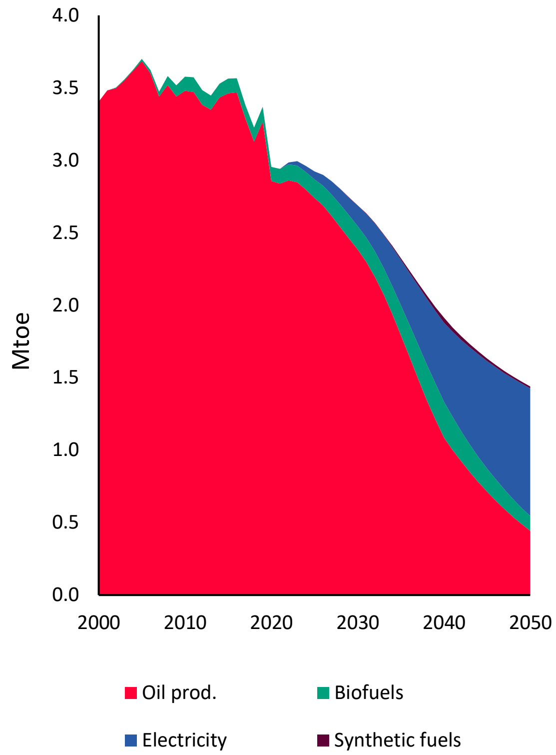


Figure 53. FEC for powered 2-wheelers



Source: POTEnCIA

3.3.2.4 Road Freight Transport

Compared to passenger transport, both domestic and international road freight transport were less severely impacted by the COVID 2021 pandemic, with a relatively modest freight activity drop in 2020. Compared to pre-COVID 2019-levels, road freight transport activity expressed in tkm is projected to increase by 25% and 24% in 2030 for light commercial vehicles (LCVs) and heavy goods vehicles (HGVs), respectively. This growth is sustained until 2050, with a cumulative growth reaching 49% for LCVs and 46% for HGVs (see Figure 54 and Figure 56).

Despite the increasing demand, both sectors' energy consumption revert to 2019-levels in the late 2020s, as shown in Figure 55 and Figure 57. Starting from 2030, the LCV sector decarbonizes similarly to the passenger car sector by predominantly switching towards BEV. Incremental energy efficiency improvements together with the progressive switch to zero-emission vehicles, especially BEV, with lower specific energy consumption than ICE powertrains effectively offset the energy demand of the increasing activities. As a result, FEC drops by 66% in 2050 compared to 2019-levels.

In the HGV sector, fleet dynamics follow a different decarbonisation trajectory: Especially for long-haul transportation, BEVs face strong competition from ICE vehicles fuelled with increasingly high renewable fuel blends in the short-term and also, increasingly in the long-term, hydrogen-fuelled FCEV. In the 2030s, BEVs are the dominant zero-emission technology for new investments, closely followed by hydrogen-fuelled FCEVs, respectively reaching 38% and 21% of total fleet shares in 2040 (when summing up domestic and international HGVs in Figure 58). After 2040, the BEV fleet shares continue to rise to reach 64% (4.7 mn vehicles), while FCEV HGVs only see a marginal further increase to 23% (1.7 mn vehicles) in 2050. The remaining 13% of HGV stock are ICEs, primarily diesel-fuelled but also –to a lesser degree- natural gas fuelled. The remaining emissions of diesel HGVs are mitigated by increasing blending shares of biodiesel (and smaller amounts of synthetic diesel), surging from 7% in 2021 to 44% in 2040 and further increasing slightly until 2050[46]. Despite the strong activity growth and the incomplete electrification, the energy consumption of HGVs reduces by 31% in 2050 compared to 2019.

For both LCVs and HGVs, the transition towards more efficient and increasingly zero-emission fleets is crucially driven by the sector-specific CO2 standards, accompanied by enabling measures such as AFIR. However, in contrast to light-duty vehicles, the CO2 standards for heavy-goods vehicles prescribe for the long term a 90% reduction of new-fleet-averaged tailpipe emissions rather than only allowing for the sale of zero-emission vehicles. With the remaining emissions of diesel HGVs mitigated by increasingly high renewable fuel blending shares, HGV emissions drop from 163 Mt CO2 in 2019 to 10 Mt CO2 in 2050. The LCV sector, from 90 Mt CO2 in 2019, is essentially fully decarbonised by 2050.

Figure 54. Key indicators for LCVs

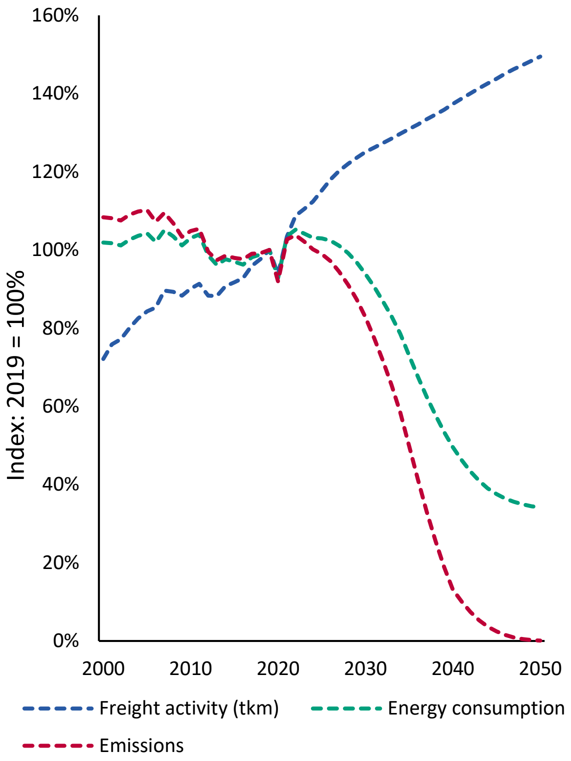
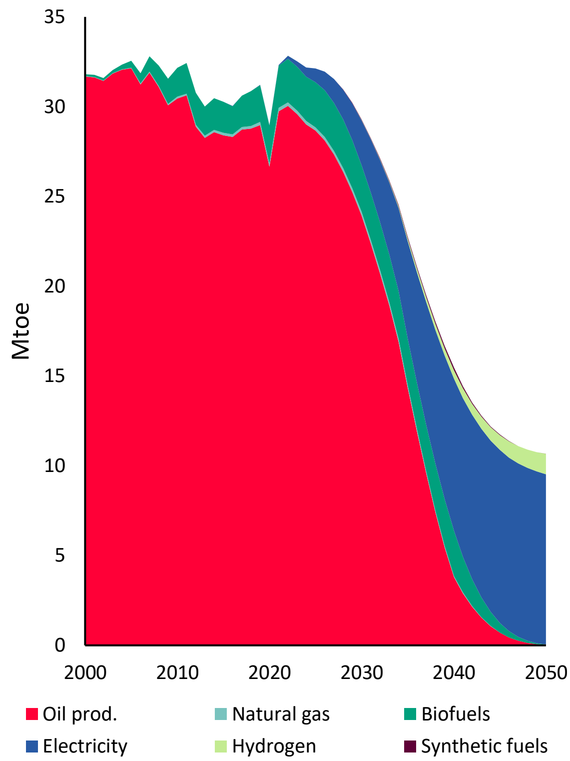


Figure 55. FEC for LCVs



Source: POTEnCIA

[46] This includes high shares of advanced biodiesels enabling high blending shares

Figure 56. Key indicators for HGVs[47]

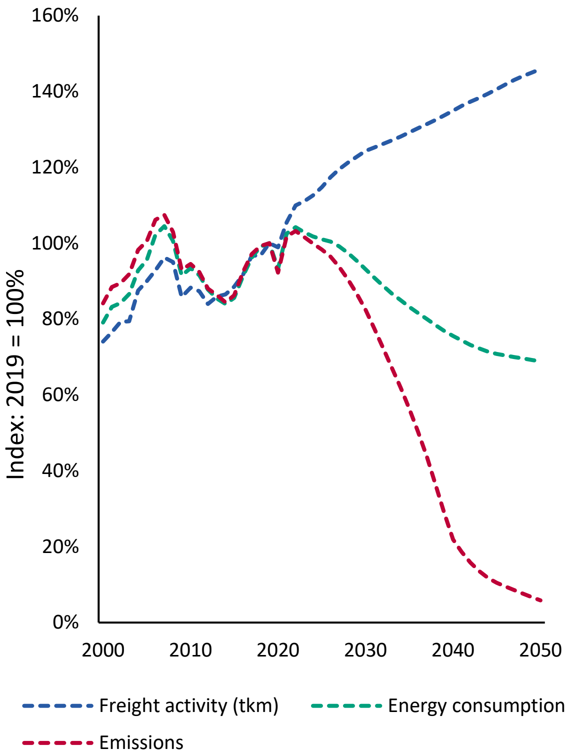
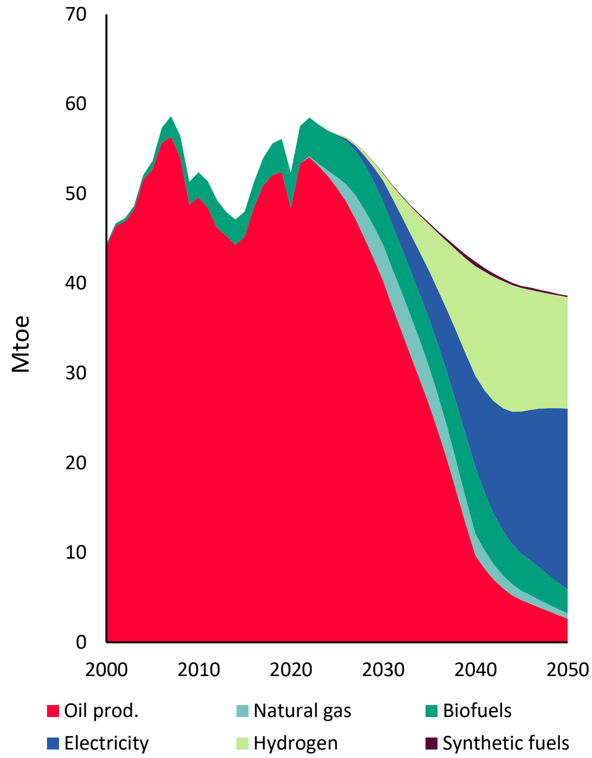
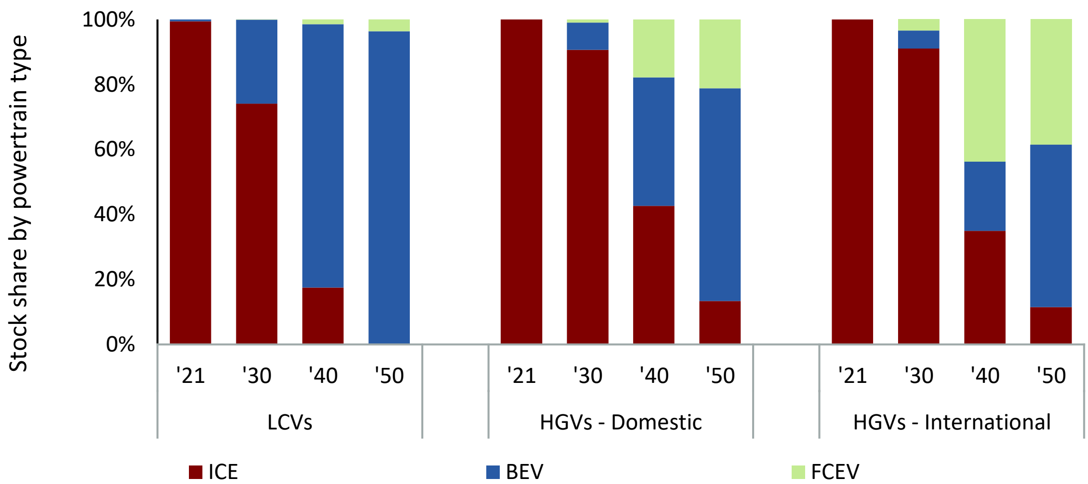


Figure 57. FEC for HGVs[48]



Source: POTEnCIA

Figure 58. Vehicle stock by powertrain type[49]



Source: POTEnCIA

[47] Includes domestic as well as international heavy goods vehicles

3.3.2.5 Rail and Metro

Supported by a policy framework[50] that promotes modal shifts from road to rail, rail transport is projected to experience strong growth: Compared to 2019, rail freight activity almost doubles by 2050 and rail passenger activity, after recovering from the COVID shock to its 2019 activity level in the mid-2020s, expands by an additional 55% by 2050 (see Figure 59). The rapid growth causes an increase in total FEC of 25% by 2030 and then an additional 6% by 2050. While in the past decades, FEC of both electricity and oil products has been reduced, in the next decades this trend is reversed for electricity consumption as electric trains are the fastest growing option to satisfy passenger and freight transport demand. As most rail transport is electrified already, emission reductions after 2030 are due to further incremental increases in electrification rates and, for hard-to-electrify rail routes, increasing shares of biofuels in the diesel blends (see Figure 60). As a result, CO2 emissions fall to 1.9 Mt CO2 by 2050, exactly half of the 2019-level.

Figure 59. Key indicators for rail and metro[51]

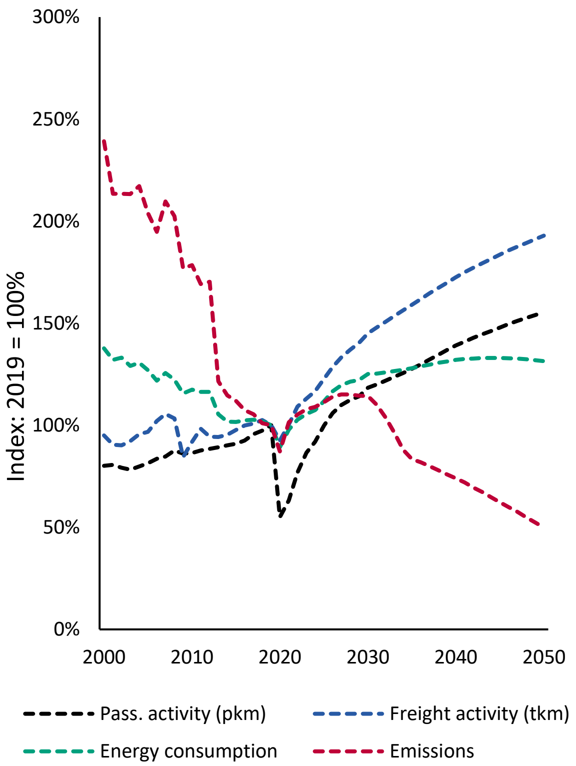
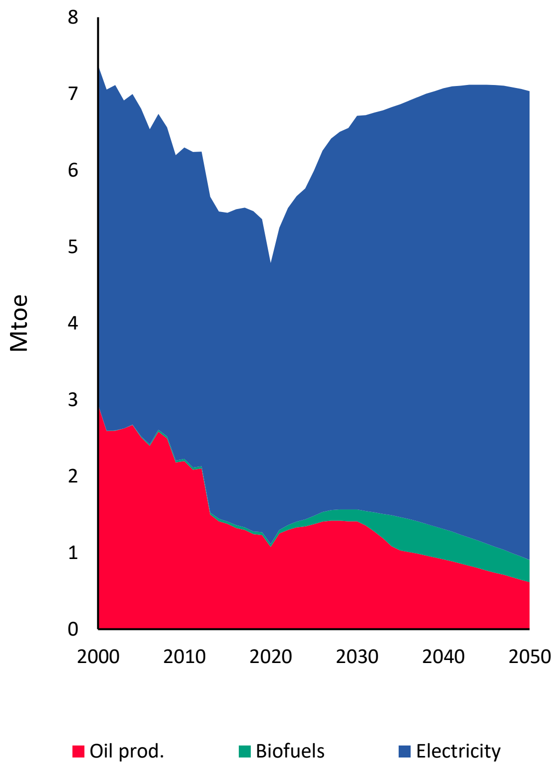


Figure 60. FEC for rail and metro



Source: POTEnCIA

[48] Includes domestic as well as international heavy goods vehicles

[49] BEV include plug-in hybrid ICE vehicles

[50] This includes the TEN-T initiative aiming to enhance cross-border rail connections and to improve the overall rail infrastructure, as well as a number of additional policies introduced by the EU and by individual Member States

[51] Emissions and energy consumption from freight and person transport have been aggregated for rail transport

3.3.2.6 Aviation[52]

After decades of steady growth, CO_2 emissions from EU aviation reached 145 Mt CO_2 in 2019, but were then heavily affected by the COVID crisis with an unprecedented 72% loss of air passenger activity, from 1453 bn pkm in 2019 down to 407 bn pkm in 2020. Figure 61 highlights how the unprecedented loss of air passenger activity, determined by the COVID crisis in 2020, is quickly recovered in the early 2020s to reach 1775 bn pkm in 2030 and 2095 bn pkm by 2050, a growth of 44% compared to pre-COVID 2019-levels. Freight aviation operates on a comparatively much smaller scale, but its growth rate mirrors passenger aviation's.

