European Environment Agency

Renewables, electrification and flexibility
For a competitive EU energy system transformation by 2030

EEA Report 16/2024

European Environment Agency

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Luxembourg: Publications Office of the European Union, 2025

ISBN 978-92-9480-728-1
ISSN 1977-8449
doi:10.2800/4558900

Cover design: EEA
Cover photo: © Colin Watts/Unsplash
Layout: Eworx/EEA

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Acknowledgements

The European Environment Agency (EEA) would like to thank the experts, stakeholders, partners from the European Environment Information and Observation Network, the European Commission and its Scientific Committee for their valuable support and feedback on this report.

In particular, the EEA would like to thank Frank Geels and Stefan Lechtenböhmer, as past and current members of the EEA Scientific Committee, and the Ecologic Institute and Ramboll for the substantial involvement and contributions for this publication.

Executive summary

The European Union is on a pathway to achieve climate neutrality by 2050. This report explores the historic and necessary efforts to align Europe's electricity, heating and transport systems with transformative EU benchmarks for 2030 to meet that longer-term goal. CO_2 emissions have declined significantly in the EU electricity subsystem over the past few decades. This presents an important opportunity to decarbonise rapidly in the near future and to roll out electrification to other sectors, while strengthening energy independence, security and competitiveness for all EU countries. Through accelerated gains in energy and resource efficiency and the alignment of Member States' efforts within a more coherent EU energy system, the rapid electrification of buildings, transport and industry can greatly reduce Europe's reliance on foreign fossil fuels and unlock critical progress in heating and transport.

Over the past five years, EU policy frameworks for climate mitigation and energy system transformation have become far more coherent and complete. Infrastructure security and resilience have been bolstered through integrated climate and energy planning in tandem with national and cross-border efforts to ensure sound policy implementation. It is now critical that decision-makers translate objectives and priorities for the energy system transition into actionable measures. This includes crafting fiscal strategies to finance key upfront infrastructure investments; distributing the cost of capital proportionally to not overburden taxpayers; aligning taxation, pricing and information signals across the whole energy system; and regularly monitoring and evaluating performance to recalibrate policies when needed.

Europe has demonstrated that a successful energy shift is possible

The last decade has seen a rapid and successful shift in all Member States away from fossil fuels and into more sustainable energy sources. This is especially true for electricity but also in heating and transport. Meanwhile, policies to improve energy efficiency have kept energy demand growth in check. This has contributed to significant and ongoing reductions in greenhouse gas emissions across the EU. The most recent reduction, documented in 2023, reported levels 37% lower than in 1990 (30.5% below 2005).

The collective achievement of the EU climate and energy transformation targets for 2020 demonstrates clearly that Member States can shape and accelerate energy and industrial transitions — as intended with the new Clean Industrial Deal — when they align shorter-term actions with longer-term policy goals (EC, 2025c). Clarifying the intermediate EU climate goal for 2040 will thereby help increase predictability.

For 2030, most countries have recently outlined renewed ambitions and commitments for 2030 in their updated National Energy and Climate Plans (NECPs), putting the EU well on track to meeting the agreed targets for 2030 if full implementation is ensured (EC, 2025f). They are now reporting on progress toward these commitments. This all falls under the integrated monitoring and cooperation process set by the EU Governance Regulation.

When assessing decarbonisation efforts across three key energy subsystems — electricity, heating and transport — electricity presents the most significant business opportunities and fastest historic progress. The main driver is variable renewable generation from solar and wind, though recent developments in battery systems and a growing interest from prosumers are now supporting these trends. However, efforts must be accelerated and scaled up further to meet the EU 2030 transformation benchmarks. More horizontal efforts to improve efficiency and circularity are equally important in the short term. Deeper EU and cross-sectoral energy planning, cooperation and progress monitoring is equally important to lower the inefficiencies of unaligned national efforts. Such efforts can bring forward more cost-efficient, secure and optimally integrated energy infrastructures.

Accelerating the deployment of renewables and improving energy efficiency within the EU are strategic necessities, especially in the face of escalating geopolitical tensions

Oil and gas are the two most widely used fossil fuels in the EU. As domestic production is dwindling, Member States face a widening gap between demand and supply. In 2022, 98% of all oil and of all gas used in Member States was imported. This risks supply shortages and price volatility. Meanwhile, the EU energy import bill increased to almost 4% of GDP that year (roughly twice as much as average historic levels). This placed a substantial burden on all Member States — a toll that could have been far heavier had countries not systematically pursued efforts to improve energy efficiency, increase renewable energy supply and reduce their economic dependency on fossil fuels.

Against this backdrop, the European Green Deal (EGD) offers far more than an alignment of the EU energy system to climate commitments. It is the main avenue through which Member States can secure access to domestic energy resources — especially renewable electricity supply — and reduce import dependency in the medium and longer term. The latest set of frameworks tabled by the European Commission (EC) in 2025 — the Competitiveness Compass, Clean Industrial Deal and the Action Plan for Affordable Energy — set out ambitious strategies for growth and investments that enhance decarbonisation efforts and decrease energy costs for citizens and businesses (EC, 2025a, 2025c, 2025b).

Key drivers for accelerating the EU energy system transformation

Upscaling renewable electricity generation to meet the EU's 2030 climate and energy targets could lower the variable costs of EU electricity generation by up to 57% below 2023 levels. Yet capital costs will go up as short term investments are required.

As assessed in this report, annual spot power prices could fall by 57% in all EU countries and electricity markets compared with 2023, if the benchmark levels for 2030 for renewable capacity, demand and storage are met. This would mark a significant decrease from the peak wholesale prices of the past four years, even as future levels of these variable electricity costs will not fall below the lowest values seen in 2016. Over time, this creates strong potential to lower consumer prices and increase energy independence. However, in the short term, part of the savings will likely be offset by necessary investments to accelerate renewable capacity deployment and to modernise important energy infrastructure, including grids.

In 2024, high gas prices remained a determinant factor for European electricity prices. Average EU electricity prices rose, even as strong growth in renewable generation had pushed them down from their peak in 2022. Solar PV, wind turbines and other renewables can produce electricity at lower marginal costs. This pushes electricity prices down. However, even as solar and wind technologies have become cost-competitive, spot prices in the market are set by the most expensive marginal generation units — usually gas peaker plants.

Gas therefore continues to play a key role in marginal price-setting through much of the year. Solar and wind capacity must be boosted to limit the disproportionate impact of high gas prices on EU competitiveness and supply security.

For that, three hurdles must be cleared in the short term:

- Policymakers must improve the availability of capital and the overall investment leverage to attract more investments in renewable energy capacity. For electricity, scenarios indicate renewables need to increase to 77% of all installed power capacity by 2030 (equivalent to a threefold increase, compared with 2022), to reach 2030 targets (EC, 2022b, 2021d, 2021b).

- An equal or stronger push is needed to upgrade and digitalise power grids and to roll out demand response and storage, to double the flexibility resources across the EU electricity system by 2030. Against the backdrop of strained national budgets, policymakers should reflect on how to realise urgent investments — including in innovative technologies — and optimally redistribute costs in time and over end-users to ensure electrification takes off.

- Keeping the EU energy system's transformation secure and cost-effective also requires enhancing pan-European coordination. Cross-border planning, cooperating on key energy infrastructure, flexibility solutions, resilience and market integration remain key to reducing inefficiencies and maximising the benefits of this transition.

In the medium term, as average electricity prices decrease it will become more difficult to compensate investors for the additional upfront cost of renewable capacity deployment and system integration. Decisionmakers should consider whether today's policy toolboxes — which already enable two-way contracts for differences and power purchase agreements — will need further adjustments to keep renewable electricity investments attractive beyond 2030.

Stronger electrification signals are needed

Additional efforts are required to increase substantially the share of EU final electricity consumption and roll out electrification to end-use sectors

Electricity must become the predominant energy carrier by 2030 according to recent EU decarbonisation scenarios (EC, 2024c). Yet the historic trend since 2005 is stagnant. Rolling out electrification to end-use sectors will boost efficiency across the entire EU energy system. But this trend will not take off unless more signals are provided — in the very short term — to enhance the economic desirability of electricity over fossil fuels for consumers.

Moreover, the recent evolution of the EU electricity subsystem in response to gas price shocks fell out of step with a cost-optimal systemic transformation. The past four years saw a record build-out of EU liquefied natural gas (LNG) terminals to receive more gas, while fossil fuel subsidies reached their highest levels ever in 2022 and 2023. Meanwhile, subsidies for renewable energy sources have decreased compared with levels reached before the COVID crisis. Renewables have become increasingly competitive without financial support.

Policymakers must make a stronger case for electrification and ensure that consumers receive coherent signals from across all energy system components. Necessary measures include: the phasing out of fossil fuel subsidies; aligning energy product taxation based on actual energy content; adopting more dynamic electricity pricing to activate demand response; supporting further investments through tax credits; and two-way contracts for difference and power purchase agreements. Coordination across Member States in strategy planning and implementation is critical to foster the emergence of optimal EU pathways.

More generally, global evidence from the past two decades finds that price signals tend to work well with businesses. Yet well-designed combinations of pricing, regulation, information and subsidy tools are needed to address the specific challenges and needs of private consumers. This is especially true regarding electrification. Continuous public dialogue, educational programmes and energy literacy campaigns can foster public support for the energy system transition and address information gaps, possible misconceptions and misinformation.

To succeed, policymakers should seek to prioritize known and innovative sector-specific good practices that complement without distorting existing EU frameworks, such as the EU ETS, rather than increasing policy quantity per se. In general, fossil fuel subsidies — including recent financial consumption support introduced in 2021 in response to the energy crisis — must be phased out as soon as possible.

Ultimately, rapid **electrification of end-use sectors will be overcompensated by even larger gains in energy efficiency across the entire energy system**. These benefits can complement ongoing efforts to conserve energy and improve resource efficiency, thereby ensuring a more cost-effective transformation of the EU energy system by 2030.

The EU energy system today is at best 65% efficient. Over a third of all energy is lost as waste heat, contributing to higher emissions and pollution without delivering useful energy services. Shifting to more efficient electricity generation technologies such as solar and wind, while rolling out electrification to end-use sectors via heat pumps and electric vehicles, can reduce this inefficiency and the environmental and health impacts associated with the wasted energy significantly — although renewable power sources are not entirely impact free.

Box ES 1

Decarbonising the heating and transport subsystems

Decarbonising heating requires rapid electrification, with heat pumps serving as a key component to phase out fossil fuels. Enhancing energy efficiency and circularity is essential, particularly through the deep energy renovation of inefficient buildings and the electrification of low- and medium-temperature industrial processes. Demand response and other flexibility solutions must be scaled up to reduce costs and accelerate deployment of intermittent renewable electricity sources. Policy measures include revising energy taxation and phasing out fossil fuel subsidies to close the gap between electricity and fossil fuel commodities. Targeted incentive programmes and funding can drive electrification, promote energy efficiency and savings, encourage innovation, while supporting vulnerable groups to participate in mitigation efforts.

In transport, accelerating the deployment of electric vehicles is an important factor that complements a broader shift towards more active and sustainable modes of travel, such as walking and collective transport. Policy options include subsidies or tax adjustments to reduce the upfront cost disparity between electric and conventional vehicles and measures encouraging the greening of corporate car fleets. The replacement of regular vehicles with battery electric vehicles (BEVs) could accompany investments in infrastructures for active transport modes (e.g. pedestrian and cycle lanes), while ensuring seamless transfers for the last-mile commutes and funding for rail and waterborne transport infrastructure.

Across the EU energy systems, non-technical and non-financial barriers are important too. Policymakers must address these too to increase public trust, reduce energy literacy gaps and sometimes mitigate misinformation. Moreover, public authorities at central, regional and local level play a key role in interacting with EU citizens as they translate national and EU climate, energy, competitiveness and security objectives into domestic local measures. New strategies are needed to prepare authorities for the unprecedented transformation and speed at which they are expected to deliver it, while helping them to solve trade-offs adequately and efficiently. Authorities will need to be provided with the knowledge, digital, data and communication skills necessary to unlock the full potential of digitalisation.

Practical examples are numerous and will include:

- simplifying administrative procedures through best practice sharing, for instance regarding the identification of low-conflict, beneficial areas for renewable energy expansion (with the protection of the environment and citizens);
- removing unjustified market barriers for the participation of non-fossil flexibility resources (such as demand response and energy storage);
- supporting the initiation of renewable energy communities and prosumers in general, while facilitating the co-ownership of generation and transmission assets by regional utilities, energy cooperatives, banks and small to medium sized enterprises;
- devising transparent public information tools and tailored policy incentives, such as recycling and redistributing carbon revenues, that help consumers — including vulnerable groups — to make informed investment choices (for instance on private heating systems, energy retrofits in buildings and mobility).

1 Introduction

1.1 Scope, aim and structure of this report

Scope and aim of this report

Energy systems are essential to human well-being. Modern energy systems comprise long, parallel chains of value creation for the production, transport, distribution and consumption of energy. This provides resources for uses across society, including lighting, heating, cooling, cooking, transport and manufacturing. Each chain includes resource-specific physical infrastructures (e.g. technologies and grids), stakeholders, processes and operation rules.

With the exception of oil, which is used vastly in vehicle internal combustion engines (EEA, 2024n), most energy resources produce electricity and heating (Aalto, P, 2021; EC, 2020b). This justifies a focus on three distinct energy subsystems, which broadly compete to meet sectoral energy needs yet are closely connected: the electricity, heating ([1]) and transport energy subsystems. The EU energy system — the network of national electricity, heating and transport subsystems ([2]) — is governed by harmonised EU energy rules, for example on competition, trading, security and climate and environmental protection. One of the main aims of the EU energy system is to ensure secure, sustainable and affordable energy through enhanced cooperation (EC, 2015).

This report analyses the transformation required to achieve a sustainable EU energy system, focusing more specifically on climate mitigation. It explores and contrasts historic and prospective changes within the electricity, heating and transport subsystems. It also summarises key transformation levers and areas that need increased policy attention to overcome barriers to accelerating the EU energy transformation. Renewables-based electrification, flexibility and energy and resource efficiency emerge from this assessment as the most relevant solutions in the short term, especially when paired with more cross-cutting energy and resource efficiency efforts. This aligns well with findings from the supplementary analysis to the Communication on Europe's 2040 climate target and path to climate neutrality by 2050, which concluded i.a. that a faster decarbonisation of electricity supply and to the electrification of end-use sectors would enhance the sustainable transformation of the entire EU energy system and bring economic benefits (EC, 2024c).

([1]) Including thermal energy needs for cooling, except when these are met by e.g. compressor units running on electricity.
([2]) Excluding inland navigation.

Key data and scenarios underpinning the assessment

To analyse the transition of the EU energy system towards climate neutrality, we first identify a broad set of indicator 'benchmarks' for 2030. These are based on the impact assessment accompanying Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society (EC, 2024c), while building on the 2030 Climate Target Plan impact assessment (EC, 2020c). For each of these benchmarks, we compare average annual historic changes (using the trendline over the past six years), with the average annual changes needed after 2023 to reach the 2030 scenario benchmarks ([3]). The report's focus is 2030, where all scenarios achieve the 2030 EU climate and energy targets. With that follows a more limited discussion regarding the main technologies and fuels expected to become more prominent after 2030. This includes carbon capture, utilisation and storage (CCUS) and hydrogen. A more structured, comprehensive and strategic development of pan-European infrastructure is considered for these elements (as opposed to less coordinated national initiatives).

To analyse the challenges and opportunities of accelerating electricity decarbonisation by 2030, a thorough quantitative analysis was concluded for this report using Rambøll's European Electricity Market Model ([4]). This analysis simulated the operation of the European grid in 2030, reproducing hourly generation and demand dispatch, electricity prices and electricity flows across market zones in a way that aligns with the European day-ahead market single price coupling algorithm. The exercise took stock of planned and approved interconnections and expansions available at the Ten-Year Network Development Plan (TYNDP) 2022 Project Collection. It used the year 2020 as a basis to construct 2030 generation profiles of weather-dependent (variable) renewable electricity sources solar and wind. While future updated assessments could use the TYNDP 2024 results (or later) for grid interconnections and run additional sensitivities around different weather-years, resource limitations prevented including these dimensions under the scope of this assessment.

The quantitative assessment complements previous European Environment Agency (EEA) and ACER work with an updated reference scenario (REF) for 2030, which meets the latest decarbonisation benchmarks for the EU electricity system (EEA and ACER, 2023). This does not make the reference path a projection; figures that underpin it are seen as necessary to accomplish specific end goals by 2030. In reality, factors such as economic profitability, technology, political constraints, users' behaviours and other unpredictable developments may hinder or facilitate a rapid upscaling of key technologies and infrastructures. Illustrating 'what if' developments, the reference scenario is outlined in the following table.

In addition to this new modelling run, this report also synthesises findings from a number of recent EEA publications that address specific environmental and climate challenges in Europe's energy system.

([3]) Historical datasets — including energy balances and GHG inventories —sourced mainly from EU institutions including Eurostat and the EEA.

([4]) Rambøll's European Electricity Market Model is a partial equilibrium model that assumes that the electricity market is fully liberalised and perfectly competitive. It simulates the operation of 45 European electricity markets (including cross-border capacities) at an hourly time step, aiming to minimise production costs by considering hourly electricity exchanges.

Table 1.1 Reference Scenario constructed by EEA for the EU electricity system assessment by 2030

Reference (REF)	REF simulates a European electricity system that achieves the key 2030 parameters of the target-reaching scenarios in the Climate Target Path 2040 (CTP2040) impact assessment. It incorporates the anticipated installed capacities for fossil fuels, nuclear energy, solar, wind and other renewable sources, as well as Power-to-X (PtX) technologies. It also accounts for energy storage through battery systems and pumped hydro storage capacities. In addition, it incorporates demand blocks broken down into industry, buildings, services and transport demand, as well as electric vehicle (EV) demand figures from the CTP2040 runs, ensuring alignment with the benchmark energy consumption patterns for 2030. The weather profile for REF and for all sensitivities is based on 2020, which was randomly selected to provide generation profile curves for the weather-dependent (variable) renewable energy sources (RES) solar and wind.

Structure of the report

The report is structured to provide a comprehensive analysis and roadmap for transforming the EU energy system. Chapter 2 examines the current state of the EU energy system (2.1) and envisions its transformation by 2030 (2.2). Chapter 3 focuses on the specific changes required within and across energy subsystems to achieve this transformation. It analyses the EU electricity subsystem (3.1), explores critical shifts in the EU heating subsystem (3.2) and outlines strategies for a rapid transition in the EU transport and mobility subsystem (3.3). Individual sub-chapters on supply and demand, challenges and drivers, existing policies as well as key actions and recommendations are provided for each subsystem. Chapter 4 consolidates the findings into overarching actions and broader strategies for advancing and accelerating the EU and national energy transition (4).

Box 1.1

Potential synergies and trade-offs between climate change mitigation and air pollution measures

Measures designed to mitigate emissions of greenhouse gases (GHGs) and reduce air pollutant emissions normally fall under the scope of distinct EU and national policy frameworks, yet they often share target sources. In most cases, their effects are strongly synergistic and countries are attentive of the links between measures for climate mitigation, energy and air pollution (EEA, 2022a, 2020c, 2019c).