Significant efficiency gains achieved by newer aeroplane models causing energy consumption per pkm to drop by 27% from 2019 to 2050, are still outpaced by the strong growth in activity demand resulting in increasing fuel consumption. To accelerate decarbonisation, the recently updated EU legislative framework for Climate and Energy (in particular through the inclusion of aviation in the EU ETS and through the ReFuelEU Aviation Regulation's requirement to progressively increase the share of sustainable aviation fuels (SAFs) in fuel blends) confronts the aviation sector with decarbonisation requirements beyond the reach of efficiency measures alone.

Over the projection period increasing shares of biokerosene and synthetic kerosene are blended in aviation fuels supplied at EU airports, as shown in Figure 62. As the definition of SAFs excludes fuels derived from food and feed crops, biokerosene is initially supplied via the HEFA route using as feedstock used cooking oils or intermediate crops. As rapidly increasing demand exceeds the available supply of the relatively cheap HEFA fuel, advanced Fischer-Tropsch biokerosene as well as Synthetic kerosene (which is also subject to a specific RFNBO sub-target of ReFuelEU Aviation) follow in the 2030s and ramp up rapidly in the 2040s. Thus, SAFs reach combined blending shares of 6% in 2030, 34% in 2040, and 70% in 2050. This results initially in the peaking of aviation emissions above pre-COVID levels in the late 2020s reaching 158 Mt CO_2, 9% above the 2019-level. However, then mitigation measures lead to a fast reduction to 107 Mt CO_2 in 2040 and 47 Mt CO_2 in 2050, reductions of 26% and 68% compared to 2019-levels, respectively.

[52] Including all Extra-EU aviation for both passengers & freight in this chapter and displayed graphs

Figure 61. Key indicators for aviation

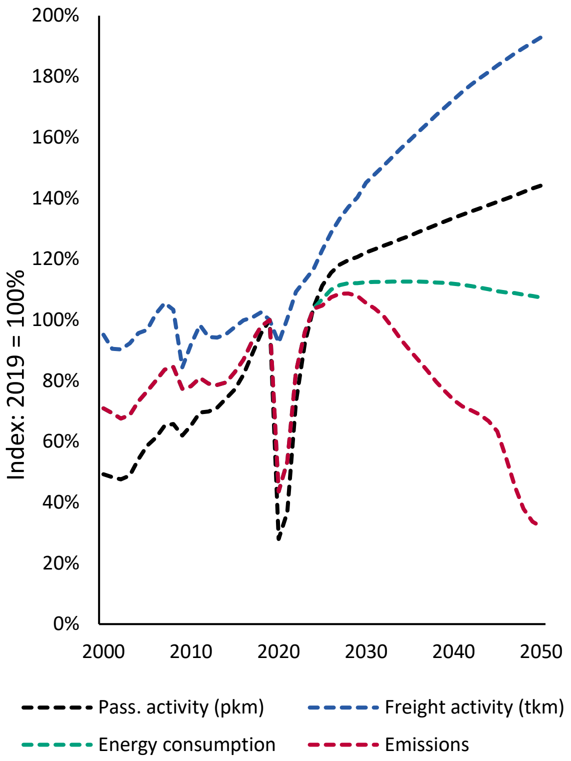
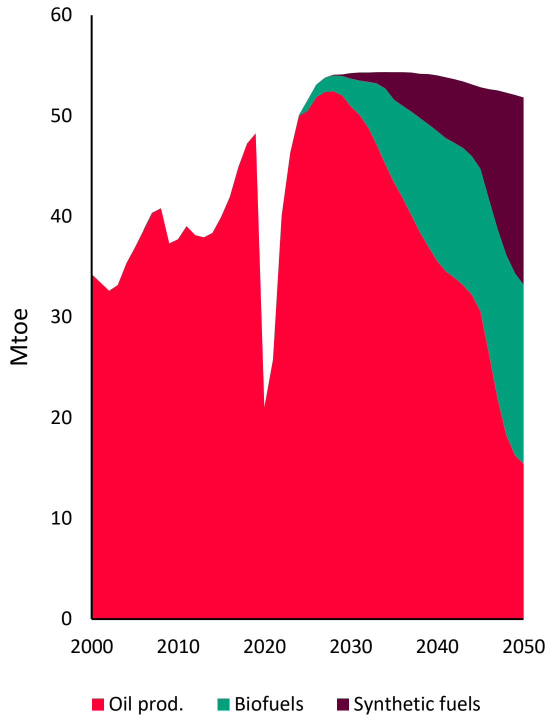


Figure 62. Energy demand for aviation



Source: POTEnCIA

3.3.2.7 Shipping[53]

Similarly to aviation, shipping has a strong international component, which dominates its overall energy use and is closely related to a strong projected growth through the lever of international trade demand. With the inclusion of maritime transport within the revised EU ETS, RED III, and the Fuel EU Maritime regulation, the EU has provided emission reduction targets. In the international policy context, the IMO EEDI[54] provides mandatory energy efficiency measures to be taken for different new-built ship types and sizes with the wider objective of reducing GHG emissions of the global sector. The historical growth of waterborne freight led to an activity increase of 56% from 5537 bn tkm in 2000 to 8643 bn tkm in 2019. Projections shown in Figure 63 add another 29% by 2030 and 52% by 2050, reaching 13140 bn tkm.

In the short-term, emission reduction targets are met through two main dynamics: the partial replacement of heavy fuel oil with biofuels and the penetration of less carbon intensive liquefied natural gas (LNG) vessels in the fleet, with biofuels (incl. biogas) and natural gas reaching 3% and 13% of energy demand by 2030, respectively (see Figure 64). With growing availability and tightening emission reduction requirements, the use of biofuels and RFNBOs enter at increased pace in the 2030s in

[53] Including all Extra-EU shipping in this chapter and displayed graphs

[54] The IMO also provides the 2023 IMO GHG Strategy aiming to reduce GHG intensity and total GHG emissions of international shipping. Specifically, it targets at least 5% low-carbon fuels by 2030, which is met for the EU region in the scenario.

liquid-fuel-powered vessels, while biomethane replaces some of the natural gas in LNG ships. These renewable fuels can be used in fuel blends of existing engines with no or manageable technical adaptations. Conversely, alternative fuels like hydrogen, methanol (of biogenic or synthetic origin), or ammonia require either more complex retrofit of the ship's engine and fuel system or entirely new vessels. By 2040, the energy demand share of conventional oil products drops to 44%, with natural gas covering 20% and renewable fuels making up the remaining 36%. In 2050, several competing fuel types coexist, in contrast to the almost complete reliance on oil products today. Synthetic fuels take the largest share (31%), 82% of which being synthetic ammonia and 16% synthetic methanol. Biofuels (including both bioliquids and biomethane) attain approximately 29% energy demand share each, followed by hydrogen with 22% and the remaining fossil fuels at 18%. This results in an emission decline of 79% by 2050 compared to pre-COVID 2019-levels, which rapidly accelerates after 2030.

Figure 63. Key indicators for shipping

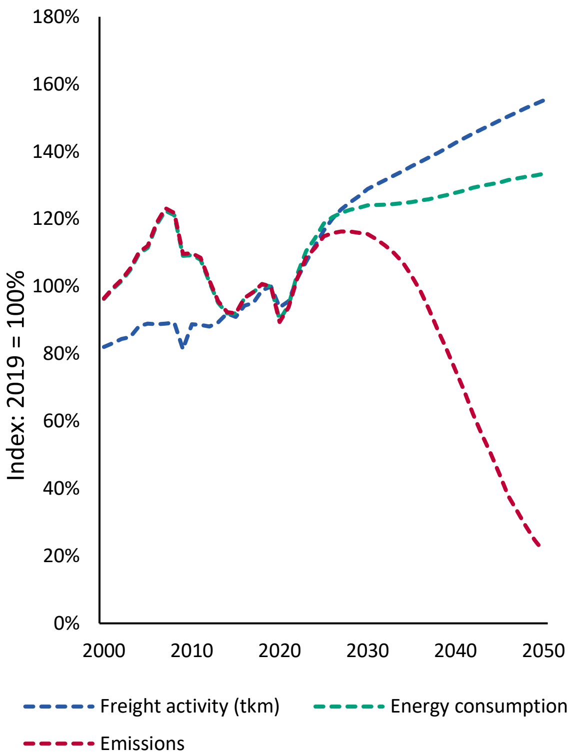
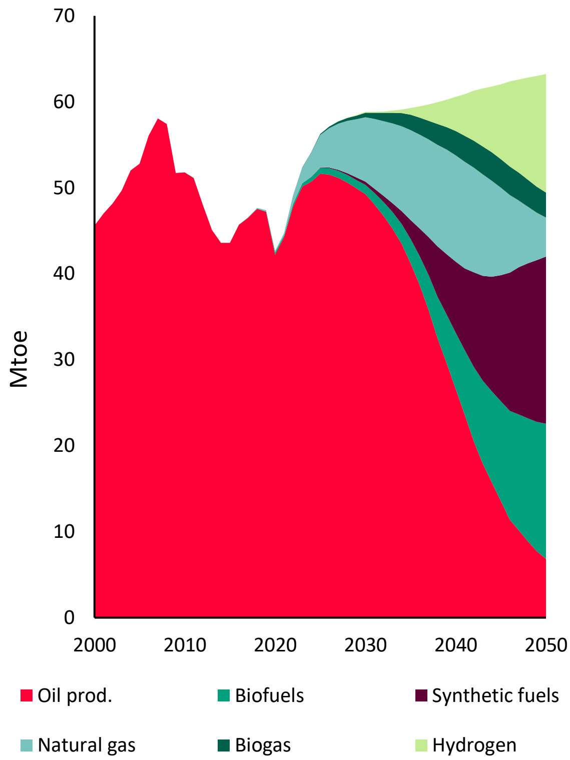


Figure 64. Energy demand for shipping



Source: POTEnCIA

3.3.3 Residential and Services sectors

Despite almost stagnating population numbers (see Figure 3), demand for residential and services surface area has grown 26% and 29%, respectively, from 2000 to 2021, and is projected to continue growing, driven by increasing living standards and economic growth (see Figure 65). At the same time, penetration of air conditioning systems has increased, the ownership of white and brown appliances[55] has widened, while use and energy consumption of ICT equipment has grown strongly in both the residential and services sector, see Figure 66 for examples.

Figure 65. Useful surface area of the residential and services sectors

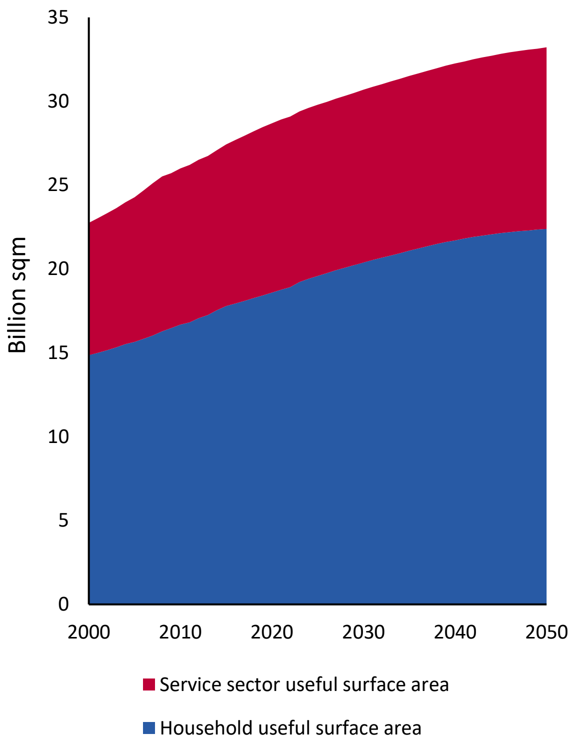
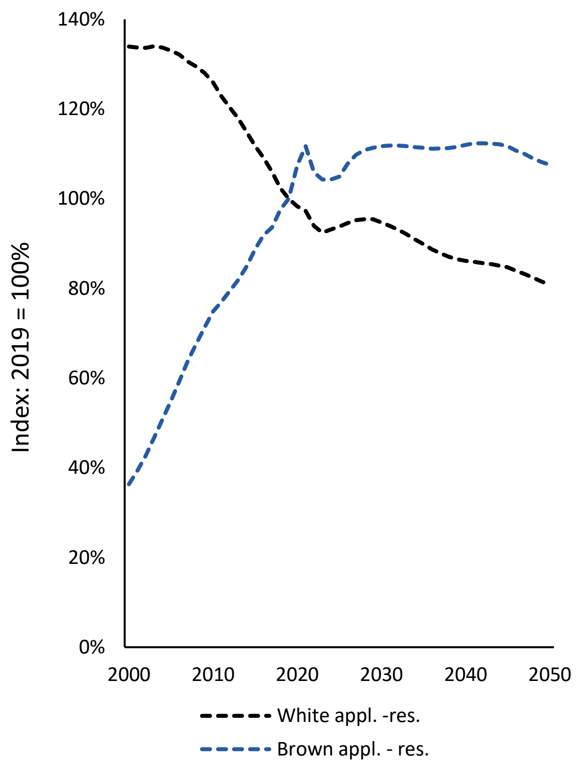


Figure 66. Energy consumption of selected appliances[56]



Source: POTEnCIA

Despite the sustained push of these drivers towards higher energy demand, FEC in 2021 was 10% below the peak level recorded in 2010, largely due to energy efficiency measures addressing a variety of elements of energy demand: minimum energy efficiency standards for new appliances are set by the Ecodesign Directive, improved building insulation is driven by the EPBD, and overall energy consumption limits established by the EED translated into incentives for energy saving measures. Over the projection period, significant additional electricity demand especially for ICT, including data centres, is strongly counteracted by an acceleration of energy efficiency improvements. The mitigation of energy consumed in space heating, historically representing by far the greatest share of

[55] White appliances refer to major household appliances such as refrigerators and freezers, clothes dryers, dishwashers, and washing machines; brown appliances refer to consumer electronics such as TVs and multimedia and ICT equipment

[56] ICT& Multimedia includes data centres

the buildings' FEC, plays a pivotal role in this process, acting on two main levers: the curbing of thermal energy demand through improved performance of thermal envelopes, and the mass deployment of heat pumps, which allows for a leap change in energy efficiency. As a consequence, the FEC of buildings drops by 2040 to 154 Mtoe, equivalent to 37% of the 2010 peak, and remains broadly stable up to 2050, see Figure 67.

In terms of energy mix, additional drivers for transitioning towards carbon-neutral energy carriers are represented by the national emission caps of the ESR and by the new ETS2. In the long term, electricity makes up the great majority of FEC (73%), with biomass (together with biogas) and district heating maintaining 11 and 7% of the shares. Fossil fuels, including coal, heating oil, and eventually also natural gas, are progressively phased out and –combined- by 2040 comprise only 5% of buildings' energy demand, as shown in Figure 68. Additionally, solar thermal heat rises to obtain notable FEC shares from 1% in 2021 to 6% in 2050.