For instance, emissions of GHGs and air pollutants from energy supply have decreased strongly since 2004. EU industrial emissions legislation is credited with an important role in initially driving down emissions from large coal-firing installations, before climate mitigation policies — including EU targets to transform the energy system — became the most influential (EEA, 2019a).

Additionally, when renewable energy is produced via non-combustion processes (as is the case of solar and wind power), air quality improves. As such, the deployment of renewable energy has led to an estimated 16.8% reduction in GHG emissions in 2023 (compared with 2005 levels) and has reduced other air pollutant emissions across the energy system (EEA, 2024b). However, while increased biomass burning has lowered the demand for fossil fuels, for instance in buildings, it may have led to higher emissions of particulate matter and volatile organic compounds (VOCs), especially across the heating system in almost all EU countries (EEA, 2024b).

Assessing such interdependencies help policymakers identify and mitigate important trade-offs. To achieve the agreed zero pollution targets by 2030, fuller implementation and enforcement of environmental legislation will be key (EEA and JRC, 2025).

2 Rethinking the EU energy system – a transformation at the crossroads

Nearly a quarter of all EU energy consumption in 2023 was supplied by renewable sources. Nevertheless, today's energy system is still largely dependent on fossil fuels. Energy prices have been volatile in recent years, highlighting the large exposure of fossil fuel imports to geopolitical instability. Low gas supplies since 2021 have caused prices to soar. In 2022, this propelled the EU's energy import bill to 3.8% of EU GDP in 2022 — roughly double the levels seen since 2014 ([5]) (EC, 2025h). Even as fossil fuel imports weigh heavily on the EU's energy import bill, over a third of all energy is currently wasted (as reject heat) mainly across the electricity and transport subsystems, along with industrial uses such as those related to the heating subsystem ([6]).

Box 2.1

What are the economic losses from climate-related extremes in Europe?

The negative impacts of climate change are increasingly visible. National and EU measures are needed to mitigate GHG emissions and prepare for higher future risks and impacts (EEA, 2024f).

The C3S Climate bulletin of April 2025 showed that the average global temperature in 21 months out of the 22-month period between February 2023 and April 2025 exceeded preindustrial levels by 1.5°C. In 2024, the warmest year on record for over 100,000 years globally, temperatures were at 1.6°C above pre-industrial levels. Ocean temperatures were unprecedented. The Global Climate Highlights report from C3S stated that in Europe, 2024 was the warmest since instrumental records began. Most days in 2023 recorded higher temperatures than the average temperature for the years 1991-2020 in Europe. Even if the EU accounted for only 6-7% of global GHG emissions in 2023 ([7]), Europe currently is the fastest-warming continent, with temperatures growing at roughly twice the global rate (EEA, 2024f).

From 1980 to 2023, economic losses from climate-related extremes were valued at a substantial EUR 738 billion for the 27 EU Member States. These are projected to rise further (EEA, 2024c). Economic losses linked to climate-related extremes vary significantly across EU Member States. Aggregated from 1980 to 2023, Belgium, Germany and Luxembourg recorded the highest losses per area, while Germany, Luxembourg, Slovenia, Switzerland and suffered the highest losses per capita (Climate-ADAPT, 2024).

The arising climate impacts are extremely serious. The World Economic Forum's Global Risk Report recognised climate change and extreme weather events as the top global threat in 2024 (WEF, 2024). This assessment drew on insights from almost 1,500 experts from academia, government, business and civil society.

([5]) Between 2014 and 2020, the EU energy import bill fluctuated between 1.5% and 2.8% of EU GDP.
([6]) Losses occur throughout the entire life cycle, from resource extraction to refinement and transport. Though the most significant losses occur when upgrading fossil fuels to more suitable energy forms for final consumption, notably electricity, as well as when heat is used in mechanical work.
([7]) Behind China (30%), the US and India (11% and 8%, respectively).

Despite such challenges, the EU energy system has changed profoundly and its sustainability has grown over the past three or four decades (EEA, 2023d, 2023e). The main drivers of change were global oil and gas prices, security, climate and environmental concerns, resource availability, decreasing costs and innovations for renewable energy technologies, as well as broader structural changes across the economy and society.

Most remarkably, the last decade has seen a rapid and successful shift in all Member States away from fossil fuels and into more sustainable energy sources in electricity, heating and transport. Policies to improve energy efficiency have also kept energy demand growth in check. The collective achievement of the EU climate and energy targets for 2020 demonstrates that Member States can shape and accelerate desired energy and industrial transformations when shorter-term solutions are guided by strategic, longer-term objectives.

The fastest transformation of the energy mix during the past decade was achieved in the electricity subsystem, as this chapter explores. Exceptional developments in solar and wind generation — and increasingly in storage — combined successfully with targeted EU and national policies to decarbonise electricity supply. Today, the electricity subsystem continues to hold more promises for a swift and cost-efficient decarbonisation to achieve the climate change mitigation targets by 2030, than the fossil fuel-dependent heating and transport subsystems, where growth in renewables (except for biomass) was slower.

National strategies to roll out clean electricity to sectors locked in fossil energy use will increase the efficiency of the entire energy system. In the medium and longer term this will lower the variable cost of electricity generation. Replacing fossil fuels in electricity, heating and transport with solar and wind generation makes high efficiency gains possible across most value chains, though this requires high upfront investments. Boosting solar and wind capacity to levels necessary for meeting the EU's climate and energy targets by 2030 would lower annual spot electricity prices in all EU countries and market regions, compared with 2023. This is discussed in the quantitative assessment in Chapter 3.1.

Although historic electrification trends are stagnating in most EU countries, electrification must grow to phase out fossil fuels in heating and transport. Concurrently, cross-cutting efforts will remain essential to build a nimbler, more cost-efficient EU electricity and energy system. These will rely on the promotion of energy and resource efficiency improvements and savings across all energy-demanding sectors and the build-out of non-fossil flexibility from demand response.

The co-benefits of this intended energy system transition are clear by 2030 and beyond, for all Member States and the EU (see, e.g. section 'Coordinated action: key to a more sustainable and secure EU energy system', in Chapter 2.1). Yet several hurdles must be addressed in the short term to deploy more renewables, improve the roll out of electrification to industry, buildings and transport, increase the flexibility of the EU electricity system — including with strong policies promoting greater energy efficiency, demand-side management and storage — and boost investments in clean energy infrastructure, energy efficiency measures, public engagement and education.

However, strategies to roll out clean electrification in end-use sectors must make it more attractive than fossil fuels. This is unlikely the case today across all sectors and all Member States. In 2023, fossil fuel subsidies disbursed by EU countries accounted for 34% of the EU's total energy subsides, whereas renewables received just 17% (down from 40% in 2021), in part because renewables have become cost-competitive in many markets even without financial support (EC, 2025g). Meanwhile, for households, average gas and heating oil prices were lower than electricity prices in 2023 (EC, 2025h). Despite the efficiency gains, reduced environmental impacts and lower operational costs associated with heat pumps and battery electric vehicles (BEVs) over their lifetime, higher upfront costs and this subsidy imbalance have most likely dissuaded households to invest in electrification.

The revised Energy Taxation Directive proposal of 2021 would allow countries to reduce electricity taxes and tax fossil fuels consumed in intra-EU air transport, maritime transport and fishing. Yet a balanced compromise must still be reached in the European Council (EC), where unanimity is required (EP, 2025). To enable electrification in the short term, policymakers should seek to harmonise taxes and levies placed on energy carriers and stimulate clean electricity demand in sectors such as industry, buildings and transport. This would replace more polluting fossil fuels in heating and transport and accelerate the transition.

Finally, the success of the energy transformation will depend greatly on the effectiveness and efficiency of national climate and energy policy implementation and, with this, on the ability and commitment of competent authorities to solving ensuing trade-offs. It will require broad policy adjustments that address land use competition; improve the sustainability of raw material supply chains; promote circular business models to recover critical resources; ensure the transformation remains affordable and just; and ultimately enhance the resilience of energy infrastructure to climate change (EEA, 2024f).

2.1 EU energy system overview

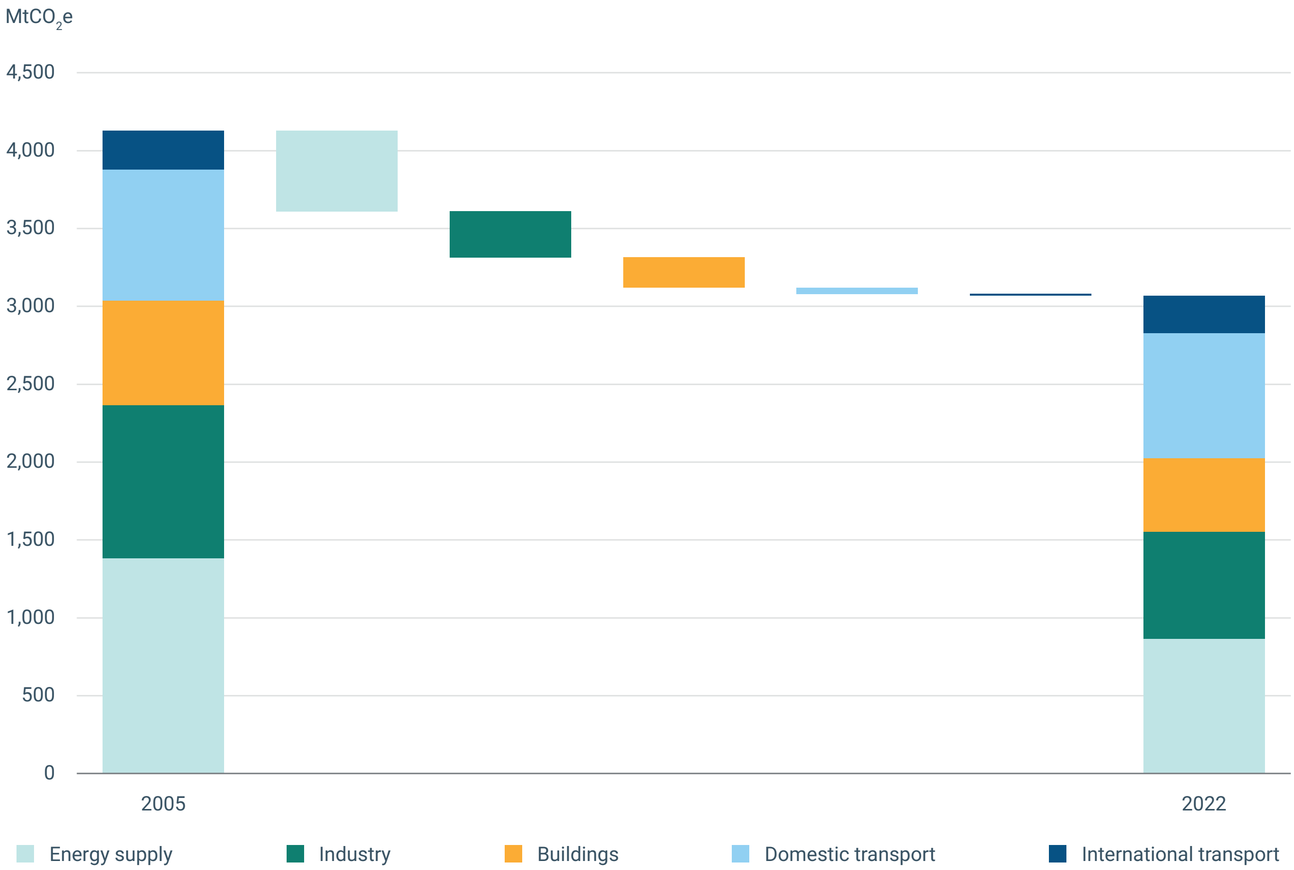
Energy-related GHG emissions in the EU

Climate and energy policies are vital for EU competitiveness, security and for decarbonising the economy in line with international commitments. Past decades have seen national and international energy value chains, energy prices and energy system policies support the use of energy-dense fossil fuels in electricity, heating and transport to better meet societal needs. This led to large economies of scale for fossil value chains and infrastructural, institutional and behavioural lock-ins. It also produced vast GHG and air pollutant emissions and further detrimental impacts on ecosystems (EEA, 2019d, 2016).

From 1990, the EU moved to first stabilise (EUCO, 1993) and then reduce GHG emissions in line with science-based policy targets, with the goal of reaching net zero GHG emissions by 2050 (EC, 2008; EU, 2021). The broad success of these national and EU measures demonstrates how targeted policy intervention can achieve desired outcomes in the transformation of the energy system (EEA, 2024o).

GHG emissions associated with energy use in the EU decreased by nearly 26% between 2005 and 2022, dropping from 4,044 megatons (Mt) CO_2 to 2,995MtCO_2 (see Figure 2.1). In 2022, the largest share of energy-related GHG emissions came from domestic and international transport (35%), followed by energy supply (29%), industry (23%) and the buildings sector (13%). These sectors have all reduced emissions since 2005, albeit at significantly varying rates. The fastest decarbonisation rates occurred in energy supply (-37%), buildings (-32%) and industry (-30%). Domestic and international transport recorded only modest reductions over the same period (-5% and -4%, respectively).

Figure 2.1 **GHG emissions from energy-related sectors in the EU between 2005 and 2022**



Notes: Annual greenhouse gas (GHG) emissions from energy producing and consuming sectors (i.e. the energy system). 'Energy Supply' equals emissions associated with the production and distribution of energy. 'Industry' includes GHG emissions from energy use and industrial process emissions. 'Buildings' represents emissions resulting from energy use in the residential and service sectors. 'International Transport' includes emissions from international maritime transport and aviation. 'Domestic Transport' represents total domestic transport emissions.

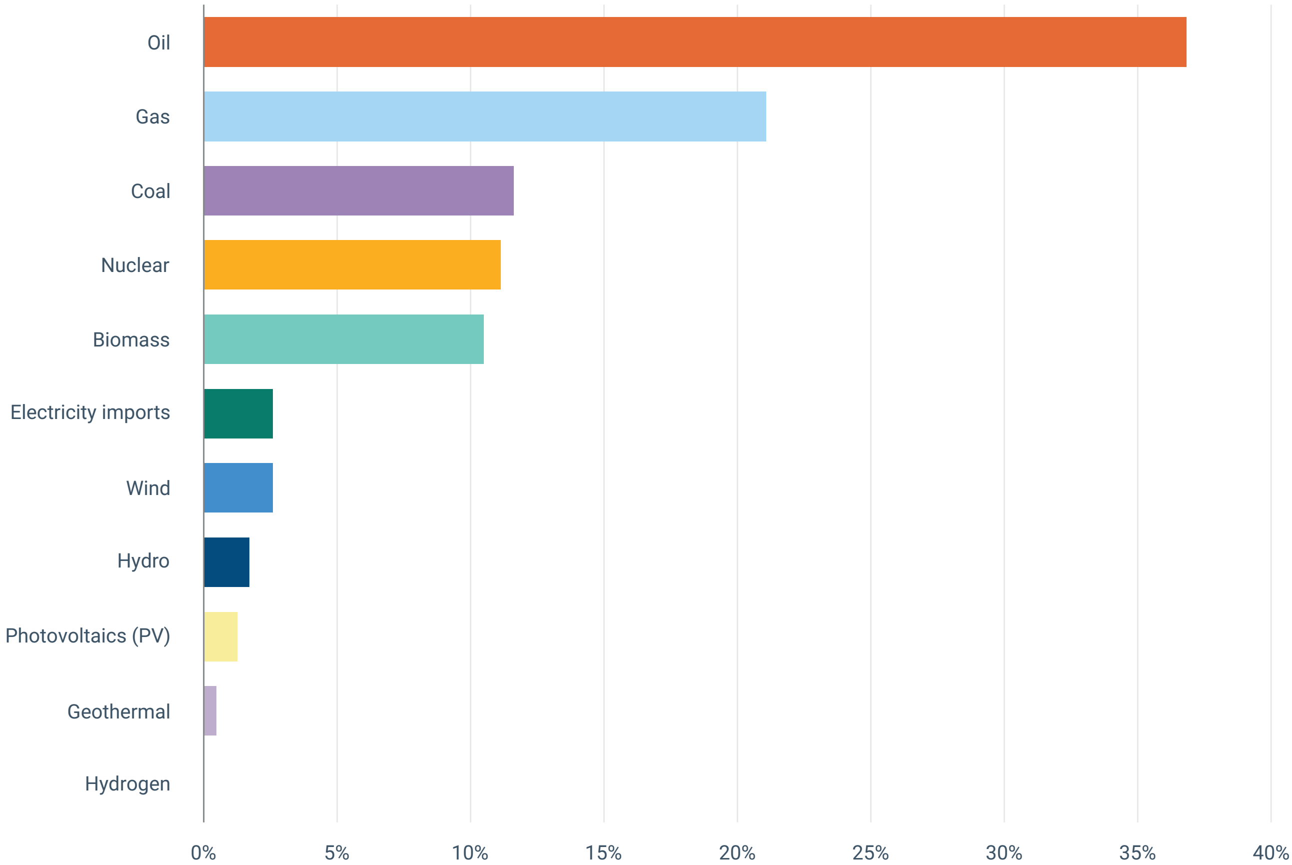
Source: EEA, 2024d.

The dominance of fossil fuels causes large inefficiencies across the EU energy system

Fossil fuels had the largest share of EU gross available energy use (70%) ([8]) in 2022 (Figure 2.2). Aside from the adverse impacts on climate, much of their energy content is lost as waste heat. This is a particular issue during conversion to electricity for consumption in motors, fans and other devices and appliances across all sectors, and heat used to perform mechanical work for instance in transport (see also Figure 2.4). Oil is primarily burned in transport and represents 37% of the EU's gross available energy use. Gas and coal are used to produce electricity and heating, (21% and 13% respectively). Renewable energy sources and nuclear energy hold lower shares (at 16% and 11%, respectively).

([8]) Gross available energy represents the quantity of energy products necessary to satisfy all energy demand. This includes deliveries to international marine bunkers, international aviation and in case of road transport 'fuel tourism'.

Figure 2.2 **Gross available energy in the EU, by energy carrier**



Source: EEA, based on data from Eurostat, 2024d.

The EU reduced its final energy consumption by 8% from 2005 to 2022 ([9]). The share of fossil fuels in gross available energy contracted far more strongly ([10]), leading to a 15% drop in gross available energy use. During this period, GDP grew by 25% and energy productivity improved by nearly 50% ([11]), against a 94% increase in the share of renewables (see Figure 2.3). This shift accomplished a 26% reduction of the EU's energy-related GHG emissions. These trends reveal how even small changes in the shares of renewable sources, particularly solar and wind power, fundamentally improve the productivity of the energy system. By lowering total energy losses across the entire energy system, they also help to mitigate unnecessary GHG emissions and other health and environmental pressures (see also 'Electrification: a pathway to greater energy system efficiency').

Biomass accounts for more than half of all gross available energy from renewable sources in 2022. Solar and wind power have grown much faster than anticipated (see also Box 2.4). In contrast to the production of energy through burning commodities, these variable renewable energy (VRE) sources produce clean electricity at low- or zero marginal costs. This highlights their importance for improving the EU energy system's competitiveness in the medium term (see also Box 2.3).

([9]) By 8% overall, with reductions of 18% in industry and 9% and 5% in buildings and services, respectively. See also Figure 2.10.
([10]) At the EU level, the share of fossil fuels in gross available energy use contracted by 23% during this period, while coal burning dropped by 37% and nuclear by 34%.
([11]) Measured as euro per kilogram of oil equivalent (kgoe). When expressed in purchasing power standards, improvement nearly doubles over the period (97%).

Figure 2.3 Gross available energy by energy carrier between 2005 and 2022

Source: EEA, based on data from Eurostat, 2024a.

Electrification: a pathway to greater energy system efficiency

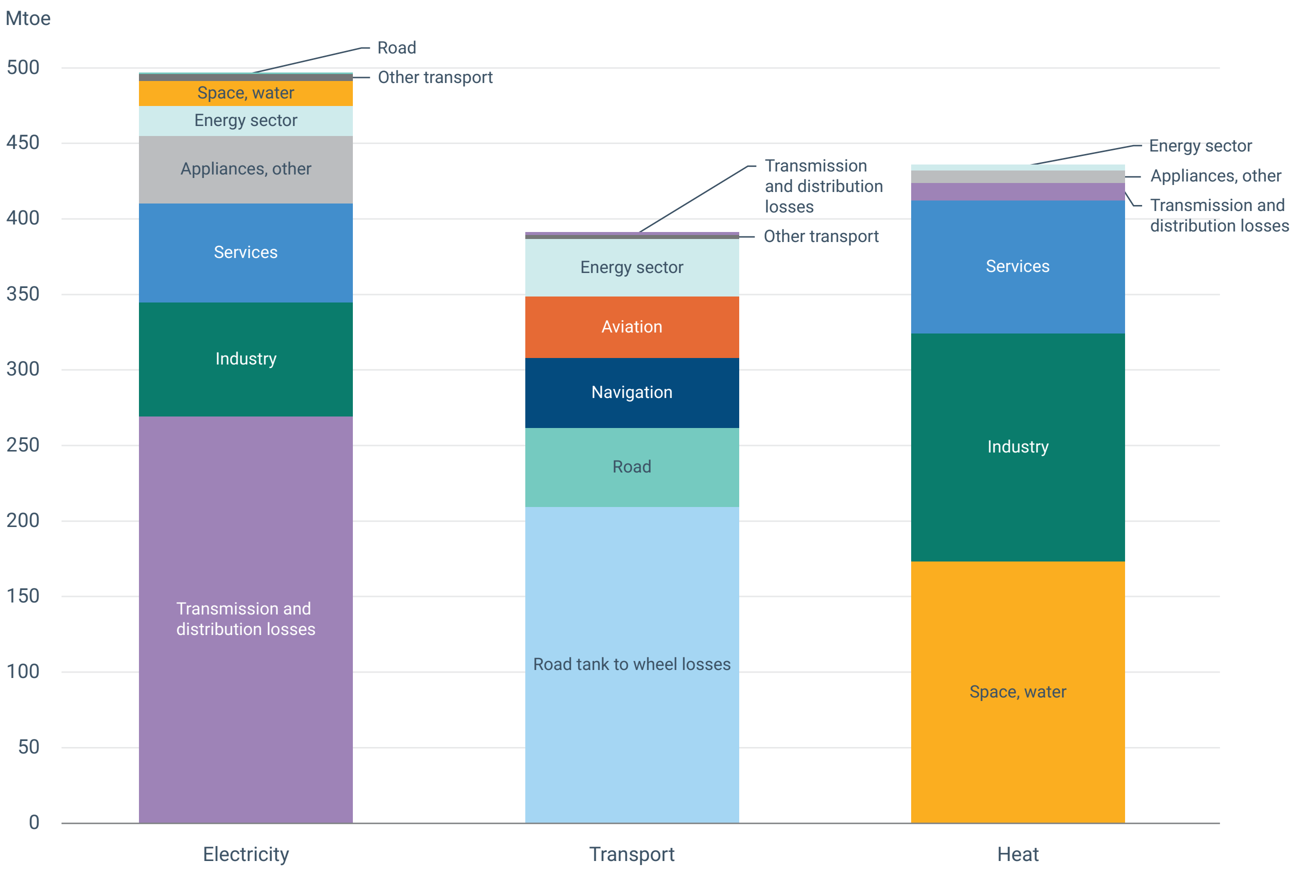
Burning commodities to produce electricity and heat for other purposes is vastly inefficient. This leads to large energy losses in the electricity, heating and transport energy subsystems.

Each of the three main energy subsystems consumed similar amounts of gross available energy in 2022. Electricity took the largest share (37%), followed by heating (33%) and transport (30%) (see Figure 2.4). This figure also shows significant transformation losses occurring across the entire EU energy system in 2022:

- Across the EU electricity subsystem, about 253 million tonnes of oil equivalent (Mtoe) were lost during the transformation of predominantly fossil-based sources. These losses are fifteen times larger than those linked with the transmission and distribution of electricity downstream ([12]).

([12]) A much smaller loss of 17Mtoe occurred during electricity transmission and distribution.

Figure 2.4 Efficiency of the EU energy system — only 65% in 2022, with over a third being lost (rejected)



Notes: Graph is based on energy balances. Data on gross available energy, final energy consumption, transformation input and output were used to allocate energy consumption data to the three energy subsystems. 'Energy sector' includes centralised power and heat generation as well as fuel production; 'electricity' includes power sector self-consumption; 'transport' includes energy consumption for the production of transport fuels e.g., from refineries. Additional losses that occur in sectors during end-use are not considered.

Source: EEA, based on data from Eurostat, 2024a and Hjelkrem et al., 2020.

- Large losses arise from the inefficiency of obtaining motion via fuel combustion across the EU transport subsystem. This process results in heat being rejected to the atmosphere as a waste product, measured as 'tank-to-wheel-efficiency' (TTW). Despite variations in the losses depending on the type of fuel and vehicle, for internal combustion engine vehicles the average efficiency is only around 20%. Four fifths of the fuel inputs are lost as heat. By contrast, for BEVs around 70% (and up to 90%) of the electricity input is converted into motion energy (see also Chapters 3.3.1 and 3.3.2) (Hjelkrem et al., 2020). Almost all vehicles still ran on internal combustion engines in 2022 (Eurostat, 2024g), meaning the transformation loss from road transport is estimated to be around 200Mtoe during that year. By contrast, had all vehicles been electric, tank-to-wheel losses would be seven times smaller (around 30Mtoe).

- In the EU heating subsystem, transformation losses stem from inefficiencies of the respective heating devices in use. Losses can result from incomplete combustion, escaping heat and/or radiative losses, for example, or when heat energy is converted by industrial turbines, compressors and other heat-driven processes into mechanical and chemical energy. In general, such losses are small and in the order of 10-25% of the fuel input (Honoré, 2018; EC, 2021g). With an overall heating demand of 436Mtoe in 2022, transformation losses would range from 44 to 109Mtoe. Transformation losses cannot be improved as radically through electrification and renewables in this subsystem as in the other two, though direct electrification and a switch from gas to heat pumps in industry and buildings would improve the efficiency threefold, if not more (IEA, 2024d). An example: switching from gas heating systems to heat pumps would require approximately 30Mtoe of electricity instead of 100Mtoe of gas.

Over a third of all gross available energy in 2022 was estimated to have been lost across all three sub-systems (roughly 500Mtoe, equivalent to 35%) during energy transformation processes ([13]). Unnecessary climate and environmental pressures will arise along all value chains associated with this 'wasted energy'. These could be broadly mitigated with policies that promote electrification and the replacement of fossil fuels with solar and wind generation. As shown elsewhere, such strategies can unlock multiple benefits for human health and the environment, even if increasing renewable power supply is not impact free (EEA, 2020b; IRP, 2017; UNEP, 2016).

Targeted measures can minimise some of the adverse effects of renewable energy deployment. Using renewable energy in manufacturing processes can lower the emission intensity of renewable energy technology components. Prioritising end-of-life material recovery reduces the demand for virgin materials and lower process emissions. Improved national spatial mapping ensures more efficient placing of renewable energy projects (ETC CME, 2020). Across the entire EU energy system, for a given demand, further overall gains in efficiency made possible by electrification are estimated to more than counterbalance higher output levels under the EU electricity subsystem.

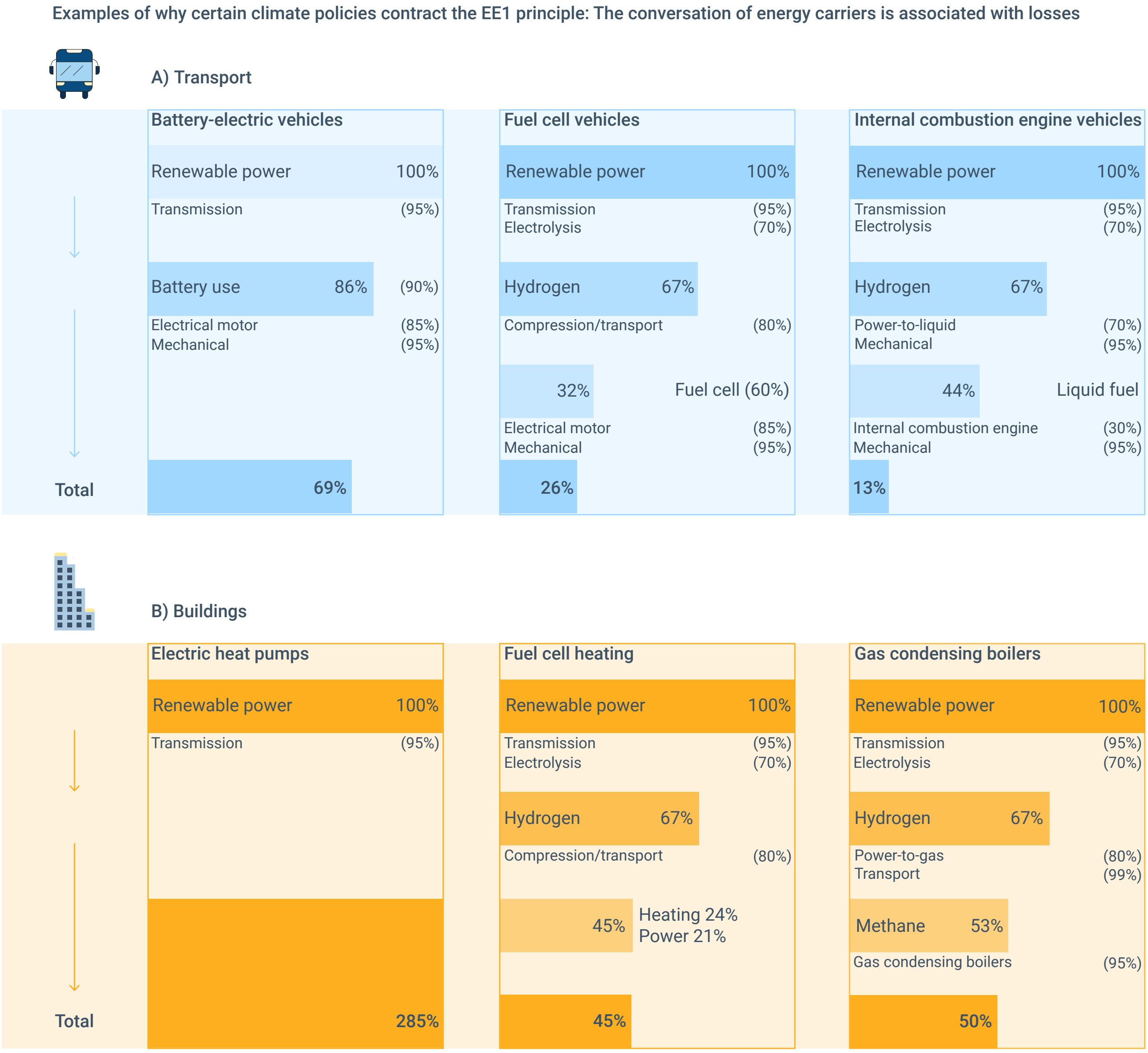
Box 2.2

Conversion losses of electricity generation

Specific energy losses during the transformation to electricity vary, depending on the fuel and power plant types. In general, coal fired power plants reach a conversion efficiency of around 38-46%. This means two-thirds of energy is lost on average, in the conversion to electricity — mainly as non-useable heat. Nuclear power plants are around 36% efficient, gas turbines range between 28 and 58% (high ranges for combined cycle gas turbines) (Zweifel et al., 2017). Solar, wind and hydro, with electricity as their main output, are attributed a transformation efficiency of 100% (EU, 2008).

([13]) Additional losses occur in end-use sectors, for instance to deliver 'useful heat' to buildings or industry. These have not been reflected here, except for transport, which is represented both as a sector and a system.

Figure 2.5 Changing energy source can mean increasing efficiencies and lowering demand for total energy



*Efficiencies: 80% (compression/transport) and 85% (total fuel cells; 45% heating, 40% power).

Note: Individual efficiencies are indicated in parentheses. Multiplied together, the individual efficiencies yield the overall cumulative efficiencies in the boxes. For heat pumps, it has been assumed an annual performance factor of three.

Source: EEA, adapted from Agora, 2018.

Electrification also provides further benefits beyond improving the efficiency of transport and heating. This includes reducing fossil fuel use, with the associated reductions in GHG emissions and air pollutants and a lowered dependency on imports of oil and gas.

Key EU policies shaping the energy system transition

The EU's energy transformation is guided by a robust policy framework under the European Green Deal (EGD) that sets the overarching goal of achieving a net 55% GHG emissions reduction by 2030 and climate neutrality by 2050. The Fit for 55 package consolidates this vision further and sets out additional measures designed to accelerate a faster, more sustainable transformation of energy supply and use across all economic sectors (EC, 2021d). More broadly, the climate, energy and environmental *acquis* (EU acquis) provides important benchmarks to transition away from fossil fuels, conserve energy and correct negative climate, environment and health impacts of certain energy carriers.

The EU Emissions Trading Scheme (EU ETS1) is a cornerstone for cost-effective and economy-wide decarbonisation. The EU ETS1 covers the bulk of EU GHG emissions from stationary installations (i.e. power generation and energy-intensive industries) and includes GHG emissions from domestic aviation. Under the Fit for 55 Package, the EU ETS was expanded to include shipping and strengthened to clarify the EU energy transformation path toward 2040. From 2027, a second ETS for buildings, road transport and additional sectors (ETS2) will seek to incentivise GHG emissions reductions in other areas that are not included under the EU ETS1 (EC, 2023; EEA, 2020d). While not a decarbonisation tool *per se*, the EU Zero Pollution Action Plan reinforces some energy system transformation goals through policies that address fossil fuel externalities, such as for air pollution and waste. These strengthen synergies and promote circular economy integration (EC, 2021c).

Much of the EU policy framework for 2030 is already in place and guiding the energy system transformation. National policy implementation — including the adoption of best practices — is vital to unlock swift and coherent policies that will enhance the ongoing energy system transition (ESABCC, 2024; ECNO, 2024b).

Specifically, the Renewable Energy Directive (RED III) requires Member States to increase the share of renewables in their energy mixes to reach an minimum level across the EU of 42.5% by 2030 (EU, 2023b). To help maximise energy use efficiency and lower overall costs of the transformation, the recast Energy Efficiency Directive (EED) aims to cut final energy consumption by around 12% at EU level ([14]) (EU, 2023a). In turn, the Energy Performance of Buildings Directive sets energy efficiency standards and improvement obligations for buildings (EU, 2024a). And the new Ecodesign for Sustainable Products Regulation (ESPR) and the Alternative Fuel Infrastructure Regulation (AFIR) help consumers make more cost-effective choices in transportation and the purchase of end-use appliances (EU, 2024f, 2023d); see also (EC, 2024e). Meanwhile, other EU policies include revisions to gas and electricity market rules. These aim to improve the efficiency of energy markets through efficient pricing signals to investors that stimulate competition (EU, 2024b, 2024f).

Coordinated action: key to a more sustainable and secure EU energy system

Energy is fundamental to wellbeing. An integrated, EU blueprint for more sustainable energy supply would bring significant benefits in security, competitiveness and sustainability for all Member States. These advantages arise from unifying the variety of national energy mixes, which provides economies of scale, increased efficiency and resilience. For instance, the EU's strong climate and energy policy frameworks for 2030 and 2050 support investments in clean energy manufacturing across the

([14]) Compared with a reference scenario (reaching 763Mtoe of EU final energy consumption).

EU, which more than doubled from 2022 to 2023. Clean energy accounted for almost one-third of EU GDP growth in 2023 (IEA, 2024a).

Without common and coordinated national efforts to decarbonise the EU's energy system and further integrate energy markets, GDP would be considerably lower by 2030 and 2050 (by 3.3% or EUR 464 billion and 5.6% or EUR 1.03 trillion lower, respectively), according to a recent analysis (EPRS, 2021). Similarly, an estimation for 2021 alone finds that the benefits of cross-border electricity trade between Member States have increased resilience and security of supply worth roughly EUR 34 billion, compared with a situation without cross-border electricity trade (ACER, 2022). Fortunately, these costs will be avoided as Member States have agreed to deepen EU-wide electricity and gas market integration and to further pursue harmonised EU climate and energy policies. The ensuing efficiency gains are lowering EU energy import needs and reducing the associated damages to the environment and climate.

Coordinated policies that promote a more efficient, integrated, renewables-based energy system are critical when considering the rate of depletion of the EU's oil and gas reservoirs and the EU's increased dependency on volatile energy imports ([15]). In 2022, 98% of the oil and gas used in Member States was imported, posing risks of supply shortages and price volatility (Eurostat, 2024b).

Yet by 2022, renewable energy use across the EU had increased by 112Mtoe compared with 2005 levels, much in response to coordinated policy efforts. This reduced the amount of gross available energy that would otherwise have been provided from fossil fuels by 24% at EU level, on top of other EU measures to save energy (see also Figure 2.3). Importantly, gas was the fuel most displaced by the growth of renewables. Estimates suggest primary demand fell by 2% per year on average since 2021, due to the expansion of solar and wind and the deployment of heat pumps, according to EEA calculations ([16]). This brought co-benefits in climate and health, with the largest transformation seen in the EU electricity system, where solar and wind power supply increased strongly (see also EEA, 2019a, 2022a, 2023b, 2024e).

Enhanced integration of the EU energy market brings benefits by collectively optimising national electricity systems. This includes reduced fossil fuel usage, stabilised short-term prices and cost savings from the use of regional renewable resources. It also enhances resilience to market shocks and reduces the need for costly backup capacity. Market integration can enhance Europe's competitiveness and ensure that electricity supply remains affordable, secure and sustainable (Bruegel, 2024). It also helps reduce dependency on international energy imports and fosters solidarity and coordinated action among Member States during external shocks and crises (EU, 2024e).