Figure 67. FEC in residential and services sectors by energy service type[57]

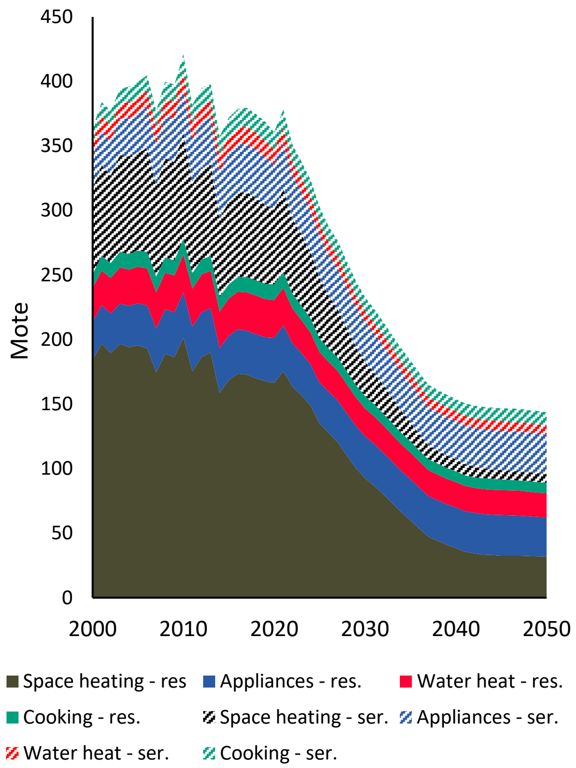
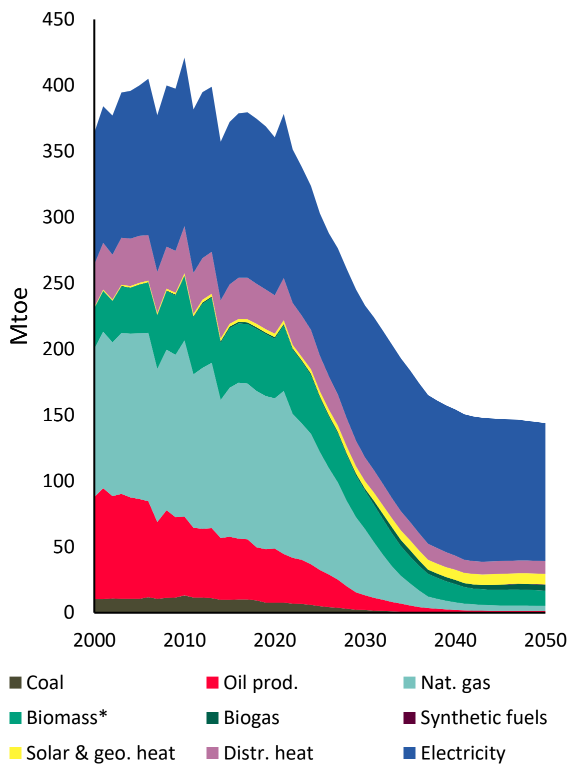


Figure 68. FEC in residential and services sectors by fuel[58]



Source: POTEnCIA

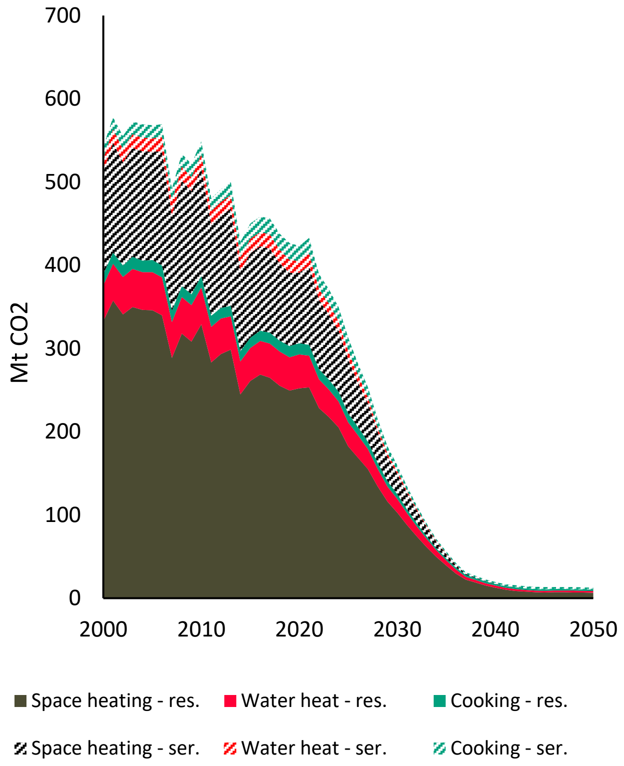
CO2 emissions, reflecting the combined dynamics of curbing energy demand and shifting towards carbon neutral sources, are reduced from the 578 Mt CO2 all-time high in the early 2000s down to

[57] Space heating includes FEC for space cooling

[58] Biomass includes waste and liquid biofuels

433 Mt in 2021. Over the projection period the reduction trend accelerates quickly, with emissions shrinking to 160 Mt in 2030 and less than 20 Mt by 2040 (see Figure 69).

Figure 69. Net emissions in residential and services sectors[59]



Source: POTEnCIA

3.3.3.1 Residential sector

With increasingly better insulated building stock, useful thermal heat energy demand is reduced by 45% by 2040, compared to pre-COVID 2019-levels, as shown in Figure 70. Together with the increasing shares of households serviced by relatively much more efficient heat pumps, rising from 8% in 2019 to 48% in 2050, the FEC for thermal services drops rapidly by 72%. During the same time frame, conventional boilers (excluding solid biomass boilers), lose household shares from 55% in 2019 down to 15% by 2050. Figure 71 shows a continued phase-out of coal and oil, but also a quick ramping down of the use of natural gas towards 2040. The distributed heat infrastructure and the number of biomass-driven boilers remain broadly stable over the projection timeframe, but their corresponding FEC is reduced due to the efficiency gains. As a result of these dynamics, the residential sector decarbonises almost completely by the mid-2040s, emitting in 2050 only 10 Mt CO2, a mere 3% of the 303 Mt CO2 in 2019.

[59] Space heating includes emissions for space cooling

Figure 70. Key indicators for the residential sector

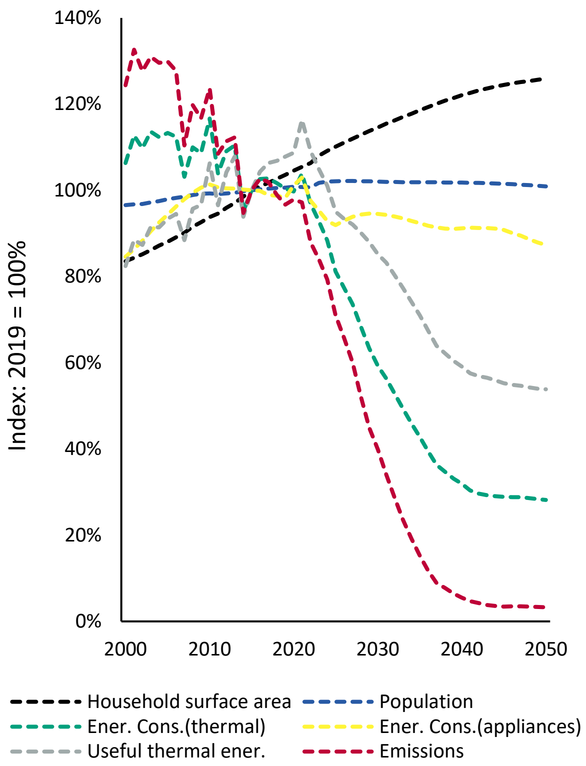
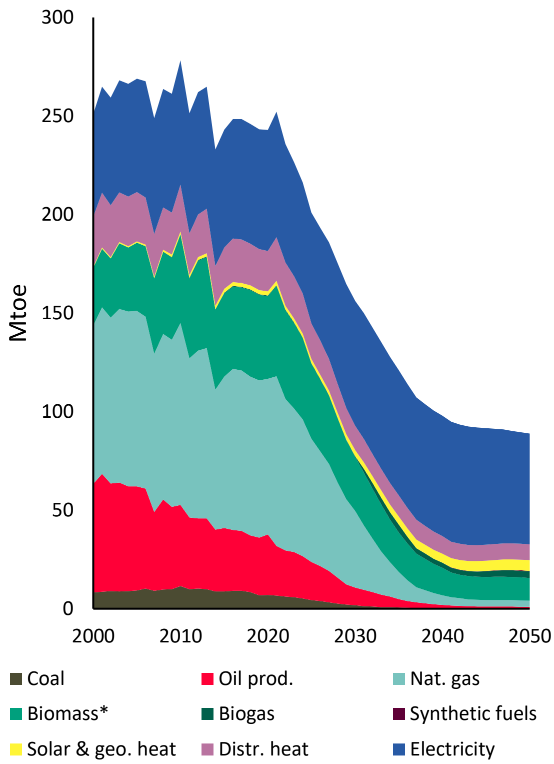


Figure 71. FEC of the residential sector[60]



Source: POTEnCIA

3.3.3.2 Services

Similarly to the residential sector, useful thermal energy demand in the services sector drops steadily due to building efficiency improvements resulting in a reduction of 48% by 2050 relative to pre-COVID 2019-levels, as shown in Figure 72. Concurrently, the improved efficiency of appliances counteracts the trend of increasing number and use of electric and electronic equipment. Heat pumps gradually replace conventional boiler systems to satisfy the remaining heating requirements, as visualized in Figure 73. Oil-fired boilers are almost entirely phased out in the early 2030s and natural gas boilers are by 2040. The resulting FEC in 2050 is roughly half of 2019-levels, with 88% being electricity, and most of the remainder being solar thermal heat and distributed heat. As a consequence, the sector's emissions all but disappear already by 2040.

[60] Biomass includes waste and liquid biofuels

Figure 72. Key indicators for the services sector

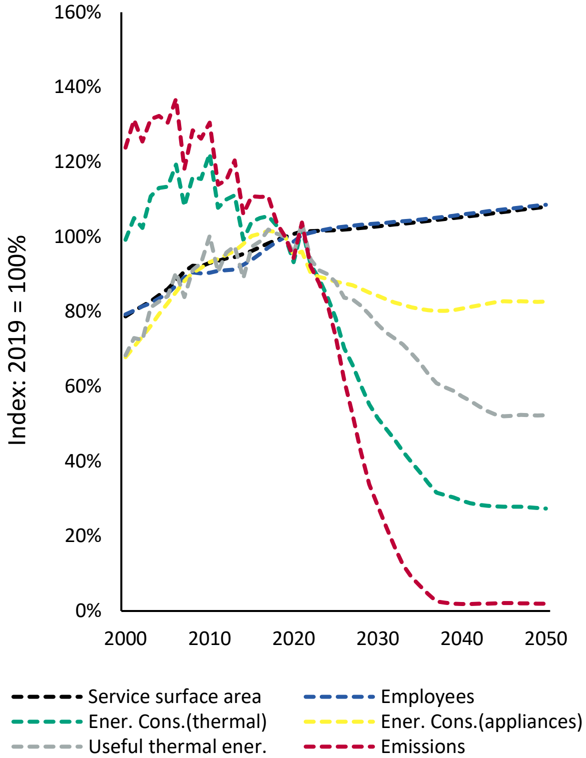
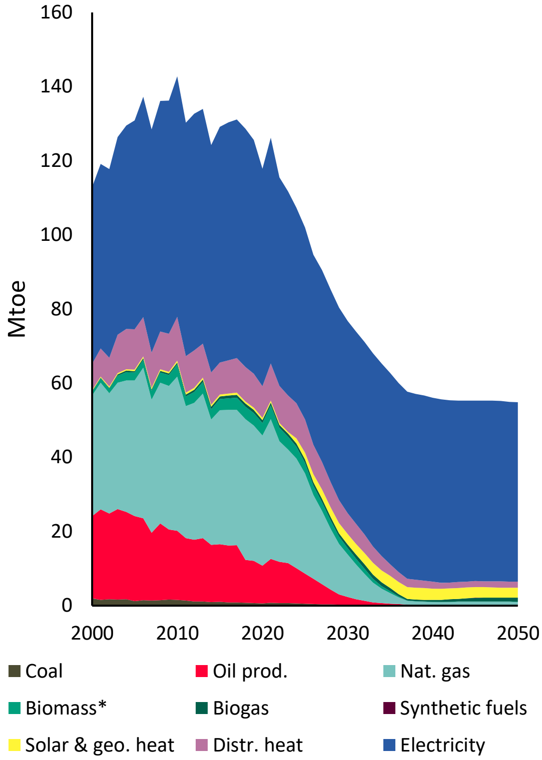


Figure 73. FEC of the services sector[61]



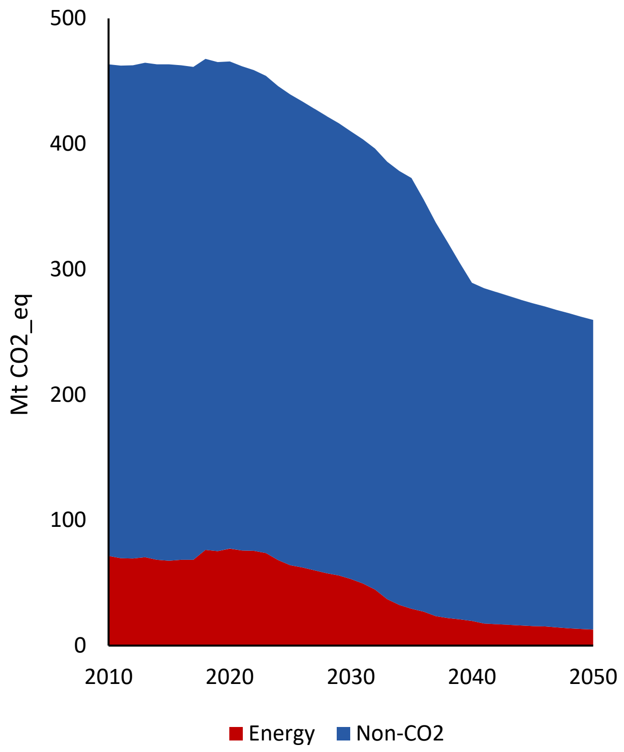
Source: POTEnCIA

[61] Biomass includes waste and liquid biofuels

3.3.4 Agriculture

In 2021, energy uses in the agricultural sector, which includes the heating and lighting of farms and greenhouses as well as the operation of (mostly diesel-driven) agricultural machinery, caused 76 Mt CO2 emissions. Non-CO2 emissions, predominantly methane and nitrous oxide, stemming mostly from livestock farming and fertilization, amounted to almost 400 Mt CO2_eq (see Figure 74). Energy uses are therefore only a relatively minor part of the greenhouse gas footprint of agricultural production. These emission levels have been broadly stable over the last two decades. Although the agriculture and forestry sectors are essential determinants of LULUCF balances (see Figure 8), the present section, within the context of an energy-system-focused report, addresses only a part of a more complex, interrelated system.

Figure 74. Agriculture emission sources[62]



Source: POTEnCIA, GAINS

Figure 76 shows that, under a projected physical output growth trajectory that remains broadly stable until 2050, energy consumption and energy-related emissions drop by 20% and 31% by 2030 compared to 2021-levels, respectively. This is to the consequence of incremental efficiency improvements in machinery and equipment, including heating systems, coupled with partial substitution of fossil fuels with solid biomass and biofuels. These processes accelerate after 2030, resulting by 2050 in a 34% reduction in energy consumption and an 85% decline in emissions, both relative to 2021. By 2050, the FEC comprises 57% biofuel resources (approximately half of which being biogas), 21% electricity, and 17% fossil fuels, with derived heat supplying the remaining minor energy portion. The FEC transition is visualized in Figure 75. In parallel to the decarbonisation of energy uses, emissions of non-CO2 emissions are reduced by around 30%, primarily due to more efficient use of fertilizers (incl. nitrogen inhibitors and precision farming) and due to mitigation efforts in the cattle industry. As a result, in 2050 the combined CO2 and non-CO2 emissions of the agricultural sector are 259 Mt, 44% below 2021-levels.