2.2 Energy system transformation by 2030

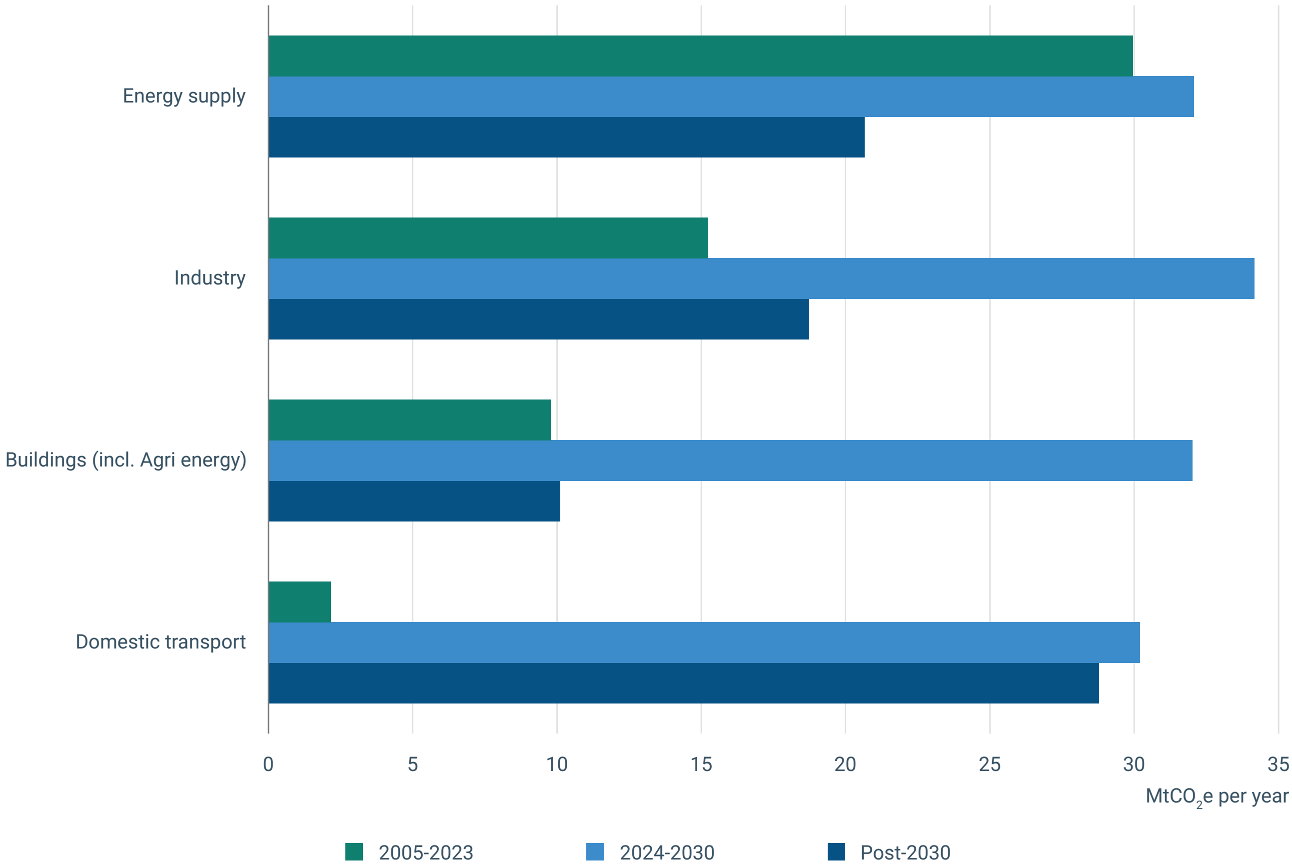
Energy-related GHG emission reductions critical for meeting 2030 and 2050 EU goals

Although energy-related GHG emissions have been declining in recent years across the EU (see Figure 2.1), efforts will need to be intensified up to 2030. To achieve the EU target by 2030, a 42% reduction in GHG emissions from energy use is needed, compared to 2022 levels, according to the latest scenarios from the Impact Assessment underlying the EC's 2040 climate target communication (EC, 2024h).

([15]) EU energy import dependency reached 62% in 2022.
([16]) EEA calculations are based on a reference situation where renewable energy supply had not increased after 2021.

Lowering emissions from domestic and international transport may be hardest: until 2030, their yearly absolute reductions must increase seven- and sixfold, respectively, compared with the average annual reductions these sectors have achieved since 2005. Cutting emissions from buildings and industry must be scaled up considerably too, requiring a doubling of the average annual GHG emissions reduction until 2030. Average annual GHG emission reductions in energy supply must be intensified by a factor of 1.7 until 2030 (ESABCC, 2024) (see Figure 2.6).

Figure 2.6 Required acceleration in energy-related sectors



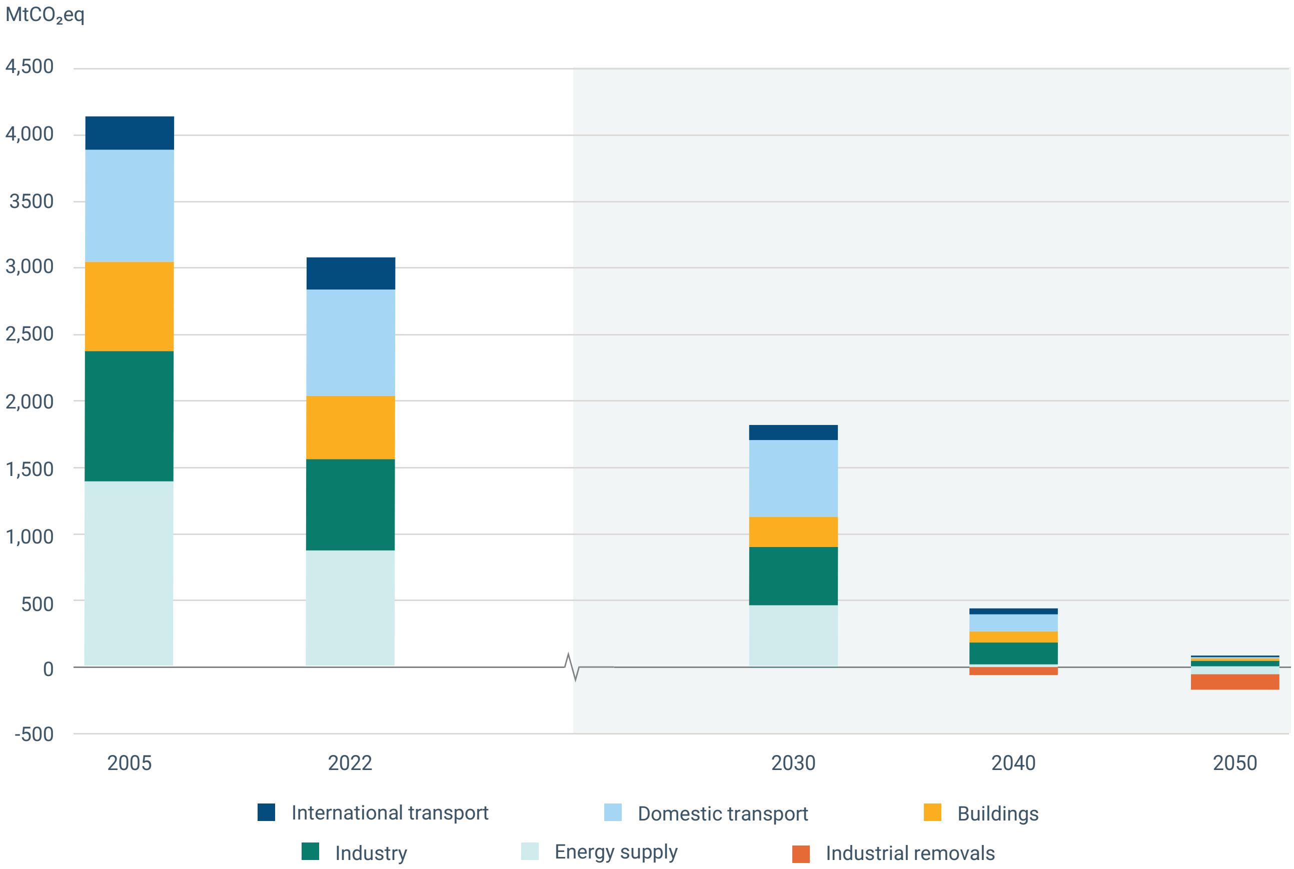
Notes: Average required in 2031-2040 based on scenarios underpinning the ESABCC's 2040 advice. Industry is 2031-2050, based on the EC's 2030 Climate Target Plan (MIX scenario).

Source: EEA, adapted from ESABCC, 2024.

Beyond 2030, sectoral emissions will need to decline further to achieve climate neutrality by mid-century, as indicated in Figure 2.7. Some GHG emissions will prevail after 2030, predominantly in a few hard-to-abate industrial sectors, requiring their balancing through carbon removals, including industrial removals of 116$MtCO_2$ ([17]).

([17]) This includes carbon capture and storage (CCS), bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS).

Figure 2.7 Energy-related GHG emissions to meet EU 2030 climate mitigation targets and outlook towards 2050



Source: EEA, based on EEA, 2024d and EC, 2024h.

Transforming EU energy supply and demand for decarbonisation

Fossil fuels made up just over 70% of the EU's gross available energy in 2022, amounting to 985Mtoe. This must fall by 33% in 2030, 67% in 2040 and 84% in 2050, compared to 2022 (see Figure 2.8; EC, 2024d).

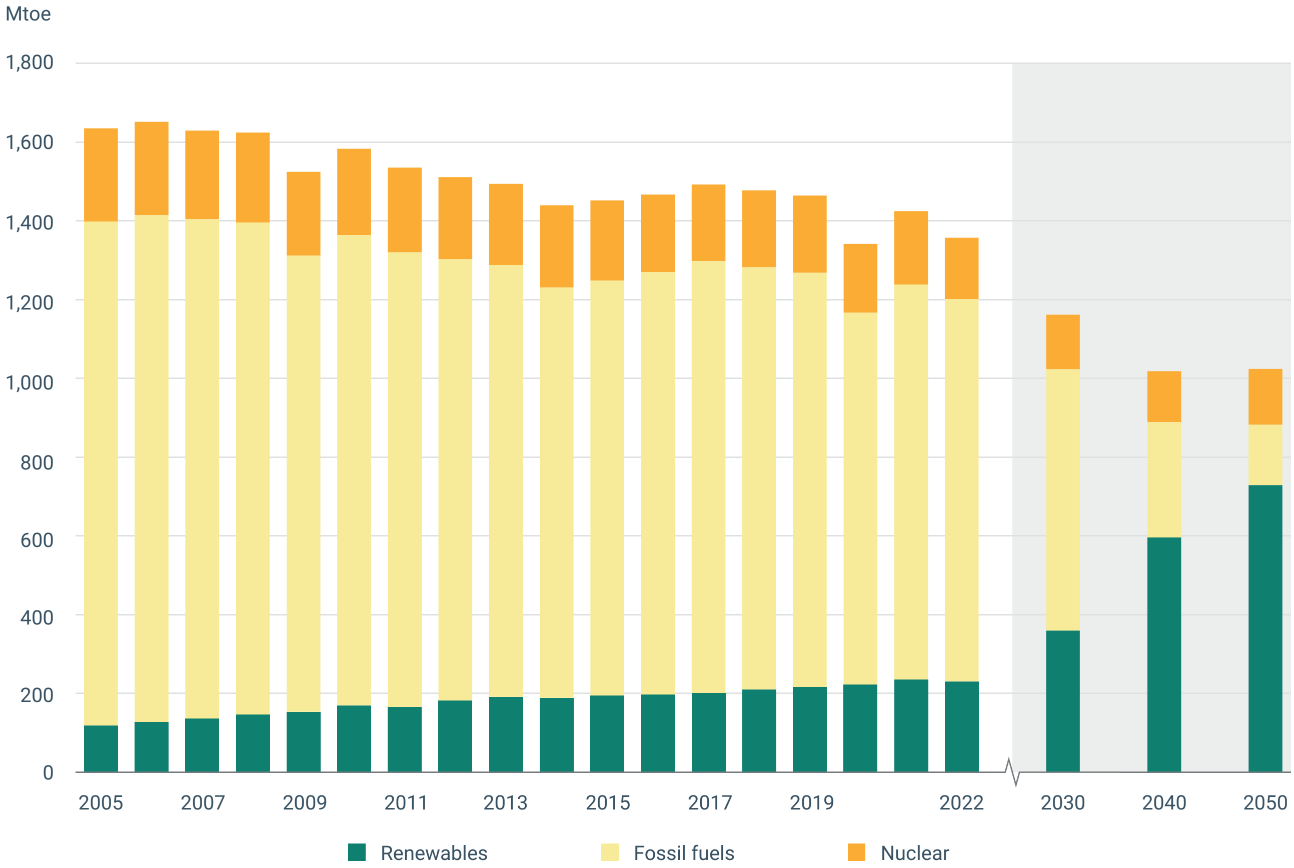
The energy system transformation has to proceed faster to ensure the EU can achieve its climate and energy targets. To increase energy security, phasing-out of fossil fuels needs to be matched by a proportional upscale of zero- or low-carbon alternatives. Reducing overall energy use through efficiency improvements (including via electrification) will make the transformation more affordable. EU gross available energy has to decline by 27%, from 1,396Mtoe in 2022 to 1,023Mtoe by 2050, for Europe to reach climate neutrality that year. On route, the EU should reduce its gross available energy by 17% (to 1,162Mtoe) by 2030 ([18]). Although the current trend in gross available energy is moving in the right direction, yearly reductions must triple (see Figure 2.8).

([18]) Gross available energy deviates from primary energy consumption as defined in the EED and where the EU target is to reduce consumption to 992.5Mtoe in 2030. Gross available energy includes international bunkers, international aviation, the non-energy use of energy carriers and gross inland consumption of ambient heat which is excluded from primary energy consumption, according to the EED.

This means the EU energy system must rapidly shift from fossil fuels to renewable energy sources (including wind, solar, hydropower and geothermal). To meet the 2030 climate targets, fossil fuel use must decrease from 70% in 2022, to 57% in 2030 and to 15% in 2050. Meanwhile, the share of renewables in gross available energy must increase from 17% in 2022 to 31% in in 2030 and 71% by 2050. The annual decline in fossil energy carriers and the annual growth in renewables must accelerate until 2030 at twice the rate of change seen from 2005 to 2022.

Specifically, measured against EC scenario benchmarks for 2030, solar and wind electricity generation need to expand more rapidly. Bioenergy should slow down, stabilising at 2022 levels by 2030, thereafter growing slightly until 2040 before gradually declining thereafter, in accordance with EC scenarios ([19]) (EC, 2020c).

Figure 2.8 **Gross available energy in the EU between 2005 and 2022 and outlook towards 2030, 2040 and 2050**



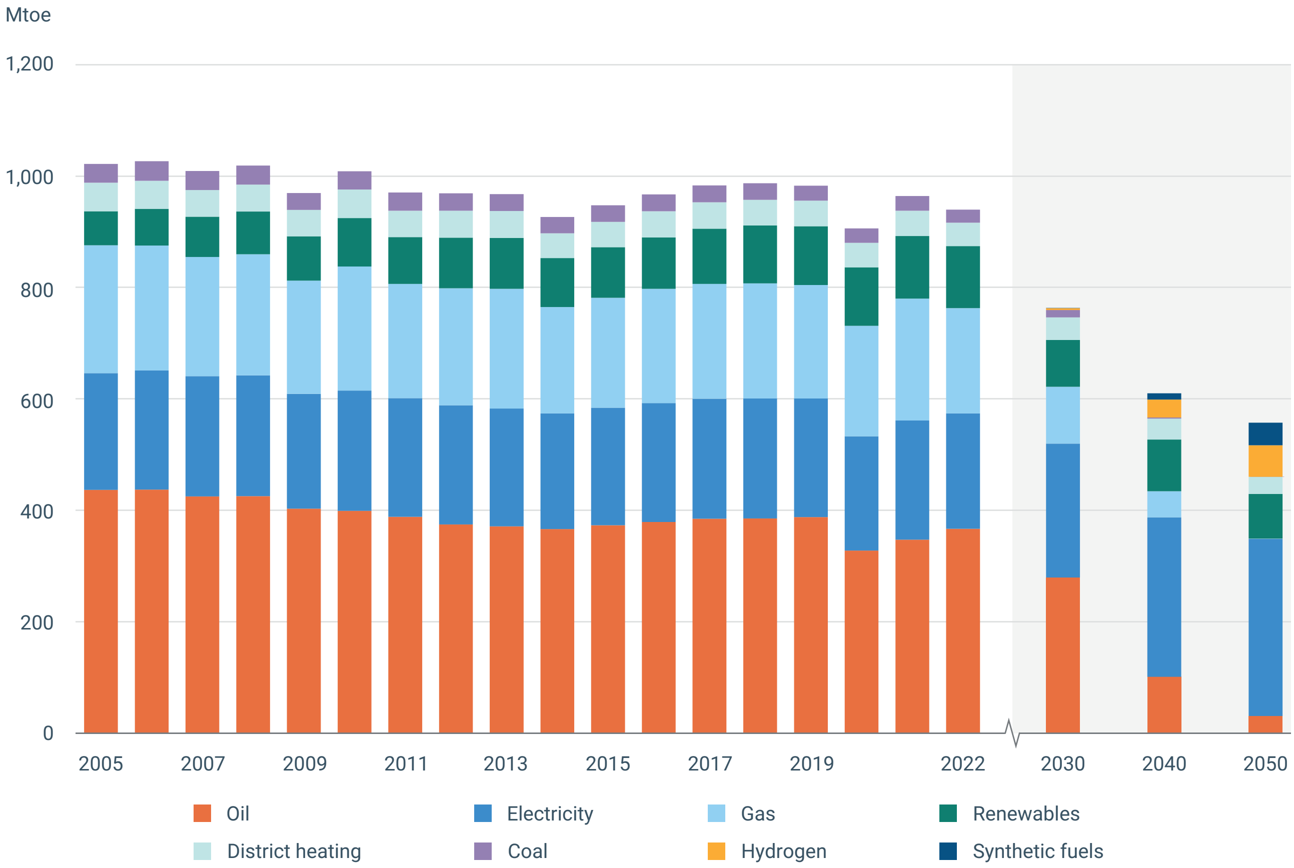
Source: EEA, based on data from EC, 2024h.

([19]) The use of biomass for energy purposes varies considerably between EU countries, as more is used in EU countries with colder climates. At the EU level, data on biomass combustion for energy purposes, as reported (as a memo item) in national GHG emission inventories, show an increase in CO_2 emissions of more than 250% between 1990 and 2022. Moreover, wood burning for domestic heating is a main source of air pollutant emissions, especially particulate matter (EEA, 2025a). A large amount of unreported wood characterises biomass flows, which require better data. Continuing the rapid historic growth of biomass could negatively impact land-based carbon stocks and biodiversity (EEA, 2023g). In the face cumulative pressures from food, energy, restoration and buildings, the gradually declining trend aims to reverse the decline in land-based carbon sinks (EC, 2020c).

Electricity is expected to become the predominant energy carrier for integrating renewables into buildings, industry and, in particular, road transport (see Figure 2.9). However, the final consumption of electricity saw a slight decline between 2005 and 2022, reaching 22% of final energy consumption in 2022. This trend needs to reverse before 2030, with electricity increasing its share to 32% by 2030 and 57% by 2050. The direct use of renewables, particularly bioenergy, will not increase further; instead, biomass consumption is expected to decrease in absolute terms by 25% by 2030 and by 28% by 2050, compared with 2022. Sectoral consumption patterns will shift however, with more biomass used in transport (aviation, navigation and road transport) and less in buildings.

The transition to electricity, along with some more limited hydrogen and synthetic fuels, will reduce fossil fuel use in the heating and transport subsystems. Yet to meet these goals, annual oil use reduction must double by 2030, while gas use must fall eightfold. This would reduce the share of fossil energy carriers from 59% in 2022 to 50% in 2030 and 6% by 2050.

Figure 2.9 **Final energy consumption by energy carrier between 2005 to 2022 and outlook towards 2030, 2040 and 2050**

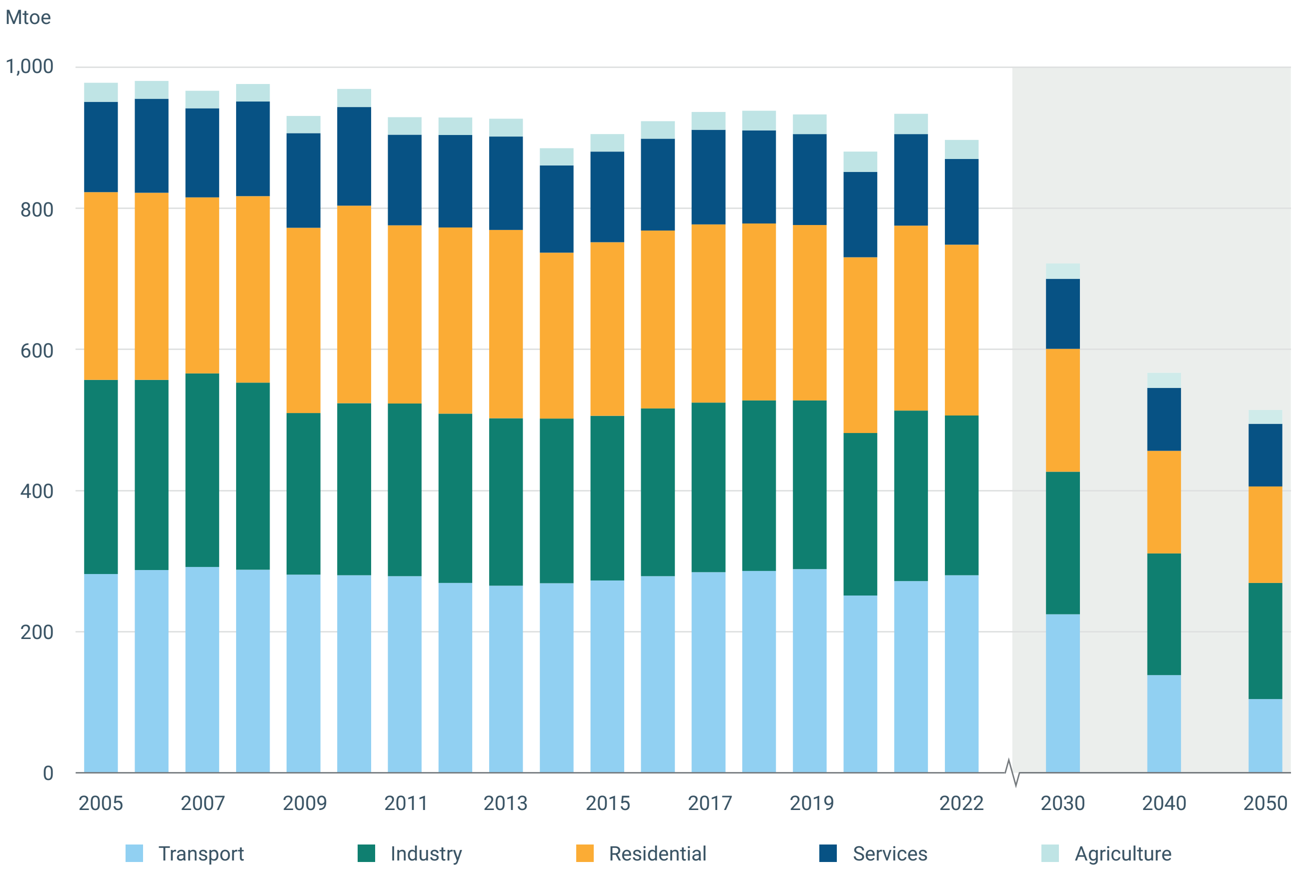


Source: EEA, based on data from EC, 2024h and Eurostat, 2024a.

Final energy consumption has shown a slight downward trend across nearly every sector between 2005 and 2022 (see Figure 2.10). Despite the decline observed over recent decades, none of the current sectoral trends are sufficient to reduce final energy consumption to reach the 2030 target of 722Mtoe ([20]). The EC modelled a pathway to reach the 2030 and 2050 climate and energy targets. In line with this, residential, transport and industry sectors must reduce their energy consumption further. Compared with trends over the past six years (until 2022), the residential sector must accelerate its annual energy reductions by a factor of 18.5, while transport must accelerate its annual demand reduction by a factor of 4.1. Industry would keep its current pace of reduction, according to the optimised transformation path modelled by the Commission (EC, 2020c, 2024h). In the services and agriculture sectors, where final energy consumption has slightly increased in recent years, current trends would need to be reversed to get back on track towards 2030.

In essence, ensuring a balanced and coordinated development of energy demand and supply is likely to reduce the energy system-related investment needs and increase the resilience of national and EU decarbonisation strategies (EC, 2020c, 2024h).

Figure 2.10 Sectoral final energy consumption between 2005 and 2022 and outlook towards 2030, 2040 and 2050



Source: EEA, based on data from EC, 2024h and Eurostat, 2024a.

([20]) Modelling outcome which is somewhat below the 2030 energy efficiency target of 763Mtoe.

Energy efficiency at the core of national energy transformation policies

Electrification will improve the overall efficiency of the EU energy system. However, additional national efforts to enhance energy efficiency and achieve greater circularity across activities and sectors will be required to meet the final EU energy consumption target of 763Mtoe by 2030. The recast Energy Efficiency Directive (EED) stipulates that energy efficiency solutions must be prioritised 'in policy, planning and investment decisions when setting new rules for the supply side and other policy areas' (EU, 2023a).

While this principle seems to be well understood in theory, countries may struggle with particular aspects during implementation (Chlechowitz et al., 2022). Recent EC guidelines clarify the transposition into national legislation of the 'energy efficiency first' principle from the recast EED. Accordingly, countries should develop and apply cost-benefit analysis methodologies that account for potential rising energy prices (e.g. due to the EU ETS expansion to buildings), as well as broader socio-economic and environmental impacts (EC, 2024b).

Policymakers should prioritise cost-effective energy efficiency solutions where available ([21]). This includes systematically considering demand-side flexibility solutions, energy storage and other smart solutions in national energy and climate plans, ten-year development plans for gas and electricity networks, national transport, urban mobility and local heating and cooling plans. To increase overall efficiency and reduce social and environmental costs, this approach should be reflected also in financing schemes, standards, energy market designs and energy and CO_2 taxes, along with cross-border interconnections (EC, 2024b).

Substantial funding is key to achieving the EU energy system transition

Energy prices have risen sharply in the wake of Russia's invasion of Ukraine. In response, the EU has already mobilised EUR 300 billion through the Recovery and Resilience Facility under the REPowerEU plan, to support clean energy production, improve energy efficiency and diversify energy supply (EC, 2022d). Recent studies have confirmed that national measures to recycle and redistribute carbon revenues can more than compensate any short-term losses vulnerable households may incur due to climate mitigation and energy transformation policies. The EU provides financial assistance to vulnerable households and small businesses impacted by increasing energy costs due to the ETS2 through the Social Climate Fund (SCF). The Sustainable Finance Framework also channels private investments into green technologies and infrastructure ([22]) (Emmerling et al., 2024).

There are clear benefits to consumers, competitiveness, security and sustainability offered by harmonised and coordinated EU decarbonisation action (see also section 'Coordinated action: key to a more sustainable and secure EU energy system' in Chapter 2.1). Despite these efforts, a substantial investment gap remains. This presents a key challenge at a time when national governments have limited fiscal space for transition investments and are facing competing priorities, including defence. The Commission estimates the need for an additional EUR 477 billion annually until 2030, to meet climate and energy targets and close the financing gap (ECB, 2024). Similarly, recent assessments suggest the EU's additional

([21]) This concerns larger public contracts and concessions, gas and electricity network planning, development and investment decisions, as well as decisions on network tariffs affecting the operation of gas and electricity infrastructure.

([22]) Since July 2023, all revenues generated by the EU ETS must be spent on climate actions (compared with 50% before July 2023), except for revenues used for indirect carbon cost.

investment needs for climate and energy this decade would amount to EUR 392 billion per year, compared with average investment levels over the last decade. Total additional investment needs would be around EUR 520 billion per year, to cover the transition across all economic sectors (ETC CE, 2024).

The EU must increase investments in its energy system to accelerate the ongoing transformation. Figure 2.11 shows the annual energy related investment needs by sector for past, current and future periods up to 2050 ([23]). Total annual energy related investment needs made up EUR 206 billion for the period of 2011-2020. This amount needs to increase by 93% to EUR 398 billion per year for the 2021-2030 period. After 2030, investment needs grow further to EUR 659 billion per year for 2031-2040 then fall slightly to EUR 633 billion per year for the 2041-2050 period.

The steepest energy related investments will be needed in the residential and service sector, with EUR 265 billion for 2021-2030, EUR 298 billion for 2031-2040 and EUR 306 billion for 2041-2050. In contrast, industry investment needs rank lowest, with EUR 19 billion in the period 2021-2030 and EUR 47 billion per year in the period 2031-2040. This will halve to EUR 23 billion between 2041 and 2050. Power grid investments decline marginally in the later period, while a small increase is needed for power plants and the service sector. Investment needs in other energy supply, which consists of non-electricity energy sources such as hydrogen, bioenergy and synthetic fuels, remain largely static at roughly EUR 80 billion in 2031-2040 and 2041-2050.

Stronger national efforts needed to phase out fossil fuel subsidies

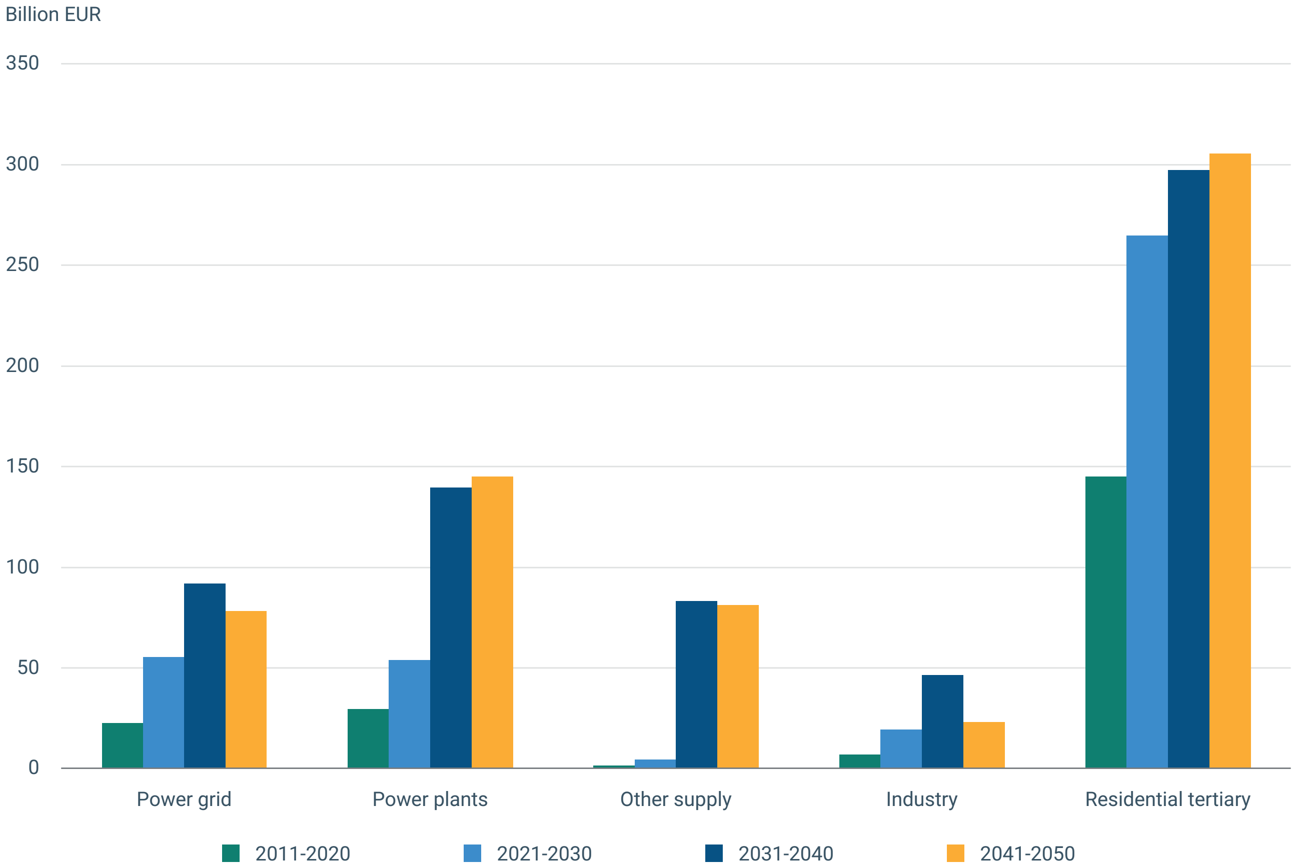
By approving its 8th Environment Action Programme (8th EAP), the EU decided to reduce fossil fuel and other environmentally harmful subsidies and reaffirmed its commitment to phase them out at all levels without delay until 2030 (EU, 2022). However, the European Environment Agency (EEA) assessed the realisation of this goal as 'unlikely but uncertain' without additional efforts from Member States (EEA, 2023e).

Almost all EU Member States have stated an intention to move away from fossil fuels (EC, 2025i), though timelines vary. Coal consumption already declined by 26% from 2017 to 2022. Some countries, such as Estonia and Latvia, use no coal due to historic reasons. Belgium phased out coal in 2016, with Austria and Sweden following in 2020. Portugal's electricity generation has been coal-free since 2021. France, Italy, Spain and others plan to follow suit by 2030; Germany by 2038. Czechia, Croatia, Slovakia, Bulgaria and Romania have proposed policies to cease the use of coal in the 2030s, but so far without any legally bindings decisions. Poland plans to continue running on and subsidising coal until 2049 (EC, 2025i; Römer and Schwarz, 2024; Velten et al., 2022).

Natural gas is still used in all EU Member States. There are some countries that plan to phase out fossil gas by 2050 (Latvia, Lithuania, Luxembourg) or switch to carbon-neutral gas consumption (Austria, Slovenia). Others plan to use carbon capture and storage (CCS) technology to capture CO_2 from gas-fired plants (Greece, Finland) (Velten et al., 2022). Germany recently allowed the construction of new gas-fired power plants which must be hydrogen compatible (Römer and Schwarz, 2024) (see also section 'Identifying future flexibility needs in the EU electricity subsystem' in Chapter 3.1.2, on the strategically important applications of hydrogen).

([23]) Values shown as averages of the target-reaching scenarios S2 and S3.

Figure 2.11 **Estimates of annual energy related investment needs between 2011-2020, 2021-2030, 2031-2040 and 2041-2050**



Notes: 2022-2030 data calculated for EUR 2023 from EUR 2019 data, using baseline data from 2011-2020.

Source: EEA, based on data from EC, 2020c, 2024h.

National legislation to phase out mineral oil and its products is still lacking in almost all Member States. Exceptions include Portugal, which has set a deadline of 2040 to phase out oil for electricity production specifically, as well as Luxembourg and Latvia which are pursuing the goal to phase out all fossil fuels by 2050 (Velten et al., 2022).

Fossil fuel subsidies remained static between 2015 and 2021, at about EUR 59 billion per year on average. In 2023, three countries accounted for 65% of all fossil fuel subsidies: Germany (EUR 41 billion), Poland (EUR 16 billion) and France (EUR 15 billion) (EEA, 2023f). In response to rising energy prices driven by the Russian invasion of Ukraine, fossil fuel subsidies in the EU have increased by almost 130%, to EUR 136 billion in 2022 (EC, 2025g). This sharp increase is not considered to be permanent: 43% are planned for termination before 2025 and 9% by 2030. The remaining 48% do not have a clear end date or it falls after 2030 (EC, 2025f; EEA, 2023e).

The 8th EAP recommends Member States to include more thorough information on the phasing out of fossil fuel subsidies in their annual national energy and climate progress reports. Currently, most Member States lack specific plans outlining how and by when they aim to do so. Only Denmark, Germany, Ireland, Italy and Sweden brought forward concrete policy legislation to specify a phase-out date (EEA, 2023f; ECNO, 2024a).

Phasing out fossil fuel subsidies is essential to redirect financial flows toward climate action, helping to close the investment gap needed to meet the 2030 climate and energy targets.

Securing critical raw materials for the EU energy system transition

The energy transition is expected to reduce total global mining activities, essentially due to a reduction in coal mining and increased recycling, yet an increase in the global demand for strategic raw materials needed to build renewable energy technologies and infrastructures (such as wind turbines, solar panels, batteries, electric vehicles, power grids and other technologies) (de Haes and Lucas, 2024). Seventeen metals and minerals were defined by the EU as critical raw materials (CRM), among others aluminium, cobalt, lithium or rare earth metals (REM) such as neodymium (EU, 2024c). Nearly all of these CRMs are highly relevant for the energy system transition (EC, 2023g). The EU expects its demand for rare earth metals to increase sixfold by 2030 and sevenfold by 2050. Demand for lithium is expected to rise twelvefold by 2030 and twentyfold by 2050 (EC, 2024d). Similar trends are projected for global demand and for other materials (de Haes and Lucas, 2024). Given the EU's heavy reliance on imports, the Critical Raw Minerals act aims to secure the resilient and sustainable supply chains required to achieve its climate targets (EC, 2024d).