[62] Non-CO2 emissions are modelled on a 5-yearly basis. The values for in-between years are interpolated.

Figure 75. FEC of the agriculture sector[63]

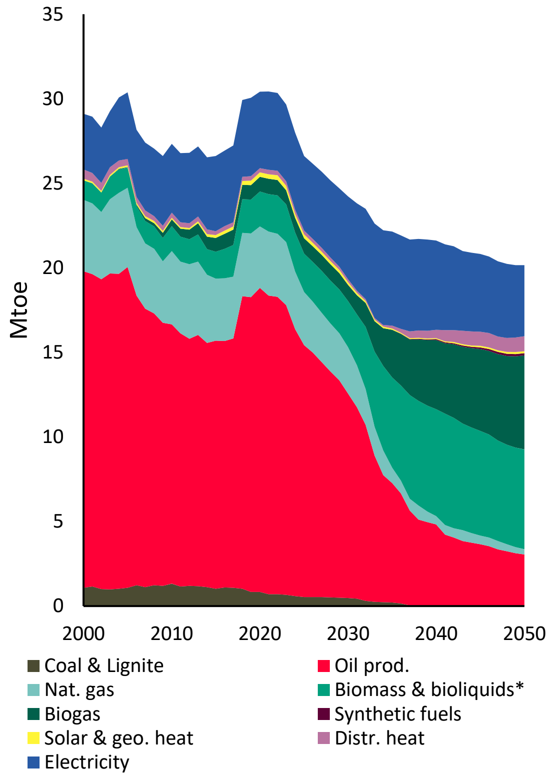
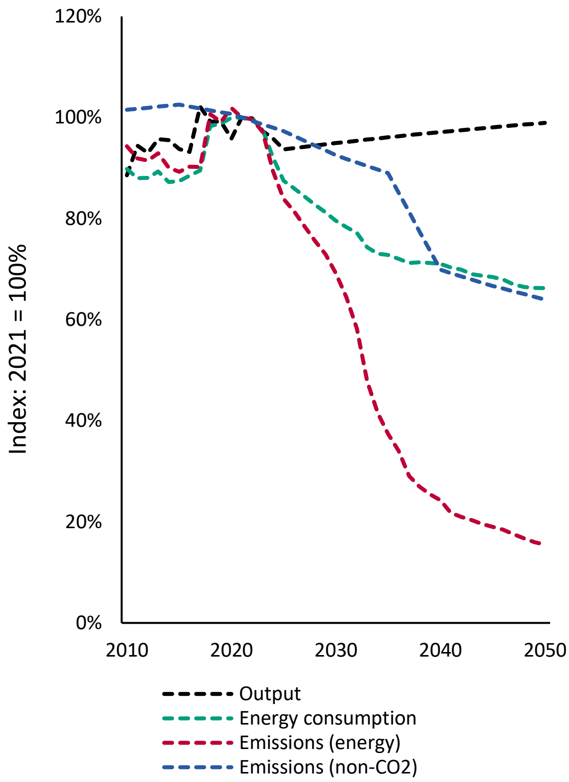


Figure 76. Key indicators for agriculture[64]



Source: POTEnCIA, GAINS

[63] Biomass & bioliquids includes minor amounts of waste (<0.1% of total FEC); The sudden oil surge in 2018 is a result of a methodological change in reporting of oil products in Germany for the national energy balances

[64] Includes forestry and fishing; Non-CO2 emissions are modelled on a 5-yearly basis. The values for in-between years are interpolated.

3.4 Energy Supply

This chapter gives an overview of the projected developments in selected energy supply sectors, which are crucial for the decarbonisation of the energy system in 2050. Section 3.4.1 lays out the general trends of the power sector, in the context of its role in the electrification of the demand sectors. Section 3.4.3 summarizes the evolution of upcoming technologies for the production of the renewable fuels, which alongside the progressive electrification of demand are projected to increasingly replace fossil fuels in the remaining combustion processes.

3.4.1 Electricity

In 2021 total electricity demand was 2763 TWh, with close to 90% of the demand coming from industry, residential, and services sectors, as shown in Figure 78. By 2050, total demand more than doubles, expanding to 5843 TWh. This increase of electricity consumption vastly surpasses the concurrent 47% growth in economic activity, and reflects the direct and indirect electrification dynamics of the final demand sectors.

At the same time, the supply of this vastly expanded electricity demand needs to undergo an almost complete decarbonisation. This happens mostly through the replacement of fossil-fuel-fired generation assets with variable renewable energy sources, whose combined generation shares rise from 20% in 2021 to 77% in 2050 (see Figure 78). This requires an unprecedented upscale of solar PV, onshore and offshore wind capacity deployment (see Figure 81) reaching 1720 GW, 514 GW, and 281 GW, respectively, by 2050, equivalent to 84% of total capacity. In contrast, unabated coal capacities are phased out almost entirely in the 2030s, while the predominant role of natural gas-fired generators changes from baseload electricity suppliers to peaking units contributing to the stability of the electricity grid when variable renewables are unable to meet the demand load. Over the projection period, gas-fired and solid biomass-fired generators are increasingly fitted with carbon capture, enabling carbon capture for 14% and 41% of their capacities by 2050, respectively

Several factors contribute to the dynamics in the power system: on one side, technology learning pushes down the cost of renewables and makes them increasingly competitive compared to traditional thermal electricity generation even in the absence of policy incentives; on the other side, a comprehensive policy framework provides price signals through the EU ETS and quantitative targets for the deployment of renewables through the RED III, which sets a target of at least 42.5% of renewable energy share by 2030 together with a goal of climate neutrality by 2050 and drives a variety of incentivising policies and measures at national level.

Figure 77. Electricity demand by sector[65]

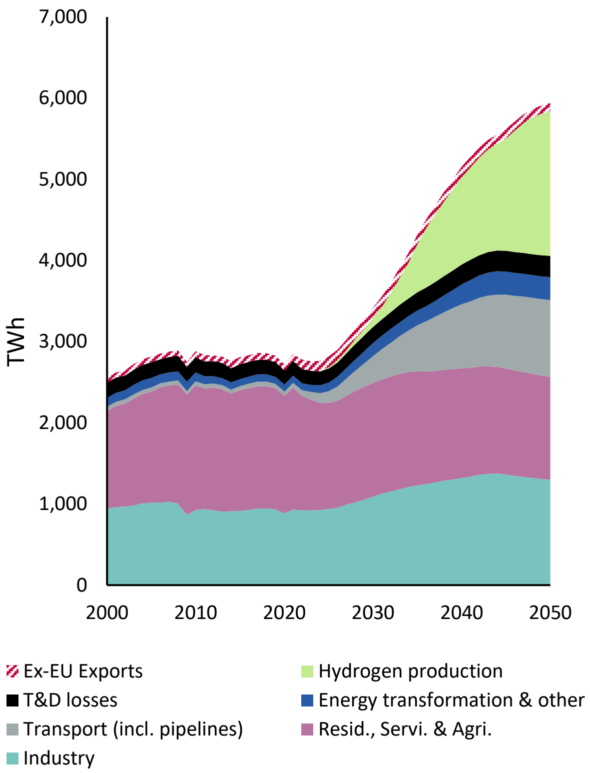
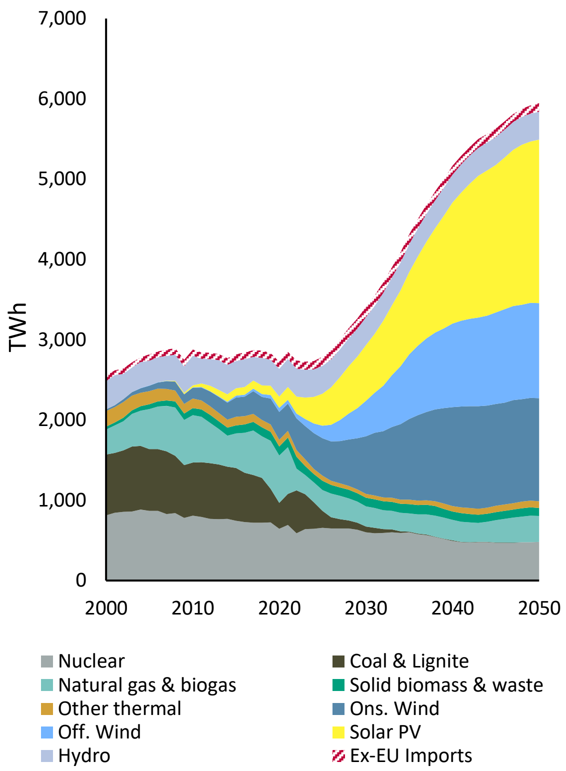


Figure 78. Net electricity generation by technology[66]



Source: POTEnCIA

The transition to a power generation system dominated by variable renewable sources is marked by several interconnected, synergetic developments:

Firstly, capacities of power plants running on natural gas, biogas, and hydrogen remain stable between 174-206 GW due to the need for dispatchable capacity, but also to satisfy steam demand through combined heat and power generation. To mitigate a part of the emissions of gas-fired power plants[67], biomethane blending share rises from 2% in 2021 to 20% in the 2030s, but eventually drops to 6% by 2050, because demand for supply-limited biomethane from other sectors (especially industry) ramps up and at the same time CCS is deployed more pervasively throughout the fleet of power generation assets.

Secondly, capacities of dedicated storage technologies (batteries, pumped hydro, and hydrogen fuel cells) increase by 116% compared to 2021 reaching 98 GW discharging capacity in 2050, to enable the required level of storage of excess electricity generated during low demand hours and discharge during peak demand hours to fill the gap between inflexible generation and total demand. In parallel,

[65] Energy transformation & other includes amongst other refineries, storage losses, CO2 capture and storage, synthetic fuel processing, and others

[66] Hydro includes run-of-river and hydro dams, and tide, wave, and ocean, but excludes hydro pump storage; Other thermal includes derived gas, refinery gas, diesel oil, fuel oil, solar thermal, and geothermal

[67] The values that follow exclude dedicated biogas-fired power plants

the use of storage capacities increases, with generation from dedicated storage capacities rising from currently approx. 30 TWh to 99 TWh by 2030 and to 174 TWh by 2040, as shown in Figure 79. In the early years, the increased storage discharge comes primarily from pumped hydro-storage plants, making up 86% of all storage generation in 2030. However, with their accelerated deployment especially in countries with favourable conditions for PV generation (e.g. Spain, Italy), batteries become the dominant utility-scale short-term storage technology, accounting for up to 69% of the total dedicated storage generation in the 2040s. Besides dedicated utility-scale storage, bidirectional vehicle-to-grid (V2G) takes on an important role, reaching 405 GW discharge capacity by 2050. However, the availability of EV batteries to provide services to the power grid is far more limited in time than that of dedicated utility-scale batteries, so that the overall discharge to the power system remains dominated by utility batteries.

Thirdly, the mass-scale deployment of flexible electrolyser capacities to satisfy the increasing demand for hydrogen and its derivatives, while mitigating curtailment of excess variable renewable electricity generation. While only minor amounts of hydrogen are then used in the power sector, with the capacity of hydrogen fuel cells for power applications limited to 10 GW net by 2050, flexible electricity demand from hydrogen electrolysers accounts for 100 TWh by 2030 and quickly rises to 1671 TWh by 2050 (see Figure 80). This, enabled by sufficient electrolyser overcapacity and hydrogen storage capacity, provides the bulk of seasonal flexibility needs of the power system in the long term.

Figure 79. Power generation from storage units

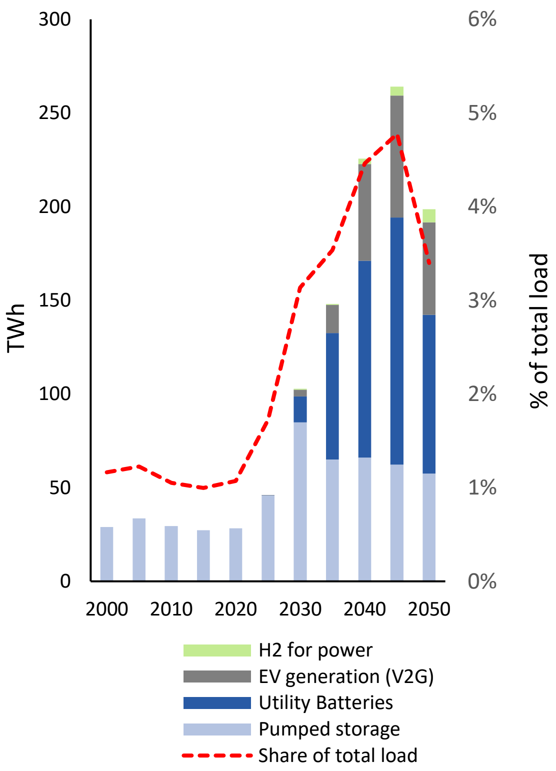
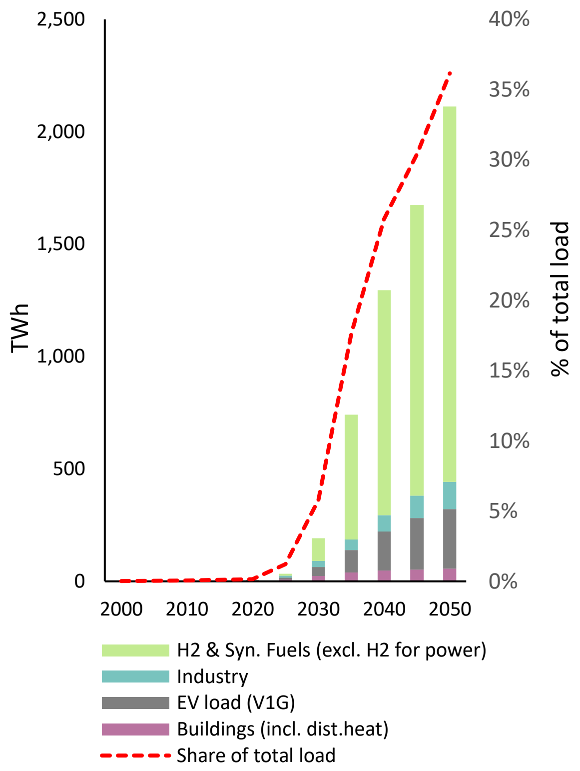


Figure 80. Flexible demand by sector



Source: POTEnCIA

Further, demand flexibility increases in all demand sectors via e.g. smart metering and power-to-heat units (heat pumps and electric boilers) in buildings and district heating, unidirectional (V1G) smart EV charging in the transport sector, and various types of demand flexibilisation in the industry sector. These combined measures in the demand sectors allow for the flexibilisation, over the hourly/daily time scale, of 8% of the total load by 2050 (11% when excluding flexible electrolyser load), with smart EV smart charging making up the largest share.

Finally, increasing numbers and capacities of interconnectors enable more efficient imports/exports within the EU MS as well as with non-EU countries such as Switzerland, the UK, and Norway. For intra-EU interconnectors, network capacities expand from 67 GW in 2021 to 94 GW in 2030 and more than doubles to 146 GW in 2050, while extra-EU capacities grow from 29 GW in 2021 to 38 GW by 2050.[68]

With the rapid decarbonisation of the EU power system, net emissions of the sector are reduced from 789 Mt in 2021 by 69% down to 244 Mt in 2030 (Figure 82). With the increasing deployment of BECCS and the parallel decommissioning of unabated fossil fuel capacities, the power sector achieves net-zero emissions in the mid-2040s. By 2050, 93 Mt CO_2 from biogenic sources are sequestered from the power sector, while released emissions from fossil fuels drop to 52 Mt. power generation becomes thus net-negative in terms of emissions, delivering the net removal of 41 Mt of CO_2.

[68] Interconnector capacities until 2030 are based on ENTSO-E databases [42,43]. For the period after 2030, POTEnCIA allows endogenously determined investment in expanding interconnector capacities, taking into account expansion potential constraints based on historical growth rates.

Figure 81. Net electricity generation capacities[69]

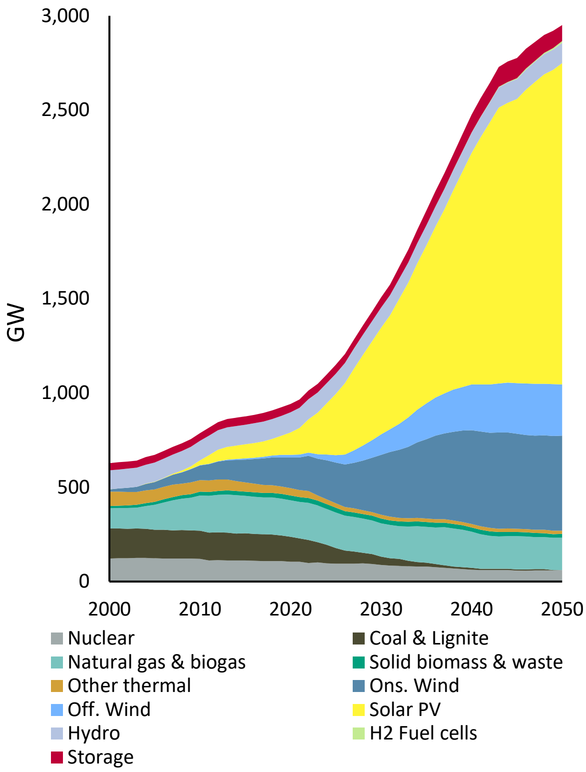
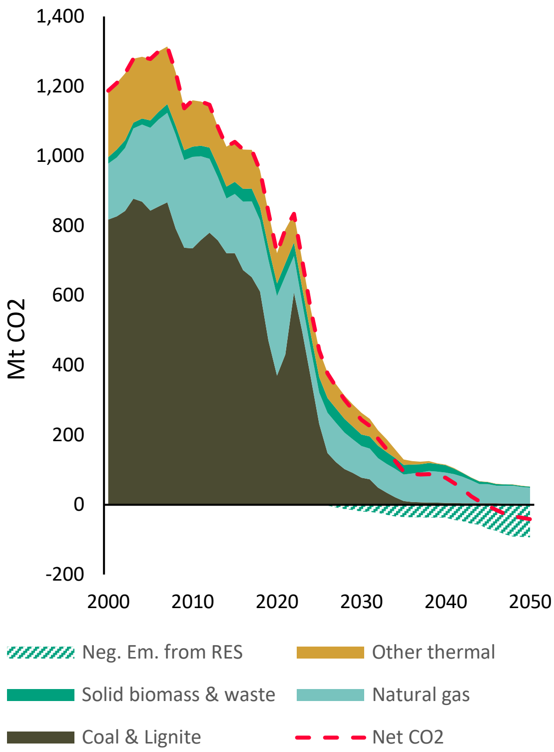


Figure 82. CO2 emissions in the power sector



Source: POTEnCIA

[69] Storage includes batteries and pumped hydro storage; Hydro includes run-of-river and hydro dams, and tide, wave, and ocean, but excludes hydro pump storage; Other thermal includes derived gas, refinery gas, diesel oil, fuel oil, solar thermal, and geothermal

3.4.2 Distributed heat

In 2021, distributed heat demand was 59 Mtoe, of which 37.3% was consumed in the residential and 16.9% in the services sector, as shown in Figure 83, to satisfy primarily space heating demand and to a lesser degree hot water services. An additional 27% of the demand comes from the industrial sector, approximately half of which in the chemical sector. On the supply side, in 2021, 68% of the distributed heat was generated based on fossil fuel combustion, either in CHPs or in dedicated heat plants, as shown in Figure 84. In the early 2000s, coal and lignite were the predominant fossil fuels used for heat generation, but by 2021 coal had been substituted by biomass and renewable waste in both CHP plants and dedicated heat plants. Over the same timeframe, the shares of natural gas CHP plants remained stable. The EU actively promotes the decarbonisation of thermal networks, for example by setting an indicative annual 1% increase of renewable energy sources in the FEC in district heating and cooling in the RED and by promoting energy efficiency and emission reduction improvements in district heating systems in the EED.

With the rapid energy efficiency gains in the residential and the services sectors, demand for distributed heat drops by 39% in the mid-2030s compared to 2021. In the longer term, however, the rising demand from the industrial sector offsets the reduced demand from buildings, so that the demand in 2050 is only 10% lower than in 2021. Non-emissive technologies rapidly substitute heat generation based on fossil fuels, resulting in the phase out of coal-based CHP and of all -fossil-fuel-based dedicated heat plants. Heat pumps, which make up only 1% of the distributed heat generation in 2021, reach a share of 28% by 2035. The rising heat demand post-2035 is primarily satisfied by new CHP plants equipped with carbon capture, so that by 2050 5 Mtoe of distributed heat are generated by natural-gas-fired CHP CCS plants and another 12 Mtoe by bioenergy-fired CHP CCUS plants, the latter supplying 84 Mt of captured CO2 to deliver negative emissions by geological storage and renewable carbon feedstock for synthetic fuels (further explained in Section 3.4.3).

Figure 83. Distributed heat demand by sector[70]

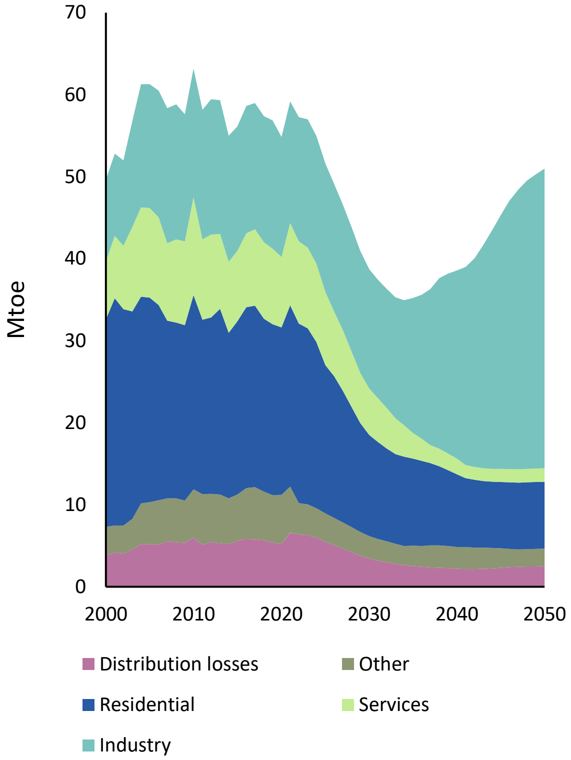
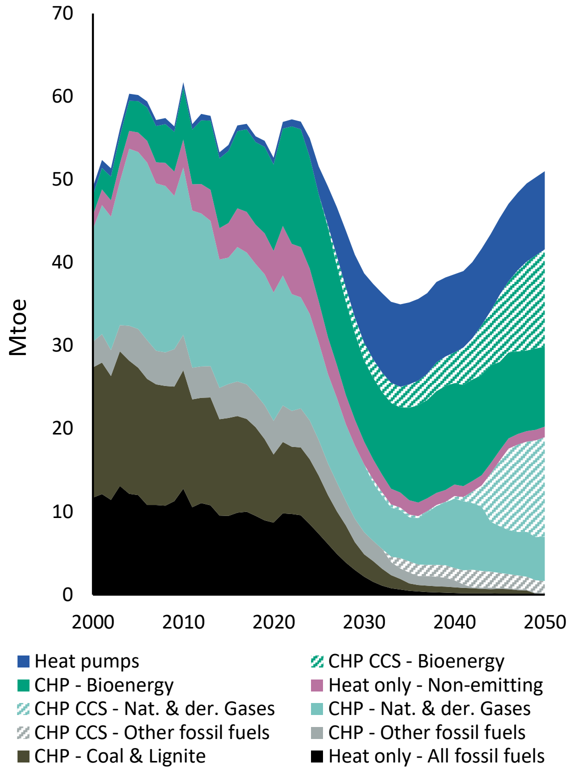


Figure 84. Distributed heat supply by technology[71]



Source: POTEnCIA

[70] Other includes consumption in energy sector, transformation input in power stations, and agriculture, forestry, and fishing.

[71] Heat only – All fossil fuels includes solid, liquid, and gaseous fossil fuels as well as non-renewable waste boilers. Heat only – Non-emitting includes biomass, solar, geothermal, hydrogen, and electric boilers

3.4.3 Renewable Fuels

Renewable fuels, including liquid biofuels, biogas, and green hydrogen and its derivatives, are crucial for the decarbonisation of the EU energy system, especially of the end uses that cannot be readily electrified. A number of EU policies guide the future development of renewable fuels, either indirectly via general emission reduction targets, or by setting specific sustainability requirements and sectorial targets. These include the Fuel EU Maritime and the ReFuelEU Aviation regulations, AFIR, ETS and ETS2, and RED III.

In the last decades biofuels have been increasingly incorporated into the supply, especially of road transport fuels, to various degrees across MS. They thus substituted significant amounts of fossil fuels. Future feedstock sources need to be sourced more responsibly and sustainably following the sustainability criteria of RED III, which sets caps on biofuels with high indirect land-use change risk and on biofuels from waste cooking oils and animal fats. In turn, this entails limits to the potential supply of biofuels and biogas, while Annex IX biofuels[72] are prioritized. Annex IX biofuels must be produced with biogenic sources in limited supply using transformation processes that in a number of cases have yet to reach widespread commercial application.

In contrast to biofuels, the technical production limit of hydrogen and hydrogen-based fuels is less of a constraint as long as there is sufficient supply of electricity and renewable CO2 feedstock. However, hydrogen-based fuels still have to prove their commercialisation potential despite promising small-scale demonstrations and rapidly increasing capital investments. Several factors will determine future economic success of hydrogen-based fuels, including: further technology improvements to reach higher efficiencies and lower production costs, access to cheap electricity, and scaling up of storage and distribution infrastructure.

3.4.3.1 Green Hydrogen[73]

In 2022 only 0.3% of the total hydrogen produced in Europe (EU + UK, NO, CH) came from water electrolysis, equivalent to 0.09 Mtoe (or 0.03 Mt H2) [59,60]. More than 90% was instead produced via thermal production methods, primarily steam reforming of natural gas. The EU supports green hydrogen through various policies, initiatives, and funding programs to promote the development and deployment of hydrogen technologies, of which the POTEnCIA CETO 2024 scenario specifically considers the RED III, FuelEU Maritime and ReFuelEU Aviation, and AFIR.

In the POTEnCIA CETO 2024 scenario, green hydrogen production increases to 6 Mtoe by 2030, with another 2.4 Mtoe being imported from countries outside of the EU, as shown in Figure 85. In the early expansion phase, the demand is primarily driven by the chemical sector, where processes consuming hydrogen primarily as feedstock have been historically established. In parallel, first demand infrastructures build up for FCEV in the road freight transport sector and for the production of hydrogen derivatives. By 2040, hydrogen demand reaches 73 Mtoe (or 25 Mt H2), 28% of which is consumed for synthetic fuel production, closely followed by 21% in the iron and steel sector, where H2-DRI becomes the dominant primary steel production route. Road transport and chemicals remain major demanding sectors with 20% each. In the 2040s, demand for hydrogen keeps ascending at a

[72] Annex IX biofuels in this report are all biofuels derived from the feedstock types listed in RED III Annex IX. They hence exclude fuels derived from food and feed crops.

[73] Green hydrogen: Hydrogen produced via electrolysis using exclusively renewable electricity

rapid pace, with the main growth driver being synthetic fuel demand for the aviation and shipping sectors. While hydrogen demand for aviation is exclusively indirect via synthetic kerosene, shipping requires hydrogen both as a direct fuel and as a feedstock for green ammonia and green methanol. Because the chemical sector uses hydrogen products to decarbonise both energy and feedstock processes, it remains a crucial consumer throughout the projection period.

Figure 85. Green Hydrogen sources

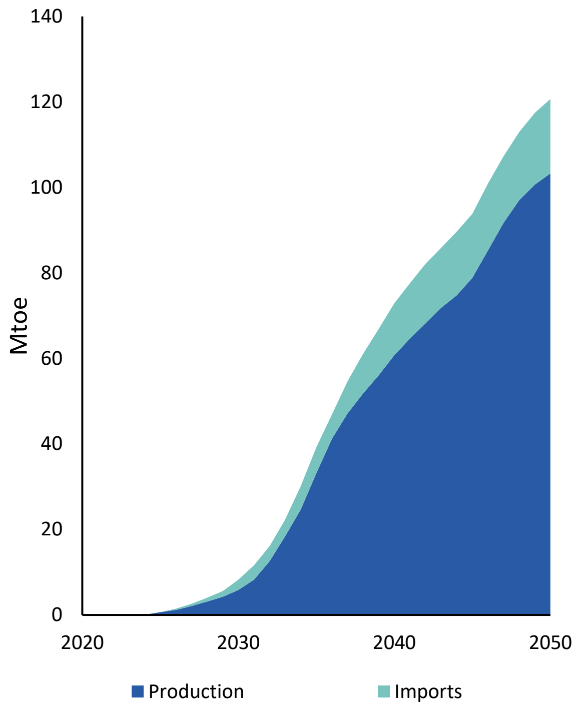
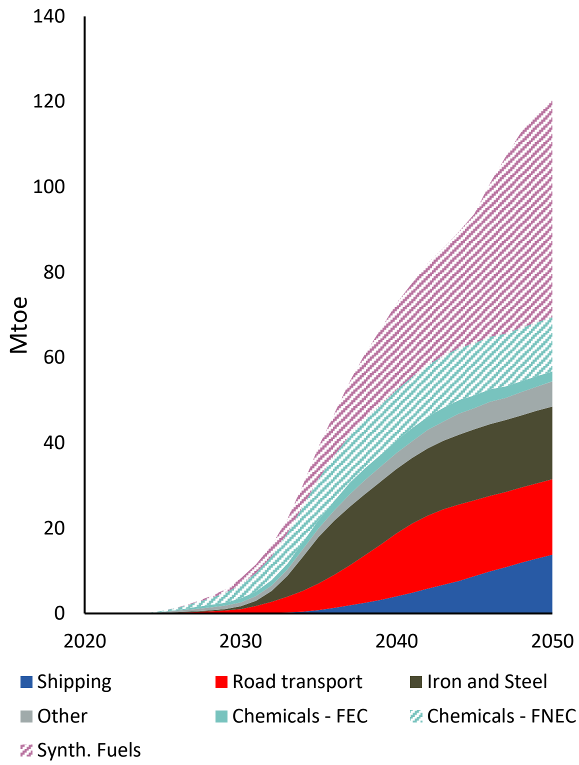


Figure 86. Green Hydrogen demand by sector[74]



Source: POTEnCIA

3.4.3.2 Synthetic Fuels[75]

In recent years, several production processes for hydrogen derivatives have demonstrated their feasibility at small scale and have reached high Technology Readiness Levels (TRLs). For each process technology, the uptake depends crucially on further process technology improvements, the availability of cost-effective hydrogen, and the development of demand. With the European Hydrogen strategy and especially with RED III, the EU has set ambitious renewable fuel targets and provided a political framework to define what requirements need to be met for synthetic fuels to be accounted for as a renewable fuel.