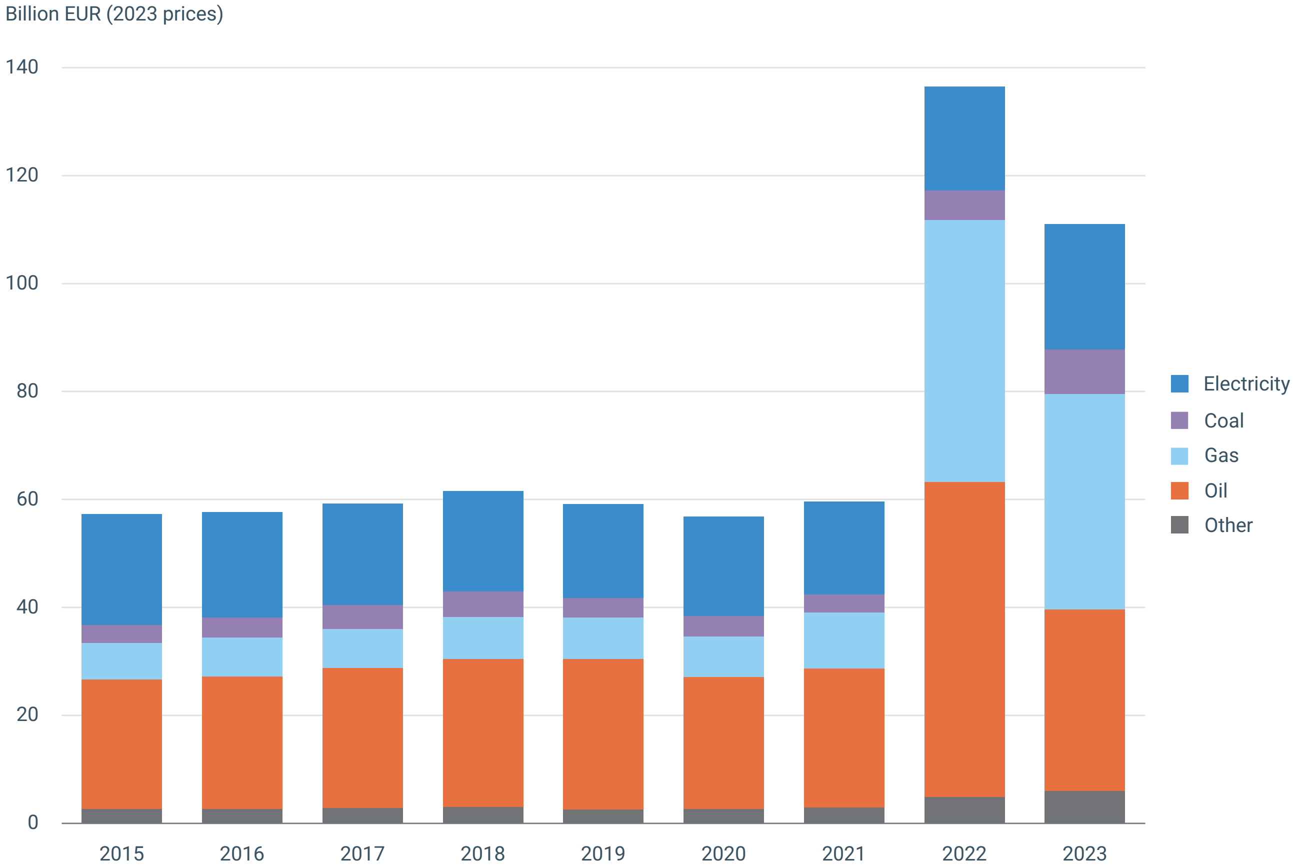
The estimated supply from existing and announced mining projects is considered sufficient to meet the projected demand needed to meet decarbonisation roadmaps until 2030-2035. The exceptions are copper and lithium. Major primary supply deficits are likely to arise for these critical raw materials after 2025, to connect rapidly electrifying energy systems and scale up batteries, including in transport (IEA, 2024c). Nevertheless, it is unlikely that a shortage of individual materials would jeopardise the energy transition, thought it may slow progress or increase costs (IRENA, 2023; IEA, 2024c).

Alongside scaling-up global mining production through new investments, secondary supply from recycling of critical raw materials will play an increasingly important role in meeting growing demand, especially after 2030 (IEA, 2023b). Recycling can reduce virgin material consumption, improve environmental performance and waste management, as well as mitigate strategic dependencies related to primary supply (IEA, 2024c). The EU plans to cover 25% of its annual strategic raw materials consumption through recycling by 2030 (EC, 2024d), as it progresses towards a more circular economy. However, recycling rates are still negligible for most CRMs, especially REMs. The exceptions are copper and cobalt, which contributed 55% and 22% to material demand in 2023, respectively. Additional efforts are needed to scale up recycling capacities and secure the reliable supply of each CRM required to achieve the energy transition (EC, 2023g). To increase the recovery of CRMs, Member States are urged to implement new measures to improve collection, sorting, reuse and recycling of CRM-rich waste (EU, 2024c). Strategies that encourage longer-lasting products and extended their use can also mitigate the expected acceleration in demand for CRMs, to some extent.

Assessing space availability for renewable energy expansion

The availability of land and maritime space is sometimes cited as a constraining factor in the expansion of renewable energy, particularly in relation to project siting, biodiversity protection and co-existence with other uses (EEA, 2024i).

Figure 2.12 Fossil fuel subsidies by energy vector in the EU, 2015 and 2023



Source: EEA, based on EC, 2025f; EEA, 2023f.

Some renewable energy infrastructure, such as wind and solar PV farms, require considerably more land than non-renewable alternatives. Yet the EU has more than enough space to meet the medium and longer-term expansion needs for these key energy sources (EEB, 2024; Kakoulaki et al., 2024; Kiesecker et al., 2024; TNC, 2025). By contrast, land currently allocated to biomass for energy purposes could face increasing pressures (EEA, 2023g). For policymakers, identifying suitable land that will not incur trade-offs for biodiversity and local communities is an important permitting challenge. Solving this will require inter-institutional cooperation — and the sharing of best practices — to overcome obstacles such as the alignment of technical expertise (e.g. for spatial planning) with data availability (on biodiversity, grids, demand centres and renewables potentials) and political ambitions (Kakoulaki et al., 2024; Kiesecker et al., 2024; TNC, 2025).

Other research suggests that exclusive activities with significant land and environmental footprints, such as golf courses and ski resorts, can take up large land areas that may exceed the total space devoted to renewable energy projects. This highlights the potential to rethink land use priorities and integrate renewable energy infrastructures in such sites, when feasible, in ways that maximise co-benefits and accelerate decarbonisation (Weinand et al., 2025).

Roughly 5% of the EU's land surface is considered suitable to build onshore wind and solar PV facilities that meet strict agricultural and environmental standards.

This includes appropriate buffer zones and sufficient solar irradiation (JRC, 2024). Estimates suggest that to establish a power system based on 100% renewables by 2040, only 2% of the EU's land surface will be needed. This assumes advances in technology efficiency, along with limited lifestyle changes — such as a small increase in the consumption of plant-based proteins. Rural areas offer the largest potential for renewable energy, accounting for 78% of suitable land for ground-mounted solar PV systems and 83% for onshore wind projects (EEB, 2024). Onshore wind in these regions produces 280 terawatt-hours (TWh) per year, but could quadruple to 1,200TWh/year with some increase in land uptake. Rural solar PV systems currently generate 136TWh/year but have the capacity to increase to 8,600TWh/year. Greater interconnectivity and integration of the electricity system will be essential to develop renewables further (*Land for Renewables: Briefing on spatial requirements for a sustainable energy transition in Europe*, forthcoming); (see also Chapter 3, Section 3.2.3 for more details).

Decarbonising the EU's economy will require an expansion of offshore wind energy. The EU's cumulative installed capacity of 19.38 gigawatts (GW) in 2023 should grow almost fivefold by 2030 to reach 88GW. This should rise to 360GW by 2050 (EC, 2023d). Maritime spatial planning, along with consideration of environmental benefits and trade-offs of offshore renewables is essential to aligning the EU's renewable energy ambitions with the protection of marine ecosystems, along with other ocean needs such as transport, fishing and recreation (EEA, 2024i).

The potential to scale up solar PV systems on already existing national infrastructures ([24]) could exceed 1 terawatt (TW), far more than the total installed PV capacity of 720GW set out in the EU Solar Energy Strategy for 2030 (Kakoulaki et al., 2024). Realising this would allow Cyprus, Estonia, Latvia, Portugal and Romania to generate as much or more electricity than they consumed in 2022, while eleven other EU countries would meet between 50% and 100% of their 2022 electricity consumption needs in this way, as shown in Figure 2.13.

Further expansion of hydropower is rather limited in the EU. Hydropower currently generates 280TWh/year and could grow by 25%, reaching 350TWh annually, under the assumption that any construction will continue to ensure healthy ecosystems and water bodies (Perpiña Castillo et al., 2024). Increasing EU electricity interconnectivity and system integration would help balance renewable electricity supply between regions with varied land availability, promot ing solidarity and reducing energy waste.

Biophysical boundaries and competing land-use demands are, nevertheless, increasingly apparent due to rising demand for biomass (for bioenergy, food, feed, fibres, materials) and expectations for the land sector to enhance its potential for carbon sequestration. Europe's land carbon sink has significantly declined over the last decade. Sustainable management of biomass is therefore essential to regulate production, extraction and use in a way that prevents pressures on ecosystems, while balancing trade-offs between different policy areas of the green transition (EEA, 2023).

Using cropland in the EU for solar energy projects could increase global land competition and vegetation loss, producing indirect emissions through land-use changes in other regions, for example through deforestation for food production or omitted future afforestation (van de Ven et al., 2021). The expansion of renewables in the EU therefore needs accurate spatial planning that uses only suitable land. This will minimise environmental impacts and reduce land-use competition with agriculture, biodiversity protection and future restoration needs (EEB, 2024).

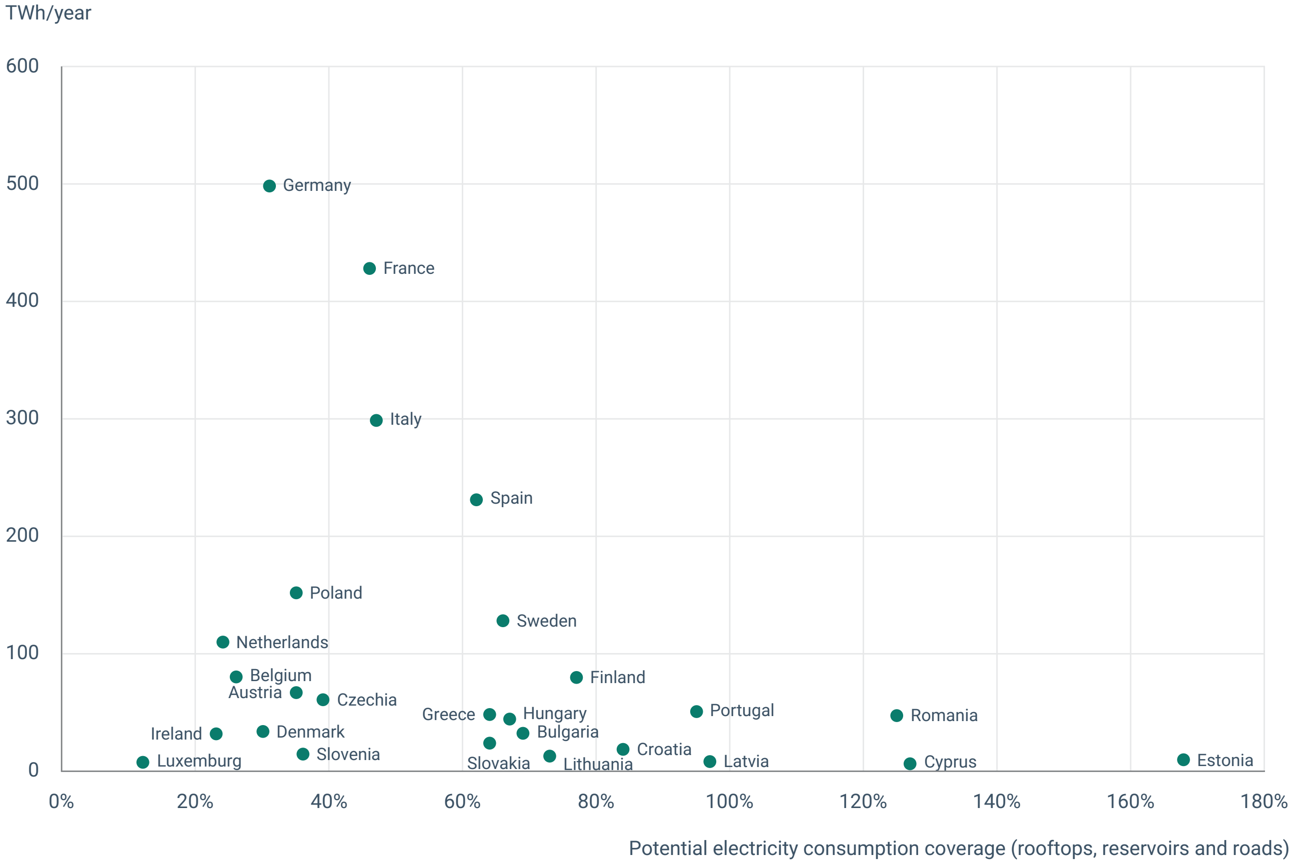
Boosting the resilience of the EU energy system to extreme weather events

Extreme weather events pose a growing threat to Europe's built environment and critical infrastructure. This risks essential services such as energy supply, water distribution and transport. The EU energy system faces multiple climate risks driven by both climatic (e.g. increasing electricity demand for cooling, more frequent droughts) and non-climatic factors (e.g. aging grid infrastructure). These risks affect the entire energy system, from production and generation, to transmission, distribution and end-use. They are already considered substantially severe and are likely to become critical by the end of the century (EEA, 2024f). Coastal or inland flooding, heatwaves and prolonged droughts all present the highest risks to energy disruption. Southern Europe is particularly susceptible to these impacts.

Enhancing the resilience of critical energy system infrastructure to climate change must become an essential part of EU climate and energy policies. Key priorities and measures are to be included in integrated national energy and climate plans (NECPs) under the EU's Governance Regulation (EU, 2018). Efforts are underway to improve climate resilience through the development of climate services standards and a mainstream adaptation to climate change in critical EU infrastructure (CEN-CENELEC, 2025). Several EU policy frameworks already support national resilience efforts, including the Critical Entities Resilience Directive (CER), the Energy Union Strategy, the regulation on Risk Preparedness in the Electricity Sector and the Trans-European Network for Energy (TEN-E) regulation. Additional initiatives — such as the EU Green Deal, RePowerEU and EU legal frameworks for energy efficiency (including in buildings) and renewable energy sources — also offer provide regulatory tools to address climate vulnerability in the energy system.

([24]) Suitable rooftop areas are conservatively estimated to generate 680TWh/year or 26% of the EU's total electricity consumption in 2022. Hydropower reservoirs (floating PV systems that improve reservoir management by reducing evaporation rates) are estimated to generate 137TWh/year or 6% of the EU total in 2022). Existing transport infrastructure (such as vertical bifacial PV systems along roads and railways) could generate an estimated 391TWh/year or 16% of the EU total in 2022) (Kakoulaki et al., 2024).

Figure 2.13 **Ratio between the technical potential for domestic electricity generation from solar PV systems mounted on existing infrastructures to national total final electricity consumption in 2022 (TWh/yr)**



Source: EEA, adapted from Kakoulaki et al., 2024.

Box 2.3

Technical measures and policy interventions to enhance energy system resilience

A broad suite of measures can be used to increase the resilience of existing and new energy infrastructure to extreme weather events, such as:

- The integration of hydrological forecasting and monitoring systems in the planning for new energy infrastructure, particularly in water-scarce regions, to mitigate risks from water scarcity and prolonged droughts. For instance, planning ought to prioritise water efficiency and account for competing water demands, while hydropower strategies should address the risk of declining water availability, especially in southern Europe. Similarly, electricity grid expansion plans ought to assess whether improved designs are necessary to withstand more extreme heatwaves and potentially stronger storms.

- Comprehensive risk assessments, proactive infrastructure maintenance and technological innovation will be key to improving system resilience. Improving energy efficiency and demand response can further enhance the security of the energy system by reducing energy supply needs and inflexible consumption, which alleviates pressures on specific components of the energy system.

- The national implementation of the Regulation on Risk-Preparedness in the Electricity Sector and the Critical Entities Resilience Directive must integrate comprehensive climate risk considerations to ensure long-term energy system stability. Additionally, social justice considerations should be central to energy adaptation planning, ensuring equitable access to energy resources and addressing energy poverty.

- Measures focused on energy system resilience, as appropriate, could be integrated in national adaptation plans.

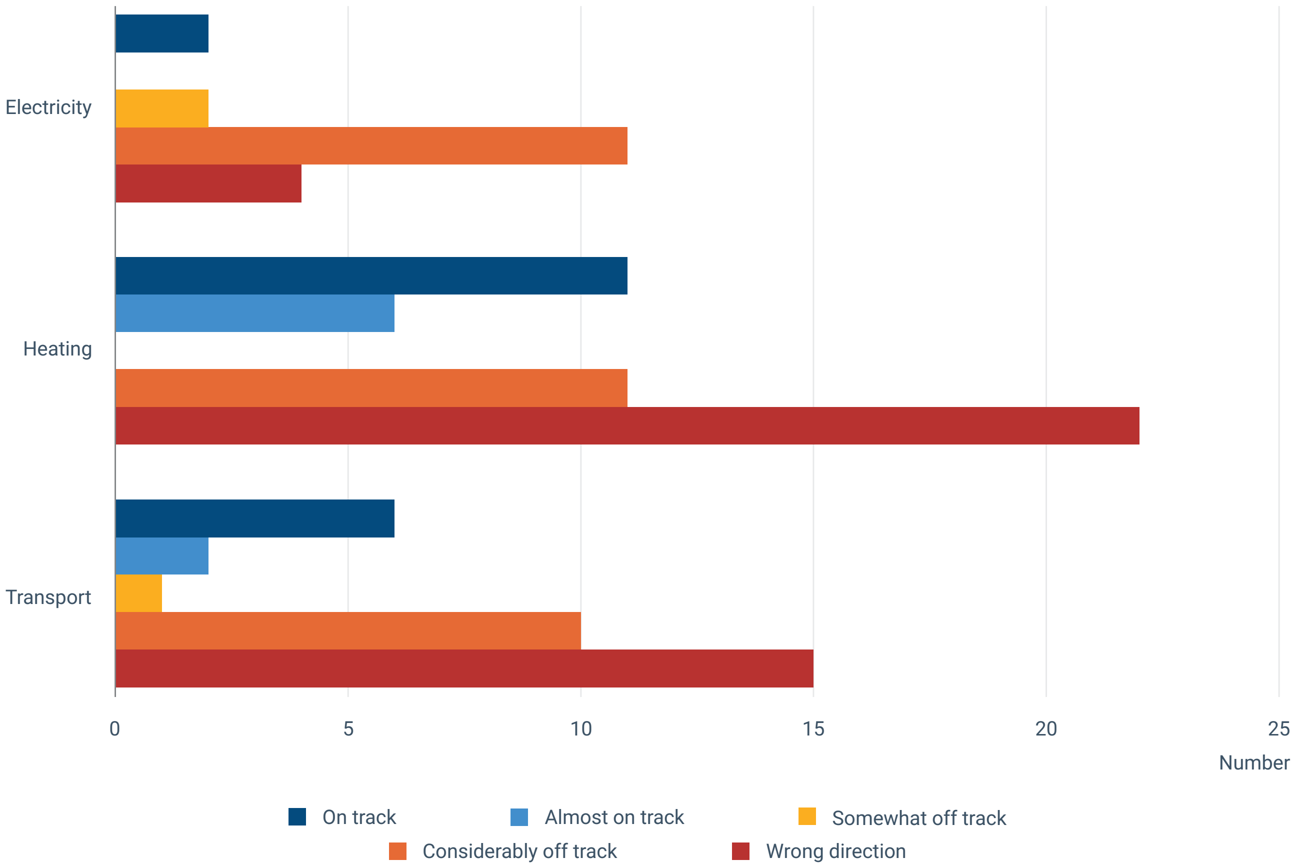
Helpful resources that policymakers can leverage include the recent EEA EUCRA report (EEA, 2024d), the European Climate Adaptation portal (see e.g. Climate-ADAPT energy page) and the EEA report on adaptation challenges and opportunities for the EU energy system.

3 Essential shifts needed in electricity, heating and transport

Energy system and subsystem progress — an overview

To identify where efforts should be accelerated, prospective annual changes required to meet targets by 2030 are compared with historical rates for a broad number of indicators ([25]). The results are shown in Figure 3.1 and explored further in Annex 1 – 'Energy system progress assessment tables'. The EU electricity subsystem holds more promise in meeting the 2030 EU benchmarks than heating and transport, owing to faster historic progress. Even if all low-carbon technologies needed by 2030 were available, most indicators for transition and scale-up are off-track for all three subsystems. This highlights an urgent need to intensify policy efforts.

Figure 3.1 Count of indicators by category and subsystem



Source: EEA, based on EC, 2020c, 2024h and Eurostat, 2025.