Figure 87 visualizes how the commercialisation of various synthetic fuel production processes starts in the late 2020s, reaching a production volume of over 1 Mtoe by 2030, predominantly composed of

[74] Other includes power & heat, distribution losses, energy transformation, and other industry sectors

[75] Synthetic fuels: Fuels synthesized using hydrogen and carbon as primary feedstock. Inputs for synthetic fuels are not limited to only green hydrogen nor to only carbon from biogenic sources (regulations for carbon as feedstock are further explained in chapter 3.5)

synthetic kerosene and green ammonia. Two synergic evolutions enable the production quantities to accelerate rapidly in the 2030s. Firstly, tightening emissions targets coupled with specific fuel penetrations targets for aviation and shipping cause a demand increase for renewable fuels. Secondly, the wider accessibility of more cost-efficient hydrogen as the most important component for synthetic fuel processes. As a consequence, by 2040 already 17 Mtoe of hydrogen derivatives are produced, with green ammonia, synthetic kerosene, and green methanol respectively contributing 7 Mtoe, 6 Mtoe, and 3 Mtoe, jointly making up 90% of total production. By 2050, production increases by another 151%, reaching 42 Mtoe in total, of which over 83% are kerosene and ammonia combined. The production of synthetic gasoline and diesel oil peaks in 2040, reaching 0.4 and 1 Mtoe, respectively, to then diminish following the widespread electrification of road transport by 2050.

Figure 88 shows that the aviation and shipping sectors are the main drivers for demand for hydrogen derivatives, requiring about 19 Mtoe of synthetic fuels each by 2050, together making up 91% of the total demand. Besides green ammonia, the shipping sector also consumes 3 Mtoe of green methanol. However, the latter is also used as a feedstock for chemicals production processes consuming 3 Mtoe in 2050 (see also Figure 30), so that total green methanol demand reaches 6 Mtoe.

Figure 87. Synthetic fuels production by type

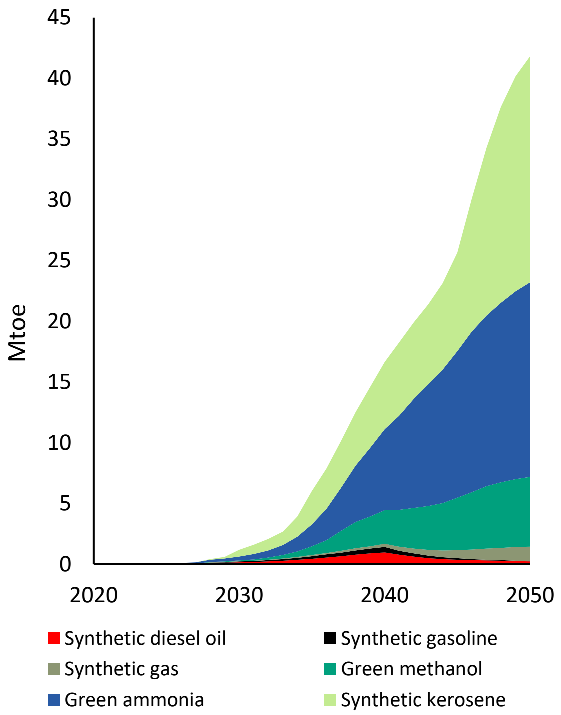
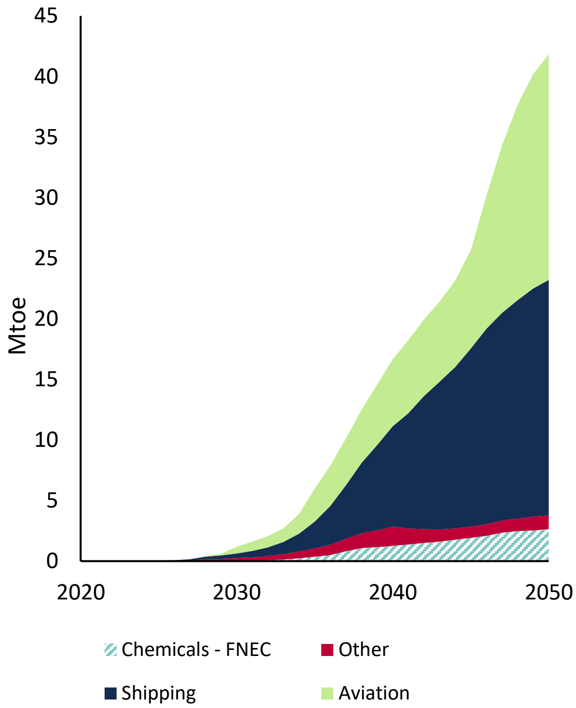


Figure 88. Synthetic fuels demand by sector[76]



Source: POTEnCIA

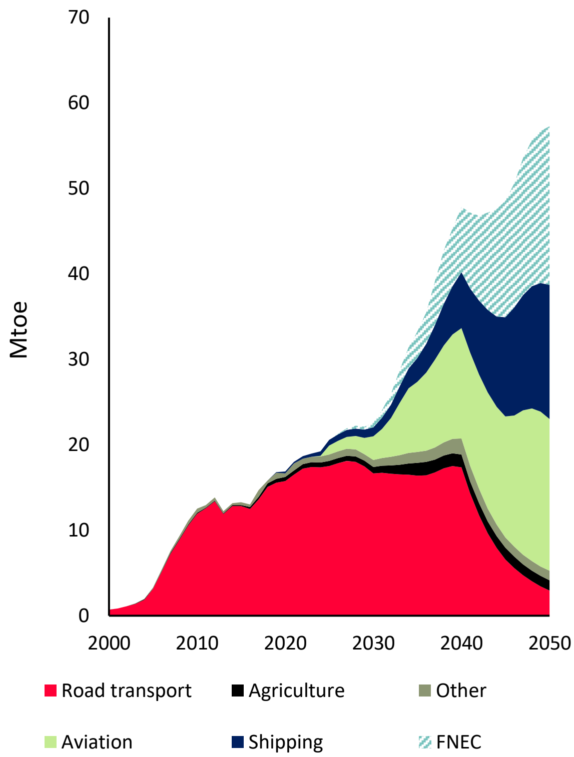
3.4.3.3 Liquid Biofuels

The EU has assigned to biofuels a key role in GHG emissions reduction since the early 2000s and has since continuously redefined and expanded its biofuel policy [25]. Figure 89 shows how since the first Renewable Energy Directive in 2003, biodiesel and to a lesser degree biogasoline have taken off rapidly, reaching in 2021 consumption volumes of 15 Mtoe and 3 Mtoe, respectively. The demand for these biofuels came primarily from ICE vehicles combusting blended fuels, predominantly in the road transport sector, see Figure 90.

[76] FNEC = Final non-energy consumption. Final non-energy fuel consumption refers to fuel used as chemical feedstock, meaning that the fuel becomes a chemical compound instead of being consumed for heat production: Other includes industry, residential, services, road transport, rail transport; shipping includes international marine bunkers

Figure 89. Biofuels consumption by type

Figure 90. Biofuel consumption by sector[77]



Source: POTEnCIA

Biofuels consumption grows across the projection years as a result of different policies such as the RED III 2030 targets, the ETS2 that stimulates progressively higher blending rates (e.g. in the road transport sector), the FuelEU Maritime reduction targets for GHG intensity of energy use in vessels, and the ReFuelEU Aviation targets for sustainable aviation fuels. The *POTEnCIA CETO 2024 Scenario* takes into account various regulatory elements affecting different biofuels types defined by the RED III, by Fuel EU Maritime, and by the ReFuelEU Aviation regulation (i.e. SAF definitions and targets), including for example the 2030 minimum penetration target for advanced biofuels and RFNBOs, the 2030 cap for food and feed crops based biofuels, or the eligibility rules for sustainable aviation fuels.

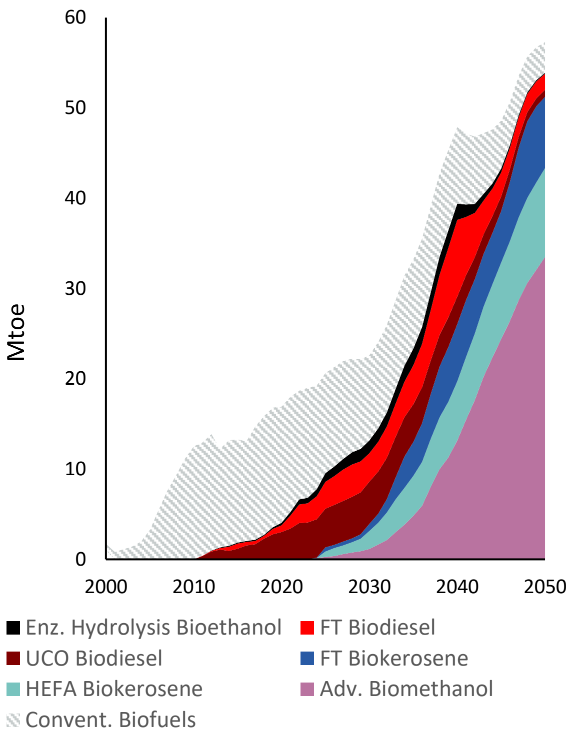
As a result, the supply of biofuels produced from the feedstock types listed in Annex IX of the RED III increases throughout the years at the expense of feed and food crop based biofuels, which lose shares progressively, as shown in Figure 91. Biofuels produced from used cooking oil and animal fats are reported in the graph as UCO (Used Cooking Oil) biodiesel and HEFA (Hydroprocessed Esters and Fatty Acids)[78] biokerosene. After an initial expansion peaking in 2035, their contribution remains constrained due to the limited feedstock availability, also reflected by a cap in the RED III. In contrast, the contribution of advanced biofuels, using processes such as biomass gasification coupled with Fischer-Tropsch (FT), biomass gasification coupled with biomethanol synthesis, and enzymatic

[77] Other includes industry, residential, services, rail transport, and pipeline transport; FNEC = Final non-energy consumption. Final non-energy fuel consumption refers to fuel used as chemical feedstock, meaning that the fuel becomes a chemical compound instead of being consumed for heat production.

[78] HEFA biokerosene pathway includes also a limited quantity of intermediate crops as feedstock

hydrolysis of biomass, becomes increasingly important over the years especially due to surging biomethanol demand.

Figure 91. Biofuels production by production route[79]



Source: POTEnCIA

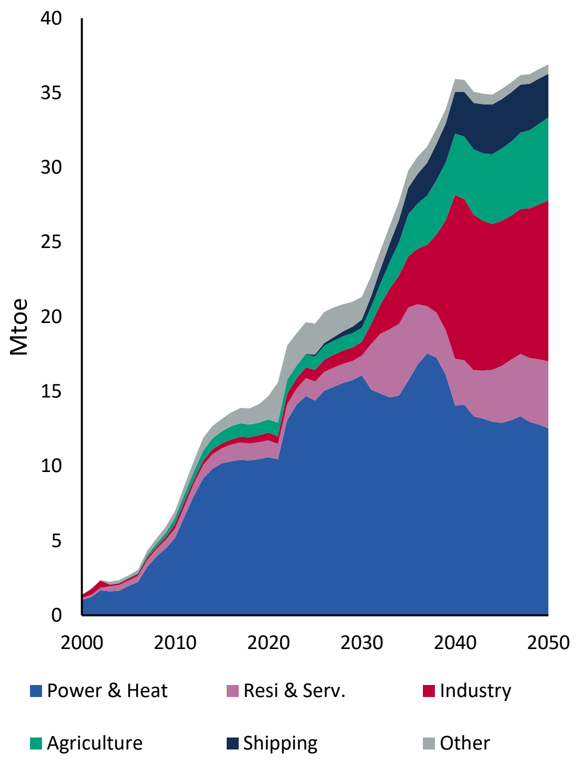
The supply of Annex IX biofuels reaches 13 Mtoe for a total biofuel consumption of 23 Mtoe by 2030, and then rapidly expands to 39 Mtoe by 2040 and 54 Mtoe by 2050. By 2050, advanced biomethanol makes up 58% of all biofuel production, followed by biokerosene production, with 17% coming from HEFA and 14% from FT processing. The growth in biokerosene supply contributes to meet the ReFuelEU Aviation targets for SAFs. While the increase in advanced biomethanol supply is driven by the FuelEU Maritime targets, and by the consumption of biomethanol in the chemical industry to replace part of the fossil feedstock (see FNEC in Figure 90), resulting in the long-term storage of renewable CO2 in materials. The combined production of biodiesel via FAME and FT, as well as of bioethanol via enzymatic hydrolysis grows incrementally from 5 Mtoe in 2021 to 12 Mtoe in 2040, but then fades out quickly mainly because of the progressive electrification of the road sector due to the CO2 emission standards for new vehicles. After 2040, overall consumption of biodiesel and bioethanol drops due to the progressive phase-out of ICE vehicles in the road sector, even though the biofuel blending shares grow over time, pushed by increasingly tight decarbonisation objectives.

[79] UCO biodiesel originated from used cooking oil and animal fats. HEFA biokerosene originated from used cooking oil & animal fats, and to a limited extent also intermediate crops

3.4.3.4 Biogas and biomethane

In 2021, biogas consumption in the EU amounted to 16 Mtoe, predominantly in CHP plants in the power & heat sector, as shown in Figure 92. Biogas consumption in power & heat keeps growing until the 2030s, when it sets on a slowly decline, explained by competing demand from other sectors and supply limits. In the industry sector, biogas consumption increases rapidly in the late 2030s, reaching around 11 Mtoe in 2040 and remaining broadly stable until 2050. Additional biogas demand progressively develops in the agricultural, residential, services, and shipping sectors. Apart from its role towards meeting the targets set by the RED, biomethane also contributes to the FuelEU Maritime targets, accounting for almost 5% of energy consumption in the maritime sector by 2050. Altogether, total biogas and biomethane consumption grows steadily until 2040, when it reaches 36 Mtoe to then flatten out towards 2050.

Figure 92. Biogas consumption by sector[80]



Source: POTEnCIA

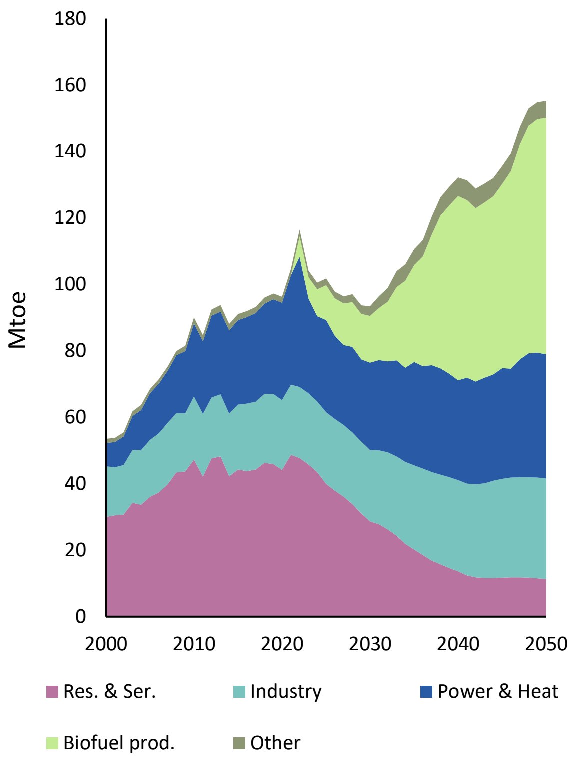
In terms of feedstock, the production of biogas from food and feed crops is gradually phased out by 2030, taken over by RED III Annex IX feedstock (e.g. manure, crop residues, wastewater treatment sludge), which is sufficient to satisfy the growing demand until 2030 and beyond. Importantly, the share of biogas that is upgraded to biomethane rises continuously, allowing for its consumption across different sectors and at the same time providing a cost-effective source of renewable CO2 as feedstock for the production of synthetic fuels.