([25]) The 2030 benchmark values are derived from the EC Impact Assessment accompanying Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society (EC, 2024c) and the 2030 Climate Target Plan impact assessment (EC, 2020c). Progress is measured by comparing the historic absolute annual change rate (derived from the historic trendline of the past six years) with the virtual absolute change rate needed during each year after 2023 to reach the 2030 scenario benchmarks (see also Section 1.2 'Scope, aim and structure of this report').

To make the energy system transformation cost-effective, national policymakers must act upon renewables, electrification and horizontal efforts to improve efficiency across all energy uses. Wind output must grow roughly three times by 2030 compared with 2022. Solar needs to quadruple, while hydro output should increase by 16% ([26]). The rate of heat pump installation in buildings should grow threefold and electric vehicle demand must increase significantly too. Meanwhile, the EU's six-year historic trend in electricity generation is stagnating, pointing the prospective electrification indicator for the EU in the wrong direction. This is largely down to the exceptional increase in electricity prices in response recent gas price shocks. As a result, indicators for the electrification of buildings and transport are considerably off-track, while the electrification of industrial heating is heading in the wrong direction.

Reversing these trends requires leveraging capital to catalyse investment to change the production, distribution and consumption of electricity, marginalise the role of gas in electricity price setting, establish long-term pricing signals for capacity deployment and make electrification more attractive to consumers by removing unnecessary policies, taxes and levies and other administrative costs from electricity prices.

The sharing of best practices between energy authorities at all levels will make transformation policies more effective and efficient, while boosting citizen trust in sound policymaking. Public authorities tasked with implementing EGD policy objectives into national frameworks must be equipped with adequate resources, as well as necessary digital and data skills, so they can find timely solutions that match the pact of change needed to transform the energy system. Non-technical barriers should be addressed to improve governance and strengthen public trust. These barriers include insufficient incentives, administrative obstacles (such as from poor spatial planning), restrictive zoning, non-digitalised, too vague or non-transparent national guidelines and permitting processes, along with staff shortages (EC, 2023h).

Authorities must also significantly strengthen cross-sectoral and pan-European planning exercises. This will lead to a cleaner, more secure and efficient EU energy system (EEA and ACER, 2023). Key planning instruments exist to improve policy coherence and rationalise transition costs. These include the biennial Ten Year Network Development Plans and European Resource Adequacy Assessment exercises run by the European Network of Transmission System Operators (ENTO-E and ENTSO-G, 2024; ENTSO-E, 2025b), as well as the National Energy and Climate Plans submitted by Member States.

Upscaling renewable electricity generation to meet the EU's 2030 climate and energy targets would contribute strongly to EU competitiveness and energy independence goals. Variable costs of EU electricity generation would fall by up to 57%, below 2023 prices ([27]).

([26]) For hydro, the average output over the past six years until 2022 is used as basis, due to the unusual dip in generation in 2022, linked to draughts.

([27]) Compared with the EU average day-ahead electricity prices for the past nine years, this would correspond to a 44% reduction of EU spot electricity prices. However, it should not be confused with retail electricity prices that include, beyond the variable cost of energy generation, the capital costs of generation and transmission infrastructure. The latter are recuperated via network charges and taxes and levies. Across EU Member States, retail electricity prices vary quite strongly, partially also due to market interventions adopted by some countries during the energy crisis.

As illustrated in Figure 3.1, progress is measured by comparing the average annual changes needed after 2023 to meet the 2030 benchmarks with the average annual historic changes over the last six years. Based on this comparison, progress is classified as in Table 3.1.

Table 3.1 Progress toward 2030 benchmarks

Classification	Description
On Track	The necessary change is being met or exceeded (ratio: 0-1).
Almost on Track	The necessary change is only slightly faster than current trends (ratio: 1-1.5).
Somewhat Off Track	Progress is slower, but the target is still achievable with moderate improvement (ratio: 1.5-2).
Considerably Off Track	Significant acceleration is needed to meet the target (ratio: >2).
Wrong Direction	Trend is moving away from the target (ration: <0).

Source: EEA, based on EC, 2020c, 2024h and Eurostat, 2025.

More details about the aggregate indicators per energy subsystem can be found in Annex 1 – 'Energy system progress assessment tables'.

3.1 Transforming the EU electricity subsystem

The EU electricity subsystem is critical for powering critical sectors such as industry, buildings, services and transport. It is increasingly well integrated across Europe. Levels of technological standardisation are high, as are the homogeneity of supply. Set transmission and distribution principles are followed, while uniform EU regulations are in place such as those concerning the governance and monitoring of markets and networks.

Transforming this subsystem involves:

- electrifying key end-use sectors such as industry, buildings and transport, to break their fossil fuels lock-in and boost energy transformation efficiency;
- accelerating the deployment of renewable sources in electricity supply, requiring novel strategies to boost investments;
- further integrating the national electricity systems and markets across borders to foster a more diverse EU generation mix, improve flexibility and reduce the risk of shortages and disruptions by activating demand, reinforcing interconnections, as well as enhancing and digitalising transmission and distribution grids and maximising storages;
- enhancing the efficiency, resilience and affordability of a more integrated EU electricity and energy system, e.g. by strengthening horizontal energy efficiency requirements across buildings, in manufacturing and in consumer products, ensuring the affordability and fairness of the system and addressing new challenges that will arise with rapid changes in the electricity mix and broader electrification.

Chapter 3.1 covers EU electricity supply, demand and key infrastructure. It outlines historic changes across this subsystem and reveals a faster, more successful transformation than in heating and transport.

3.1.1 Electricity supply and demand

The EU electricity mix today and its historic trends

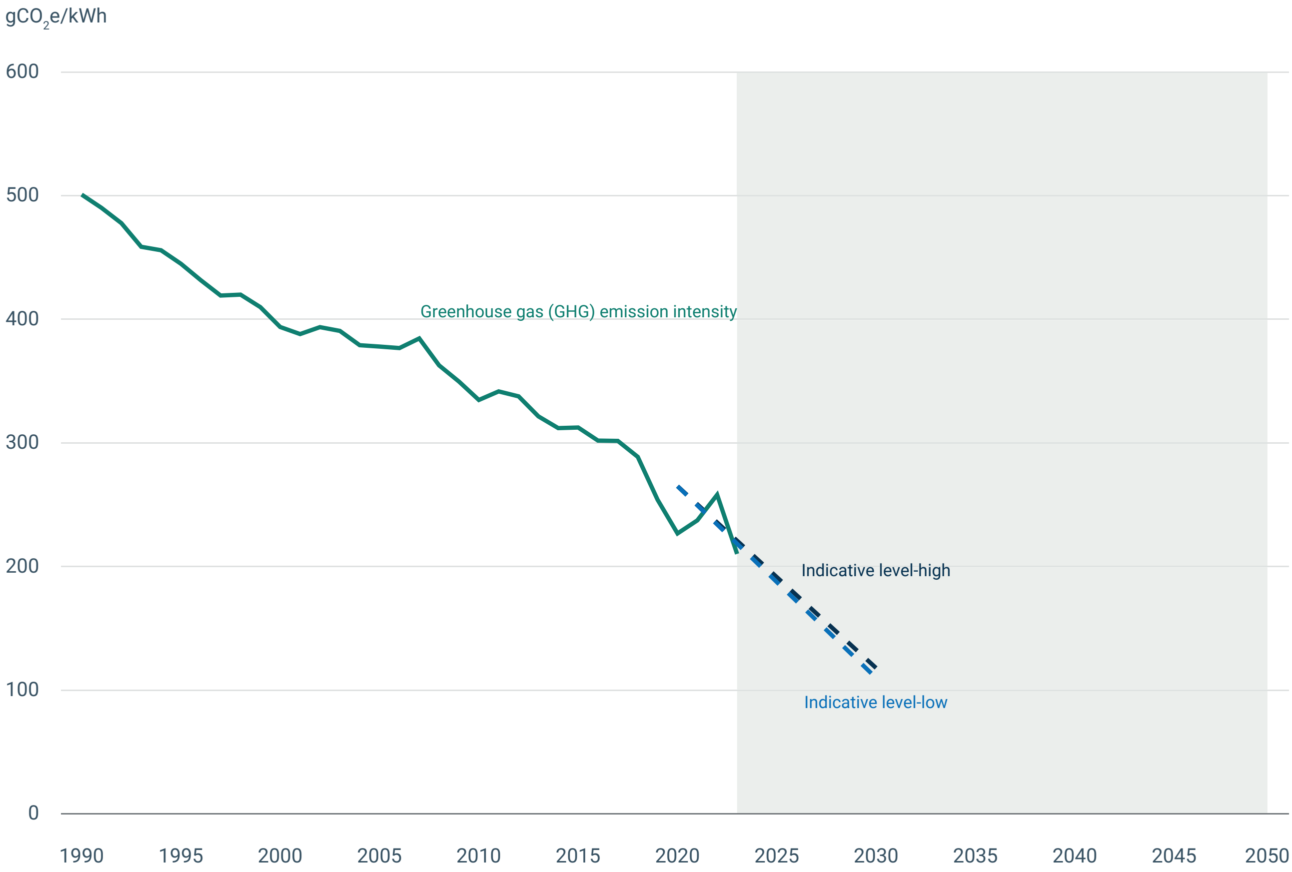
While national electricity mixes have evolved differently, most EU Member States are still burning some gas to generate a part of their electricity. In 2022, gas accounted for a fifth of EU gross electricity consumption (Eurostat, 2024f). Almost all domestic fields are largely depleted, making the EU close to 100% dependent on gas imports ([28]). By 2024, high gas prices remained a determinant factor in the formation of EU electricity prices, pulling them upward, even as strong growth in renewable generation had pushed down average EU electricity prices from their peak in 2021 (EC, 2024j, 2024m; FfE, 2025).

Boosting renewables by 2030 would strongly limit the number of hours during which gas peaker-plants can influence electricity prices. This would also spare countries the extra costs of gas imports, according to recent EU decarbonisation scenarios (EC, 2024c, 2024h). These positive impacts on prices and competitiveness are corroborated also by a quantitative analysis conducted for this study (see section on 'Current and near-term evolution of EU electricity prices and energy expenditure').

Profound supply mix-changes are not new for electricity systems and have occurred continuously in the past. These shifts have been driven by technological progress, resource availability, commodity prices and socio-economic factors, including societal demands for better health and environmental protection. For instance, producing one kilowatt-hour (kWh) of electricity across the EU emits today sixty percent less GHGs than back in 1990 (see Figure 3.2). While total EU electricity generation hardly changed from 1990, the electricity mix steadily switched from coal to gas until 2005. Since then, the formidable growth of renewable electricity sources — by 143% up to 2023 — has led to contractions of all fossil fuels and nuclear sources in the EU generation mix (by 28% and 33%, respectively) (EEA, 2024h).

([28]) In 2022, import dependency rates at the EU level stood at 90% for natural gas and at 95% for natural gas liquids (Eurostat, 2024f).

Figure 3.2 **Greenhouse gas emission intensity of EU electricity generation**



Source: EEA, 2024h.

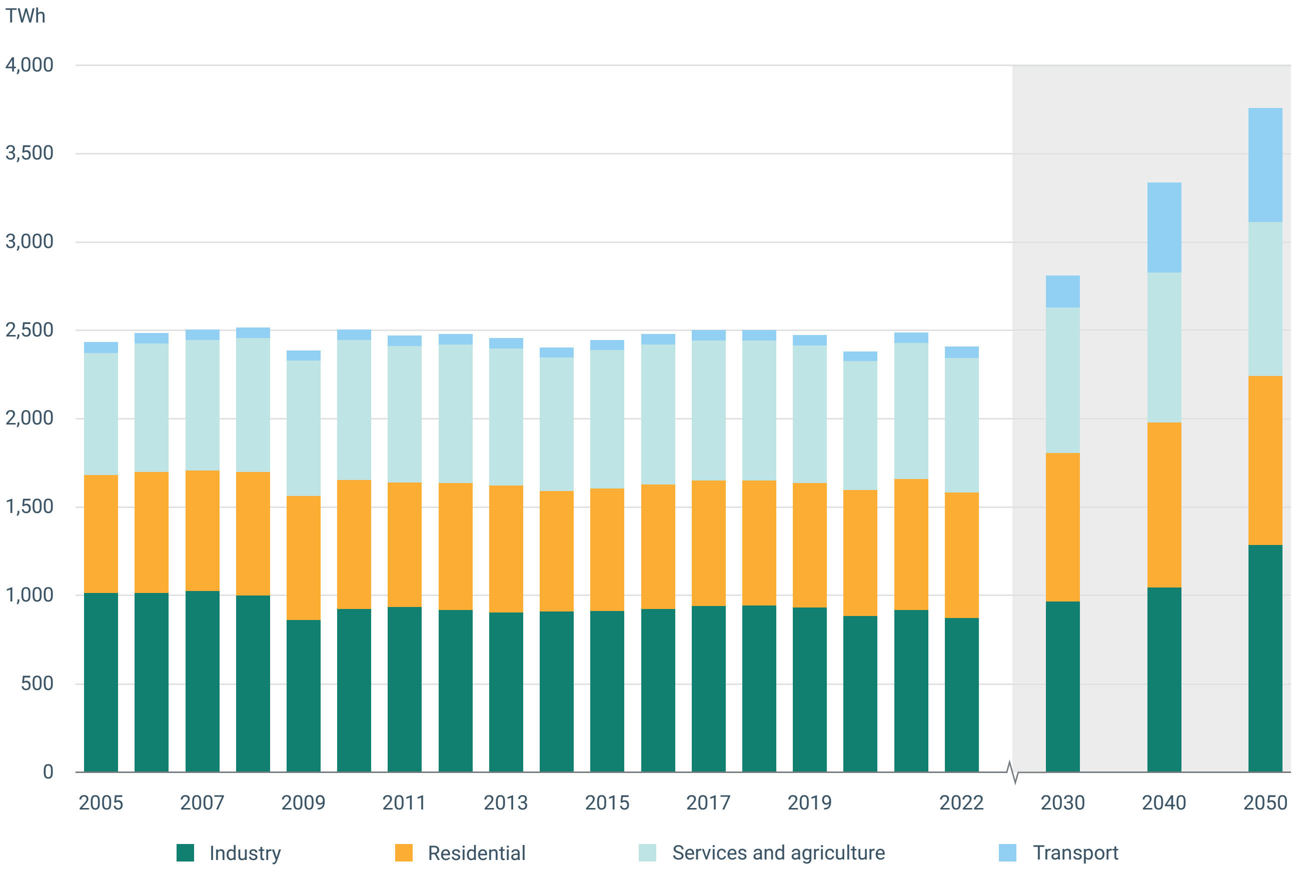
Renewables and fossil fuels now contribute roughly equal shares to EU electricity supply (each 39%), followed by nuclear power (22%). Solar PV and wind power now account for roughly 60% of renewables; these variable sources have more than doubled their share in renewable generation since 2010 ([29]).

Factors shaping electricity demand today

As shown in Figure 3.3, industry was still a key driver of final demand in 2022 (36%, particularly for electric motors in energy-intensive manufacturing branches). Services and agriculture followed at 32%, households at 29%, with transport holding a marginal role at just 3%, dominated by rail demand. Yet the trend in final electricity consumption was generally negative for industry by 2022 compared with 2005, while positive for the residential sector, services and agriculture (see also 'Current and near-term evolution of EU electricity prices and energy expenditure', in Section 3.1.2).

([29]) Variable renewable energy (VRE) sources — most typically solar PV and wind — are energy sources whose output fluctuates with weather conditions.

Figure 3.3 Electricity demand for 2022, with an outlook for 2030, 2040 and 2050



Source: EEA, based on data from Eurostat, 2024a and EC, 2024h.

Supply and demand changes to meet the EU climate and energy benchmarks by 2030

To both decarbonise the EU energy system cost-effectively and improve EU competitiveness, EU electricity generation must increase by at least 17% by 2030, 38% by 2040 and 56% by 2050, compared with 2022. These figures are drawn from the target-reaching energy scenarios modelled by the EC ([30]) (EC, 2024c, 2024h).

Reaching the 2030 benchmark levels will therefore require a reversal of historically stagnant or declining growth rates in EU electricity generation (see also Table A1.1). In 2030, for the most part, the EU generation mix should rely on renewable sources — which must triple by 2030, compared with 2022 (see Figure 3.4 and Table A1.1). Wind should become considerably more important than today, increasing to around 42% of all EU electricity generation, followed by solar and hydro, which would account for 21% and 14% of all EU production in 2030 ([31]). Nuclear would still supply roughly 14% of the EU electricity mix. By contrast, fossil fuels would mostly disappear, with gas, oil and coal providing only around 2% of total EU generation in 2030.

([30]) In accordance with benchmark values from the Impact Assessment (IA) accompanying Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society (EC, 2024c). For details, please refer to 'Scope, aim and structure of this report', under Section 1.2.

([31]) For example, expressed as capacity deployment by 2030 compared with present levels: wind should increase about three times, solar PV more than twice, hydro almost twice and batteries about 14 times. This highlights the important role of leveraging more investments to accelerate the growth of these resources in the short term.

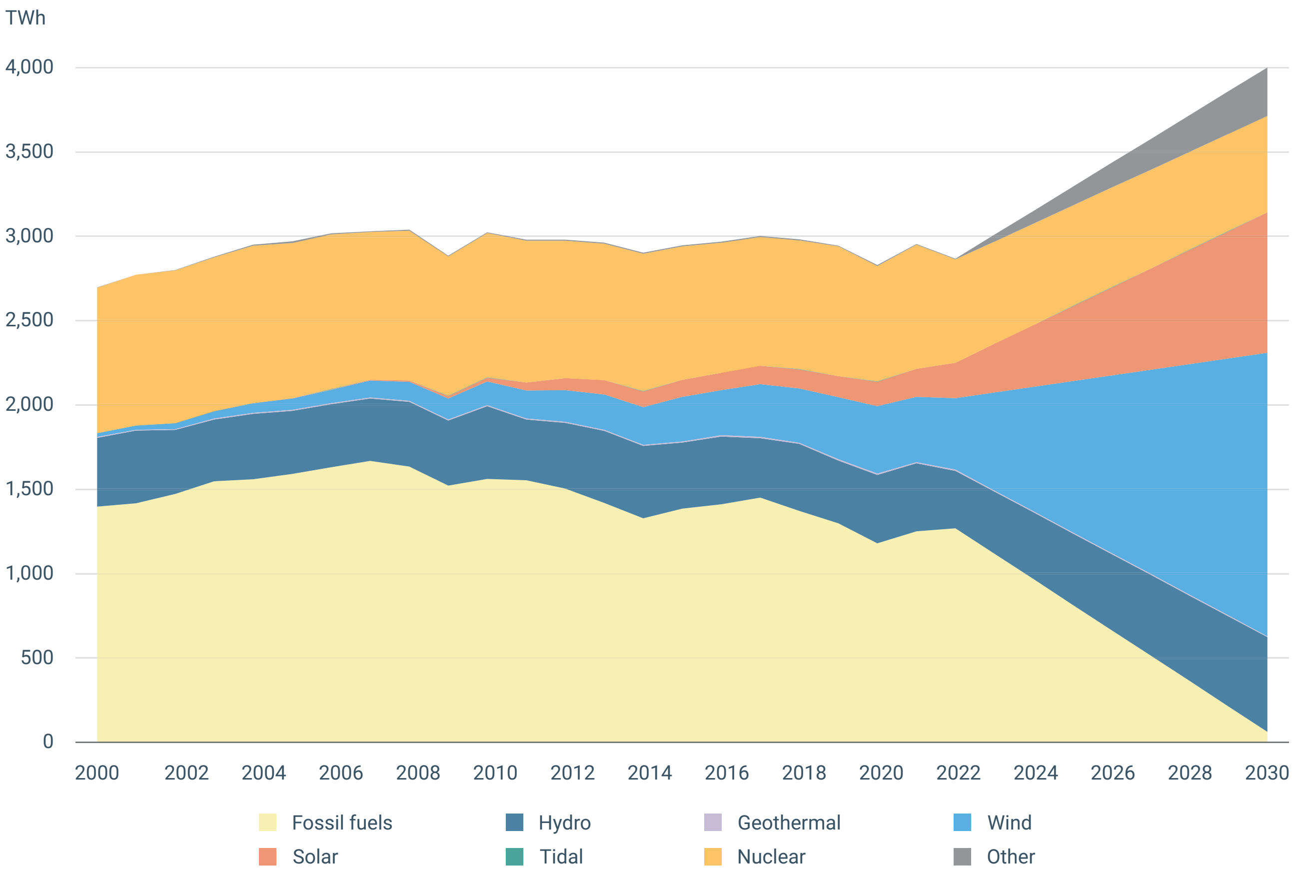
Production of the EU electricity generation mix would be considerably different in 2030 compared to 2022:

- Wind would roughly triple (from 421TWh in 2022 to 1675TWh), becoming a cornerstone of the low-carbon transition.
- Solar would quadruple (rising from 210TWh to 828TWh), underscoring rapid expansion opportunities of solar PV capacity.
- Hydro would increase by 16% (reaching around 559TWh, from various sources like reservoirs, run-of-river and pumped storage) ([32]).
- Other sources (biomass, waste, geothermal and emerging technologies) would increase substantially too, contributing to a more diverse electricity mix (from 5TWh to 287TWh).
- Nuclear would remain significant as renewables expand (declining slightly, from 609TWh to 568TWh).