3.4.3.5 Solid Biomass

In 2021, within the EU, solid biomass was predominantly utilised for heat generation through combustion, with a significant proportion of it being derived from forestry and wood processing residues [27]. Total solid biomass use in 2021 reached 105 Mtoe, of which 47% was consumed in the residential and services sectors, with the remainder being used for power and heat production in the industrial and power & heat sectors. In the *POTEnCIA CETO 2024 Scenario*, solid biomass use in the residential and service sectors is projected to decrease rapidly until 2040 (see Figure 93), driven primarily by the progressive improvements in building insulation that reduce the energy needs for space heating and the progressive adoption of heat pumps. This trend is progressively counterbalanced mainly by an increase in biomass consumption for advanced biofuel production,

[80] Other includes energy transformation sectors, distribution losses, and road transport

Figure 93. Solid biomass consumption by sector[81]



Source: POTEnCIA

which scales up rapidly after 2030. Specifically, solid biomass is gasified to provide the feedstock needed for Fischer-Tropsch as well as for biomethanol synthesis processes. Besides, solid biomass is also used as feedstock for bioethanol production via enzymatic hydrolysis. Apart from the advanced biofuel production, solid biomass becomes increasingly important in the power and industry sectors because of the progressive use of BECCS plants, which enable offsetting residual GHG emissions.

[81] Other includes energy transformation sectors, agriculture, forestry, and fishing

3.5 Carbon Capture, Utilisation, and Storage

Figure 94 shows how total captured CO2 reaches 41 Mt in 2030, followed by a steep trajectory towards 145 Mt by 2035 and 256 Mt by 2040. In the early years until 2030, most CO2 is captured from BECCS plants in the power sector, while virtually all of the CO2 is stored underground, as can be seen in Figure 95. From the 2030s, increasing amounts of CO2 are utilised for synthetic fuels, enabling the provision of carbon-neutral fuels. A small portion of carbon is utilised as feedstock for chemical materials.

Figure 94. Captured CO2 by sector of origin

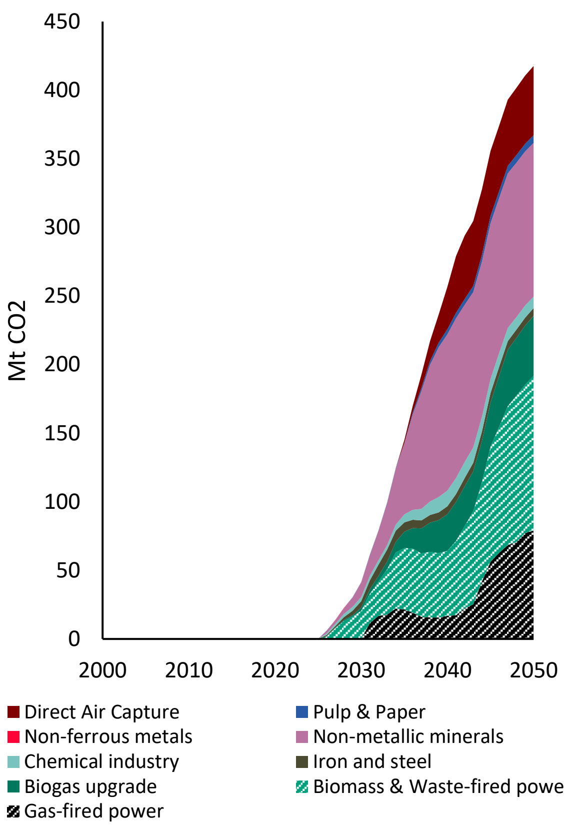
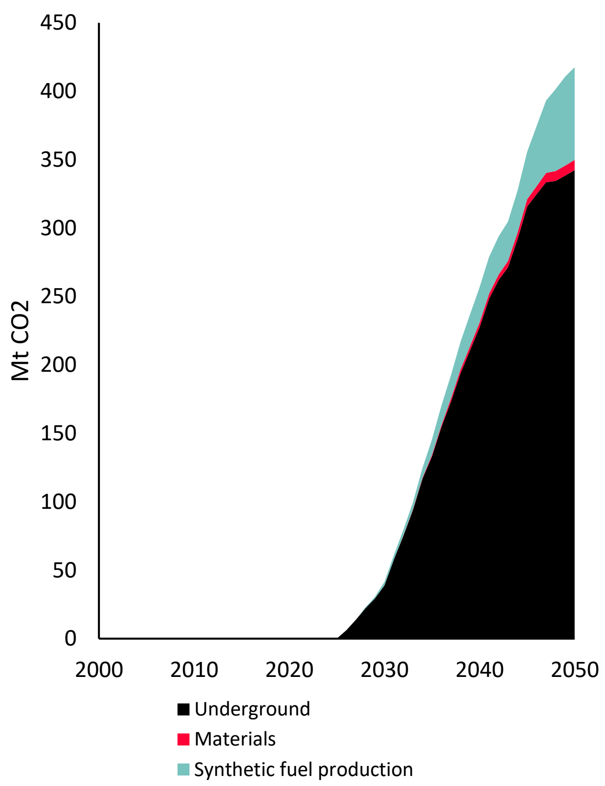


Figure 95. Captured CO2 by type of storage & use



Source: POTEnCIA

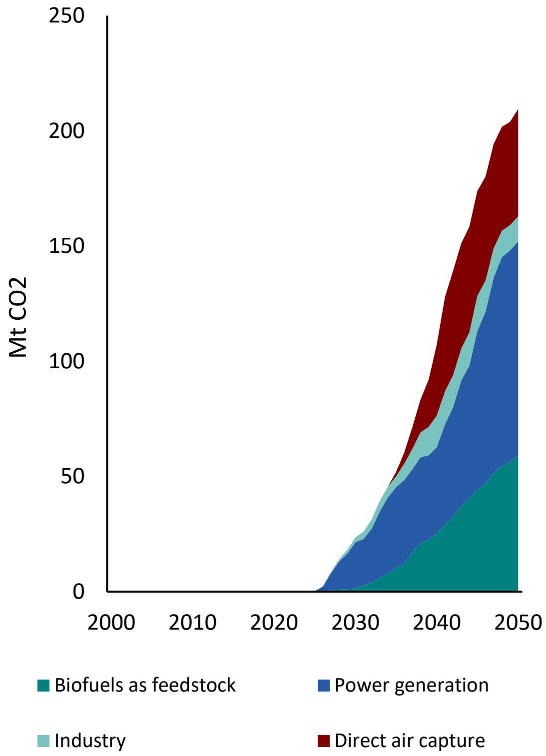
The utilisation of captured carbon for synthetic fuel production is limited to carbon originating from biogenic sources after a transitionary phase from 2030 to 2040, where small amounts of fossil-fuel-based carbon are used[82]. After 2030, various sectors adopt CCUS, with the power sector remaining dominant. Gas-fired power plants supplement BECCS demand, while in the industrial sector, CCUS technologies are primarily deployed for the production of NMMs and chemicals. Another suitable application for CCUS devices is the upgrading of biogas to high-quality biomethane. Lastly, a rapid build-up of DAC is necessary from the late 2030s onwards to reach the 2040 emissions reduction and 2050 net-zero targets. By 2050, 419 Mt of CO2 are captured, of which almost 46% originate from the

[82] For a limited period of time, fossil CO2 captured from power plants and from specific industrial installations is also allowed as feedstock for RFNBOs production, in particular until 2035 in the case of CO2 captured in power plants and until 2040 in the case of CO2 captured in specific industrial installations.

power sector, 32% from industrial sectors, 10% from biogas upgrading, and the remaining 12% from DAC.

By 2050, 343 Mt CO2, equivalent to 82% of the total captured CO2, is stored underground, of which 172 Mt are stored outside the EU in the North Sea seabed. 107 Mt CO2 captured in 2040 and 209 Mt CO2 captured in 2050 are net-negative emissions originating from biogenic sources, allowing for mitigation of emissions of hard-to-abate sectors (see Figure 96).

Figure 96. Negative emissions in EU energy system[83]



Source: POTEnCIA

[83] In the POTEnCIA CETO 2024 scenario, there are two routes for carbon from biofuels to contribute to negative emissions. Firstly, biomethanol being stored directly as a feedstock for chemical compounds. Secondly, carbon captured from biogenic sources being converted into synthetic methanol and the being stored as a feedstock for chemical compounds. The second route is here displayed as "Biogenic CO2 stored in products"

4 Conclusions

This report presents a comprehensive analysis of a technology-driven deep decarbonisation scenario for the EU energy system: the *POTEnCIA CETO 2024 scenario.* The scenario explores projections for different emerging technologies in the context of the decarbonisation of the EU economy and the ECL's overarching objectives. The key findings of this report highlight the critical role of advanced technologies and innovation in facilitating a successful transition to a decarbonized EU energy system. The scenario illustrates that the resulting technology pathways, guided by the policy incentives, and in alignment with behavioural changes and the wider EU economic development, can lead to a significant reduction in greenhouse gas emissions.

The report emphasizes the importance of accelerating the deployment of renewable energy sources, electrification, and CCUS technologies across transformation and demand sectors. This includes the power sector, which becomes a net-negative sector in the 2040s thanks to the fast deployment of intermittent renewables and storage technologies coupled with increasing BECCS capacities, substituting coal plants while satisfying the more-than-doubled electricity demand. The growing electricity demand is primarily caused by the overarching electrification of the demand sectors as well as by the rising demand for hydrogen and its derivatives, which rapidly expand from the 2030s onwards. The latter directly compete in many sectors with liquid and gaseous biofuels, where production also augments rapidly with strict feedstock requirements ensuring their long-term sustainability.

The deployment of CCUS, including BECCS, devices coupled with electrification and the utilisation of renewable fuels drive the decarbonisation of industrial processes, so that the sector reaches net-zero emissions by 2050. The transport sector, which is currently the largest emitter among all end-use sectors, can achieve significant emissions reductions through the rapid uptake of electric vehicles (especially in road transport), and low-carbon fuels (especially in aviation and shipping). The buildings sector experiences an unprecedented drop in energy demand due to the uptake of highly-efficient heat pumps coupled with energy efficiency measures.

The combined efforts lead to a gross available energy reduction of 30% by 2050 compared to 2021, where in 2050 fossil fuels play only a minor role in the EU energy system, while renewable energies become dominant. Thus, the decarbonisation of the EU energy system, together with a slight increase in the LULUCF carbon sink, allow EU emissions to drop to the target levels of the ECL, reaching net-zero in 2050.

References

[1] Schmitz A, Schade B, Garaffa R, Keramidas K, Dowling P, Fosse F, et al. Impacts of enhanced learning for clean energy technologies on global energy system scenarios - Forthcoming n.d.

[2] Mantzos L, Matei NA, Rózsai M, Russ P, Ramirez AS. POTEnCIA: A new EU-wide energy sector model. 2017 14th Int. Conf. Eur. Energy Mark. EEM, IEEE; 2017, p. 1–5.

[3] Centre JR, Studies I for PT, Mantzos L, Wiesenthal T. POTEnCIA model description – Version 0.9. Publications Office; 2016. https://doi.org/doi/10.2791/416465.

[4] European Commission - Press corner. Factsheet - Europe's 2040 climate pathway 2024.

[5] European Commission, Directorate-General for Energy. Ecodesign impact accounting annual report 2021 – Overview and status report. 2021.

[6] European Commission. Regulation (EU) 2023/851 of the European Parliament and of the Council of 19 April 2023 amending Regulation (EU) 2019/631 as regards strengthening the CO2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambition. 2023.

[7] European Commission. Regulation (EU) 2024/1610 of the European Parliament and of the Council of 14 May 2024 amending Regulation (EU) 2019/1242 as regards strengthening the CO2 emission performance standards for new heavy-duty vehicles and integrating reporting obligations, amending Regulation (EU) 2018/858 and repealing Regulation (EU) 2018/956. 2024.

[8] Rozsai M, Jaxa-Rozen M, Salvucci R, Sikora P, Tattini J, Neuwahl F. JRC-IDEES-2021 n.d.

[9] Rozsai M, Jaxa-Rozen M, Salvucci R, Sikora P, Tattini J, Neuwahl F. JRC-IDEES-2021: the Integrated Database of the European Energy System - Data update and technical documentation 2024. https://doi.org/10.2760/614599.

[10] Eurostat. Complete energy balances - annual data (code: nrg_bal_c). Last update of data: 2024-01-28. 2024.

[11] Eurostat. Production of electricity and derived heat by type of fuel (code: nrg_bal_peh). Last update of data: 2024-01-28. 2024.

[12] Eurostat. Imports of electricity and derived heat by partner country (code: nrg_ti_eh). Last update of data: 2024-01-26. 2024.

[13] Eurostat. Exports of electricity and derived heat by partner country (code: nrg_te_eh). Last update of data: 2024-01-26. 2024.

[14] Eurostat. Share of energy from renewable sources (code: energy_shares_a). Last update of data: 2023-01-17. 2023.

[15] Eurostat. Cooling and heating degree days by country - annual data (code: nrg_chdd_a). Last update of data: 2023-02-01. 2023.

[16] Eurostat. National Accounts (including GDP). 2023.

[17] Eurostat. Structural Business Statistics. Last update of data: 2023-09-08. 2023.

[18] Eurostat. Population on 1 January by age and sex (code: demo_pjan). Last update of data: 2023-07-03. 2023.

[19] Eurostat. Average household size - EU SILC survey (code: ilc_lvph01). Last update of data: 2023-07-11. 2023.

[20] Eurostat. Distribution of households by household size (code: ilc_lvph03). Last update of data: 2023-07-11. 2023.

[21] Intergovernmental Panel on Climate Change. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). 2006.

[22] United Nations Framework Convention on Climate Change. National Inventory Submissions, 2023. 2023.

[23] European Commission. Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 601/2012. 2018.

[24] European Commission. Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society - IMPACT ASSESSMENT REPORT - Document 52024SC0063 2024.

[25] Motola, V .Scarlat, N., Buffi, M., Hurtig, O., Rejtharova, J., Georgakaki, A., Mountraki, A., Letout, S., Salvucci, R., Rózsai, M. and Schade, B. Clean Energy Technology Observatory: Advanced biofuels in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[26] Bielewski, M., Pfrang, A., Quintero Pulido, D., Bobba, S., Schade, B., Georgakaki, A., Letout, S., Mountraki, A. and Ince, E. Clean Energy Technology Observatory: Battery Technology in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[27] Motola V., Scarlat N., Hurtig, O., Buffi M., Georgakaki A., Letout S., Mountraki A., Salvucci R., Schmitz, A. Clean Energy Technology Observatory: Bioenergy in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[28] Martinez Castilla, G., Tumara, D., Mountraki, A., Letout, S., Jaxa-Rozen, M., Schmitz, A., Ince, E. and Georgakaki, A. Clean Energy Technology Observatory: Carbon capture utilisation and storage in the European union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[29] Bravo Diaz, L., Weidner, E., Dolci, F., Georgakaki, A., Letout, S., Mountraki, A., Gea Bermudez, J., Wegener, M. and Schade, B. Clean Energy Technology Observatory: Fuel cell technology in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[30] Taylor, N., Georgakaki, A., Ince, E., Letout, S. Mountraki, Gea Bermudez, J. and Schmitz, A.. Clean Energy Technology Observatory: Geothermal energy in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[31] Toleikyte, A., Lecomte, E., Volt, J., Lyons, L., Roca Reina, J.C., Georgakaki, A., Letout, S., Mountraki, A., Wegener, M., Schmitz, A. Clean Energy Technology Observatory: Heat pumps in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[32] Quaranta, E., Georgakaki, A., Letout, S., Mountraki, A., Ince, E. and Gea Bermudez, J. Clean Energy Technology Observatory: Hydropower and pumped hydropower storage in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[33] Roca Reina, J.C; Volt, J; Carlsson, J; Dlugosz, M; Georgakaki, A; Ince, E; Kuokkanen, A; Letout, S; Mountraki, A; Shtjefni, D; Eulaerts, O; Grabowska, M. Clean Energy Technology Observatory: Novel thermal energy storage in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[34] Tapoglou, E., Mc Govern, L., Georgakaki, A., Mountraki, A., Letout, S., Ince, E., Gea Bermudez, J., Schmitz, A. and Grabowska, M. Clean Energy Technology Observatory: Ocean energy in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[35] Chatzipanagi, A., Jaeger-Waldau, A., Cleret De Langavant, C., Gea Bermudez, J., Letout, S., Mountraki, A., Schmitz, A., Georgakaki, A., Ince, E., Kuokkanen, A., Shtjefni, D. Clean Energy Technology Observatory: Photovoltaics in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[36] Buffi, M., Motola, V., Rejtharova, J., Scarlat, N., Hurtig, O., Georgakaki, A., Letout, S., Mountraki, A., Salvucci, R. and Schade, B.,. Clean Energy Technology Observatory: Renewable fuels of non-biological origin in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[37] De Paola, A., Andreadou, N., Kotsakis, E. Clean Energy Technology Observatory: Smart grids in the European union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[38] Volt, J., Roca Reina, J.C., Toleikyte, A., Mountraki, A., Letout, S., Wegener, M., and Black, C. Clean Energy Technology Observatory: Smart thermal networks in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[39] Carlsson, J., Taylor, N., Georgakaki, A., Letout, S., Mountraki, A., Ince, E., Schmitz, A. and Gea Bermudez, J. Clean Energy Technology Observatory: Solar thermal energy in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[40] J., Dolci, F., Gryc, K., Eynard, U., Georgakaki, A., Letout, S., Mountraki, A., Ince, E., Shtjefni, D., Rózsai, M. and Wegener, M. Clean Energy Technology Observatory: Water electrolysis and hydrogen in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[41] Mc Govern, L., Tapoglou, E., Georgakaki, A., Mountraki, A., Letout, S., Ince, E., Gea Bermudez, J., Schmitz, A. and Grabowska, M. Clean Energy Technology Observatory: Wind Energy in the European Union - 2024 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2024.

[42] ENTSO-E. ACER - Ten-Year Network Development Plan 09-24.

[43] ENTSO-E. ENTSO-E Transmission System Map 09-24.

[44] Eurostat. Population on 1st January by age, sex and type of projection (code: proj_23np). Last update of data: 2023-06-28. 2023.

[45] Directorate-General for Economic and Financial Affairs. European Economic Forecast. Spring 2024 2024. https://doi.org/10.2765/219276.

[46] Directorate-General for Economic and Financial Affairs. 2024 Ageing Report. Underlying Assumptions and Projection Methodologies. 2023.

[47] Keramidas K., Fosse F., Diaz Rincon A., Dowling P., Garaffa R., Ordonez J., et al. Global Energy and Climate Outlook 2023. Luxembourg (Luxembourg): Publications Office of the European Union; 2023. https://doi.org/10.2760/836798 (online).

[48] International Institute for Applied Systems Analysis (IIASA). Global Biosphere Management Model (GLOBIOM) 2023.

[49] International Institute for Applied Systems Analysis (IIASA). Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) 2024.

[50] European Commission. Common Agricultural Policy Regionalised Impact (CAPRI) model 2023.

[51] European Commission. DIONE - Road Transport Fleet Impact Model n.d.

[52] IEAGHG, Towards improved guidelines for cost evaluation of carbon capture and storage. IEAGHG; 2021.

[53] Technology Data for Renewable Fuels: 2023-06 v 2023.

[54] Gardarsdottir SO, De Lena E, Romano M, Roussanaly S, Voldsund M, Pérez-Calvo J-F, et al. Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis. Energies 2019;12. https://doi.org/10.3390/en12030542.

[55] Sievert K, Schmidt TS, Steffen B. Considering technology characteristics to project future costs of direct air capture. Joule 2024;8:979–99. https://doi.org/10.1016/j.joule.2024.02.005.

[56] Gea-Bermúdez J, Das K, Koduvere H, Koivisto MJ. Day-Ahead Market Modelling of Large-Scale Highly-Renewable Multi-Energy Systems: Analysis of the North Sea Region towards 2050. Energies 2021;14:88. https://doi.org/10.3390/en14010088.

[57] ENTSO-E. TYNDP 2022 - System Needs Study: Opportunities for a more efficient European power system in 2030 and 2040. Brussels: 2023.

[58] Eurostat - Statistics. Eurostat - Energy Glossary 2023.

[59] Joana Fonseca, Matus Muron, Grzegorz Pawelec, Ivan Petar Yovchev, Nicolas Bellomo, Katarina Muse, et al. Clean Hydrogen Monitor 2023 2023.

[60] Bolard, J., Dolci, F., Gryc, K., Eynard, U., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E., Shtjefni, D. Clean Energy Technology Observatory: Water electrolysis and hydrogen in the European Union - 2023 status report on technology development, trends, value chains and markets. LU: European Commission. Joint Research Centre.; 2023.

List of abbreviations and definitions

Acronym	Definitions
AFIR	Alternative Fuels Infrastructure Regulation
BECCS	Bio-Energy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
BF-BOF	Blast Furnace – Basic Oxygen Furnace
CAPRI	Common Agricultural Policy Regionalised Impact (model)
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon Capture, Utilisation, and Storage
CETO	Clean Energy Technology Observatory
CHP	Combined Heat and Power
CO2	Carbon Dioxide
CO2_eq	Carbon Dioxide Equivalent
DAC	Direct Air Capture
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EC	European Commission
EEA	European Economic Area
EEAwUK	European Economic Area and the United Kingdom
EED	Energy Efficiency Directive
EEDI	Energy Efficiency Design Index
EPBD	Energy Performance of Buildings Directive
ESR	Effort Sharing Regulation
ETS	Emissions Trading System
EU	European Union
FAME	Fatty Acid Methyl Ester
FCEV	Fuel Cell Electric Vehicle
FEC	Final Energy Consumption
FF55	Fit for 55 (policy package)
FNEC	Final Non-Energy Consumption
FT	Fischer-Tropsch
G4M	Global Forest Model
GAE	Gross Available Energy
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies (model)
GDP	Gross Domestic Product

Acronym	Definitions
GECO	Global Energy and Climate Outlook
GLOBIOM	Global Biosphere Management Model
GVA	Gross Value Added
H2	Hydrogen
HGV	Heavy Goods Vehicle
HEFA	Hydroprocessed Esters and Fatty Acids
I&S	Iron and Steel
ICE	Internal Combustion Engine
IDEES	Integrated Database of the European Energy System
ICMS	Industrial Carbon Management Strategy
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LCV	Light Commercial Vehicle
LNG	Liquefied Natural Gas
LULUCF	Land-Use, Land-Use Change and Forestry
MAC	Marginal Abatement Curve
MS	Member States
NMM	Non-Metallic Mineral
NZE	Net-Zero Emissions
NZIA	Net-Zero Industry Act
POLES	Prospective Outlook on Long-term Energy Systems (model)
POTEnCIA	Policy-Oriented Tool for Energy and Climate change Impact Assessment
RED	Renewable Energy Directive
RFNBOs	Renewable Fuels of Non-Biological Origin
SAFs	Sustainable Aviation Fuels
SETIS	Strategic Energy Technology Information System
TEN-T	Trans-European Transport Network
TRL	Technology Readiness Level
TYNDP	Ten Year Network Development Plan
UNFCC	United Nations Framework Convention on Climate Change
V1G	Unidirectional EV Smart Charging
V2G	Vehicle-to-Grid – Bidirectional EV Smart Charging

List of units

Abbreviations	Definitions
TWh	Terrawatt-hour
MWh	Megawatt-hour
kWh	Kilowatt-hour
GW	Gigawatt
t	Tonne (metric)
kt	Kilotonne (metric)
Mt	Megatonne (metric)
toe	Tonne of oil equivalent (41 868 kilojoules/kilogram)
ktoe	Kilotonne of oil equivalent
Mtoe	Megatonne of oil equivalent
Gtoe	Gigatonne of oil equivalent
sqm	Square metre
km	Kilometre
tkm	Tonne-kilometre
pkm	Passenger-kilometre
vkm	Vehicle-kilometre

List of figures

Figure 1. Overview of the POTEnCIA model 7

Figure 2. EU emission targets in the *POTEnCIA CETO 2024 scenario* 10

Figure 3. EU population & number of households projections 15

Figure 4. EU GDP projections 15

Figure 5. International fuel prices 16

Figure 6. GAE by fuel type 22

Figure 7. EU emissions overview 23

Figure 8. Non-CO2 GHG emissions by sector in the EU 23

Figure 9. EU ETS price & carbon value 25

Figure 10. Total investment expenditure by energy sector and by decade relative to GDP 26

Figure 11. Total investment expenditure by decade for residential and industry sectors, relative to total household expenditure and value added 26

Figure 12. Total energy-related cost by energy sector and by decade, relative to GDP 27

Figure 13. Total energy-related cost by decade for residential and industry sectors, relative to total household expenditure and value added 27

Figure 14. Total power and heat system costs relative to GDP 27

Figure 15. Average electricity generation cost 27

Figure 16. Energy consumption by demand sector 29

Figure 17. Fuel consumption by demand sector 29

Figure 18. Value added for the industry sector 30

Figure 19. GHG emissions for the industry sector 31

Figure 20. Unabated energy & process emissions for selected sectors 31

Figure 21. Energy demand in industry by sector 32

Figure 22. Energy demand in industry by fuel 32

Figure 23. Physical output of NMM products 34

Figure 24. FEC for NMMs products 34

Figure 25. Key indicators for NMMs 34

Figure 26. Physical production of iron and steel 36

Figure 27. Energy demand of iron and steel production 36

Figure 28. Key indicators for iron and steel 36

Figure 29. Physical output for chemicals 38

Figure 30. FEC and FNEC for chemicals 38

Figure 31. Key indicators for the chemical industry 38

Figure 32. Physical output for non-ferrous metals 40

Figure 33. FEC for non-ferrous metals 40

Figure 34. Key indicators for non-ferrous metals 41

Figure 35. Physical output for pulp and paper 42

Figure 36. FEC for pulp and paper 42

Figure 37. Key indicators for pulp & paper 42

Figure 38. Physical output for non-energy-intensive industries 44

Figure 39. FEC for non-energy-intensive industries 44

Figure 40. Key indicators for non-energy- intensive sectors 44

Figure 41. Emissions in the transport sector 45

Figure 42. Passenger transport activity by mode 46

Figure 43. Freight transport activity by mode 46

Figure 44. Relative passenger transport activity by mode 47

Figure 45. Relative freight transport activity by mode 47

Figure 46. Energy demand in transport by sector 48

Figure 47. Energy demand in transport by fuel 48

Figure 48. Key indicators for passenger cars 49

Figure 49. FEC for passenger cars 49

Figure 50. Key indicators for buses and coaches 50

Figure 51. FEC for buses and coaches 50

Figure 52. Key indicators for powered 2-wheelers 51

Figure 53. FEC for powered 2-wheelers 51

Figure 54. Key indicators for LCVs 52

Figure 55. FEC for LCVs 52

Figure 56. Key indicators for HGVs 53

Figure 57. FEC for HGVs 53

Figure 58. Vehicle stock by powertrain type 53

Figure 59. Key indicators for rail and metro 54
Figure 60. FEC for rail and metro 54
Figure 61. Key indicators for aviation 56
Figure 62. Energy demand for aviation 56
Figure 63. Key indicators for shipping 57
Figure 64. Energy demand for shipping 57
Figure 65. Useful surface area of the residential and services sectors 58
Figure 66. Energy consumption of selected appliances 58
Figure 67. FEC in residential and services sectors by energy service type 59
Figure 68. FEC in residential and services sectors by fuel 59
Figure 69. Net emissions in residential and services sectors 60
Figure 70. Key indicators for the residential sector 61
Figure 71. FEC of the residential sector 61
Figure 72. Key indicators for the services sector 62
Figure 73. FEC of the services sector 62
Figure 74. Agriculture emission sources 63
Figure 75. FEC of the agriculture sector 64
Figure 76. Key indicators for agriculture 64
Figure 77. Electricity demand by sector 66
Figure 78. Net electricity generation by technology 66
Figure 79. Power generation from storage units 67
Figure 80. Flexible demand by sector 67
Figure 81. Net electricity generation capacities 69
Figure 82. CO2 emissions in the power sector 69
Figure 83. Distributed heat demand by sector 71
Figure 84. Distributed heat supply by technology 71
Figure 85. Green Hydrogen sources 73
Figure 86. Green Hydrogen demand by sector 73
Figure 87. Synthetic fuels production by type 75
Figure 88. Synthetic fuels demand by sector 75
Figure 89. Biofuels consumption by type 76

Figure 90. Biofuel consumption by sector 76

Figure 91. Biofuels production by production route 77

Figure 92. Biogas consumption by sector 78

Figure 93. Solid biomass consumption by sector 79

Figure 94. Captured CO2 by sector of origin 80

Figure 95. Captured CO2 by type of storage & use 80

Figure 96. Negative emissions in EU energy system 81

List of tables

Table 1. CO_2 Emission Standards for New Vehicles.. 12

Table 2. Fuel aggregation and fuel codes 95

Annexes

Annex 1. Supplementary information.

All POTEnCIA CETO 2024 scenario result data files are made available through the following website of the Joint Research Centre (JRC): [Joint Research Centre Data Catalogue - POTEnCIA scenarios - European Commission][84]

Table 2. Fuel aggregation and fuel codes[85]

Fuel category	*Specific fuel*	*Energy balance fuel codes*
Coal & Lignite	Anthracite	2115
	Coking coal	2116
	Other bituminous coal	2117
	Sub-bituminous coal	2118
	Patent fuels	2112
	Coke oven coke	2121
	Gas coke	2122
	Coal tar	2130
	Lignite/brown coal	2210
	Peat	2310
	BKB (brown coal briquettes)	2230
	Peat products	2330
	Oil shale and oil sands	2410
Oil prod.	Crude oil without NGL	3105
	Natural gas liquids (NGL)	3106
	Refinery feedstocks	3191
	Additives / oxygenates	3192
	Other hydrocarbons (without biofuels)	3193
	Refinery gas (not. liquid)	3214
	Ethane	3215
	Liquified petroleum gas (LPG)	3220
	Gasoline (without biofuels)	3234
	Aviation gasoline	3235
	Gasoline type jet fuel	3246
	Kerosene type jet fuel	3247
	Other kerosene	3244
	Naphtha	3250
	Gas/diesel oil (without biofuels)	3260
	Residual fuel oil	3270A
	White spirit and sbp	3281
	Lubricants	3282
	Bitumen	3283
	Petroleum coke	3285
	Paraffin waxes	3286
	Other oil products	3295
Nat. & der. gases	Natural gas	4100
	Coke oven gas	4210
	Blast furnace gas	4220
	Gas works gas	4230
	Other recovered gases	4240
Heat	Nuclear heat	5100
	Derived heat	5200
Renewable energies (excluding biomass)	Hydro power	5510
	Wind power	5520
	Solar thermal	5532
	Solar photovoltaic	5534
	Tide, wave, and ocean	5535
	Geothermal	5550

[84]Exact link: https://data.jrc.ec.europa.eu/collection/id-00341

[85] Categories only apply if not specified differently

Biomass & Waste	Solid biofuels (wood & wood waste)	5541
	Charcoal	5544
	Biogas	5542
	Municipal waste (renewable)	55431
	Biogasoline	5546
	Biodiesels	5547
	Bio jet kerosene	5549
	Other liquid biofuels	5548
	Industrial wastes	7100
	Municipal waste (non-renewable)	55432
Hydrogen	Hydrogen	H2F
Synthetic fuels	Synthetic gas	SGAS
	Synthetic gasoline	SGSL
	Synthetic diesel oil	SGDO
	Synthetic kerosene	SKRS
	Green methanol	SMET
	Green ammonia	SAMM

Source: JRC analysis

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