Fossil fuels would plummet by 95% (from 1264TWh to just 62TWh). Gas would cease to be the main driver in the formation of electricity prices, in contrast to today (see also 'Current and near-term evolution of EU electricity prices and energy expenditure', in Section 3.1.2).

([32]) The average output of the past six years until 2022 was used as basis for hydro, due to the unusual dip in generation in 2022, due to droughts. Compared with 2022, EU hydro generation by 2030 represents a 65% increase.

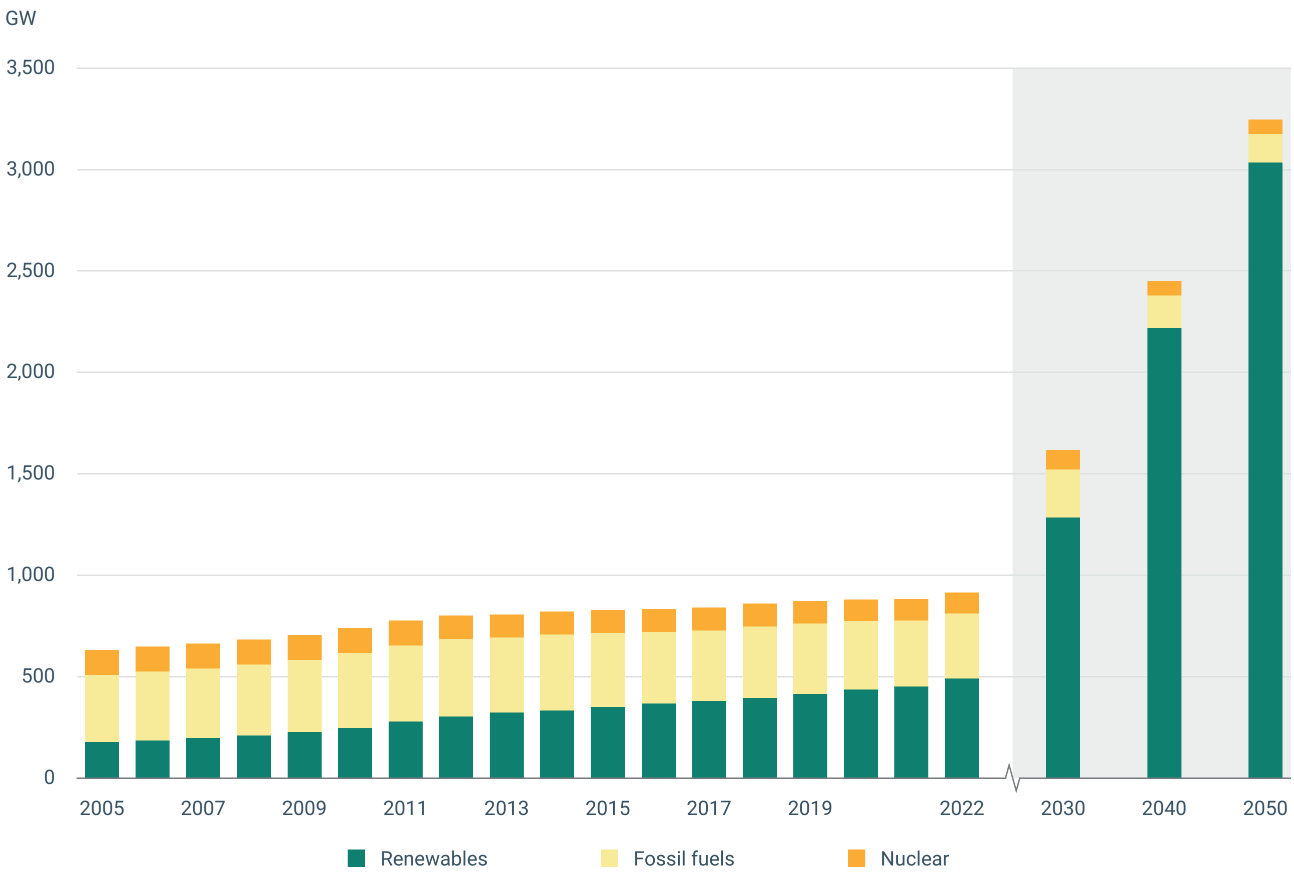
Figure 3.4 **Historic and prospective EU electricity generation by 2030**



Source: EEA, based on data from EC, 2024h and Eurostat, 2024a.

At the EU level, renewable electricity sources would total roughly 77% of all installed and grid-connected power capacity — an increase of roughly 20 percentage points compared with today's levels. Wind and solar would require proportionally more capacity installation due to their variable, non-continuous generation (see also Figure 3.5). This highlights the need to improve investment leverages and respond to growing flexibility needs in the energy system immediately. Measures should aim to accelerate deployment, while ensuring that the EU electricity system remains balanced.

Figure 3.5 **Net installed electricity capacity by energy carrier (MW), for 2005-2022, with an outlook for 2030, 2040 and 2050**



Source: EEA, based on data from Eurostat, 2024c and EC, 2024h.

Reaching the 2030 targets would also lead to large demand-side changes. As electrification replaces gas burning across society (see Figure 3.3), demand from industry and households would become roughly equal at 34% each, representing a 10% and 19% increase over 2022 consumption levels, respectively; followed by services and agriculture at 29%, (an 8% increase); and transport at 6%, (a 181% increase).

Processes that require low-temperature steam and heat in industry (up to around 200°C, typically obtained from gas) are particularly suited to switch to available electricity-based systems such as heat pumps or e-boilers ([33]). In later years, industrial processes that require higher temperatures and new technologies will drive up industrial electricity demand further (for instance from electric steam crackers, which may become available by 2040).

Electricity demand across residential, services and agriculture sectors would increase mostly for heating needs in buildings. Today these are predominantly met by fossil fuels (EEA, 2023d). Building-integrated heat pumps, electric boilers and industrial heat pumps integrated with modern district heating networks in buildings can replace gas-firing heating systems, to a large extent (see also relevant subsections in Chapter 3.2).

([33]) These are also discussed in Chapter 3.2, 'Facilitating the transformation across key heating systems'.

In transport, electricity demand would grow significantly to enable electromobility for passengers and freight by 2030.This would deliver large efficiency gains not only across the EU transport subsystem, but for the overall energy system ([34]).

Finally, emergent applications and sectors could see a faster increase of electricity demand, bouncing the optimised demand benchmarks from the EC scenarios upwards in the near future. A broader integration of AI across all workplaces (e.g. the integration of agentic and regenerative AI with telecommunication devices, computers and other appliances to augment their processing speed and interaction) could double the electricity demand of data centres globally, pushing it to 4% of global power demand in 2030 (Deloitte, 2025). The International Energy Agency (IEA) advances similar figures in relation to the emergence of AI, cloud computing, blockchain and other digital technologies. Others argue for caution when estimating future AI energy demands, highlighting the difficulty to make realistic projections based on available data (IEA, 2024b; Chen, 2025).

Historic data show the use of AI can upscale electricity demand rapidly at local and regional level, with potentially sizeable impacts. In Ireland, power demand by data centres increased from 5% to 21% of the country's total electricity consumption between 2005 and 2021. This rise outpaced demand from all urban households combined, with most data centres located on the outskirts of Dublin (CSO, 2024; Chen, 2025). In the United States (US), electricity consumption from data centres more than doubled between 2017 and 2023, largely in response to AI use (Shehabi et al., 2024).

Intriguingly though, AI could be deployed to boost energy efficiency efforts and reduce rebound effects in the future (Parker, 2025). In one trial application in Sweden, optimising the operation of heating and cooling systems in buildings saved a fifth of all energy needs (Vattenfall, 2023). The potential of helpful AI applications is even wider, ranging from helping researchers to develop novel materials (e.g. for batteries or solar cells), to assisting developers and planners with optimising the location of renewable energy infrastructure, providing grid maintenance and balancing support, as well as helping data centres reduce cooling needs (Parker, 2025). Against this background, proactive EU policies are needed to guide developments, unlock synergies between AI development and decarbonisation effort and manage new risks. The EU Code of Conduct for Data Centres (EU DC CoC) represents a key first step to addressing the growing energy consumption and environmental impact of data centres through dedicated guidance (EC, 2024f).

Setting the ground for post-2030: upscaling of innovative solutions and infrastructures

Beyond 2030, securely and cost-effectively decarbonising the EU electricity and energy system will hinge on the EU's capacity to innovate, upscale and commercialise solutions and infrastructures that are currently still at the niche, prototype or pilot scale. On the technology side, this includes electrolysers to produce renewable (green) hydrogen, power-to-X (PtX), as well as technologies to capture GHG emissions from the residual use of fossil fuels. Innovations in infrastructure will include developments of future CO_2 and hydrogen transport networks, which are unlikely to emerge from EU carbon-pricing policies alone.

Switching to green hydrogen as a raw feedstock in industry would greatly increase electricity demand beyond 2030. At the EU level, 2,795 kilo tonnes of oil

([34]) The final energy consumption of the transport system would decrease over time through electrification, thanks to important tank-to-wheel efficiency improvements. See also Section 3.3.

equivalent (Ktoe) of hydrogen are predicted to be used by the end of the decade. This may increase to 30,650Ktoe in 2050, according to the EU target-reaching scenarios. About 65% of the total produced hydrogen would be used for industry, with significantly smaller amounts used in residential areas or as a direct fuel in transport. However, in 2030, hydrogen would be too scarce and valuable for use as heat source. It would serve primarily as raw material, rather than as an energy carrier. As renewable generation grew, hydrogen would expand to fertiliser production and to replacing coking coal in steel production, while electricity would increasingly be used for power-to-X solutions to create a sustainable EU fuel industry (Johnson et al., 2025).

3.1.2 Challenges and drivers to decarbonise the electricity subsystem

Accomplishing a rapid electrification rate across all end-use sectors together with a rapid decarbonisation of the electricity mix is technically feasible and can be driven further by innovations from niche sectors (see e.g. the above section 'Setting the ground for post-2030: upscaling of innovative solutions and infrastructures'). Although accelerated electrification opens new opportunities to improve each of the energy subsystems, this transformation path may not materialise swiftly without increased political support. Some of the pressing challenges include:

- a need to increase the availability of capital to investors, to compensate for the additional upfront costs for electricity infrastructure (renewable capacity deployment and grid infrastructure) and system integration (including the accompanying flexibility resources);
- a need to shift and reduce the levels of taxes, levies and other policy costs placed on electricity, which in some countries may hamper electrification and render gas more cost-competitive, ironically;
- a need to enhance cross-border planning, cooperation and operation of grids and infrastructure to reduce shortage risks and improve the overall energy system flexibility through a more diverse EU generation mix;
- the need to also address non-technological and non-financial barriers, including the sufficiency and efficiency of administrative resources, the access to spatial planning tools and the skills of competent authorities, along with the duration of administrative procedures for solving permit-related trade-offs and improving community acceptance.

Current and near-term evolution of EU electricity prices and energy expenditure

Increasing generation from renewable sources will lower EU electricity and energy prices

Unconventional fossil fuels have transformed the US energy landscape dramatically in less than two decades. However, such developments cannot be replicated across Europe due to multiple factors, especially geological constraints, compounded by higher population densities and broader health, climate and environmental concerns ([35]). As domestic, conventional gas production is dwindling, EU Member

([35]) Including more complex subsurface formations, along with uncertain resource potentials and the lack of extraction rigs (Vollebergh et al., 2014; Gandossi, L., 2016).

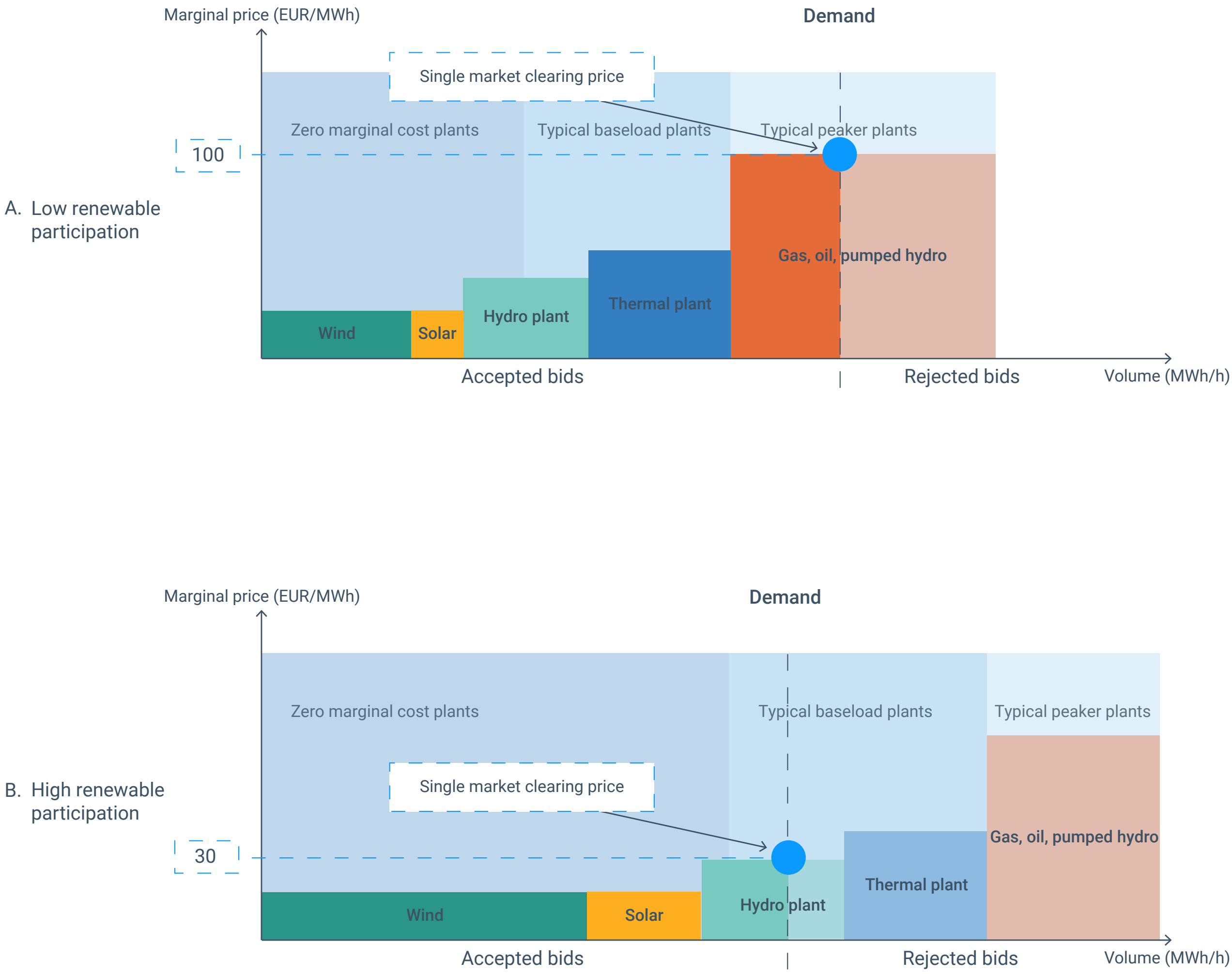
States face a widening gap between gas demand and supply, resulting from reduction in domestic gas production coupled with investments in gas-fired power plants, LNG terminals and gas pipeline infrastructures. At the same time, domestic oil reserves have largely been depleted. Against this backdrop, the EGD offers far more than the alignment of the EU energy system to climate commitments: it is the main modality for to secure long-term access to more sustainable, domestic energy resources — especially renewable electricity supply — and reduce import dependency already in the short term.

The deployment of solar PV, wind turbines and other renewables that generate at lower marginal costs creates a downward pressure on electricity prices, as illustrated in Figure 3.6 (lower illustration). However, spot prices in the market are set by the most expensive marginal generation units — today most commonly gas peaker plants (EC, 2024m; EEA and ACER, 2023). Gas therefore continues to play a key role in marginal price-setting through much of the year.

To limit the disproportionate impact of high gas prices on EU electricity prices, the plant capacity within the EU electricity mix must change must faster than historically (see 'Current and near-term evolution of EU electricity prices and energy expenditure' in Chapter 3.1.2). By contrast, attempts to lower gas prices artificially through state intervention, to reduce their impact on electricity price formation, likely would be inefficient and discourage efforts to accelerate more structural solutions across the EU. Such measures also risk locking in gas demand and either forming or increasing economic dependencies.

The recent evolution of the EU electricity subsystem in response to the gas price shocks fell out of step with the coherent logic of systemic transformation: the past four years saw a record build-out of EU LNG terminals to receive more gas; fossil fuel subsidies have reached their highest levels ever in 2022 and 2023; and subsidies for renewable energy sources have decreased compared with levels reached before the COVID crisis (EC, 2025g); (see also Chapter 2, 'Rethinking the EU energy system – a transformation at the crossroads'). The most recent national energy and climate plans (NECPs) are unclear for most countries, regarding commitments to phase out fossil fuel subsidies (ECNO, 2024a). These developments imply that policy commitments to longer-term planning were too weak, even with the knowledge that renewable energy sources are key to future price stability.

Figure 3.6 Illustration of market clearing at different level of renewable electricity generation in the electricity market



Source: EEA.

Note: The boxes indicate illustrative bids made in the day-ahead market by key participating technologies.

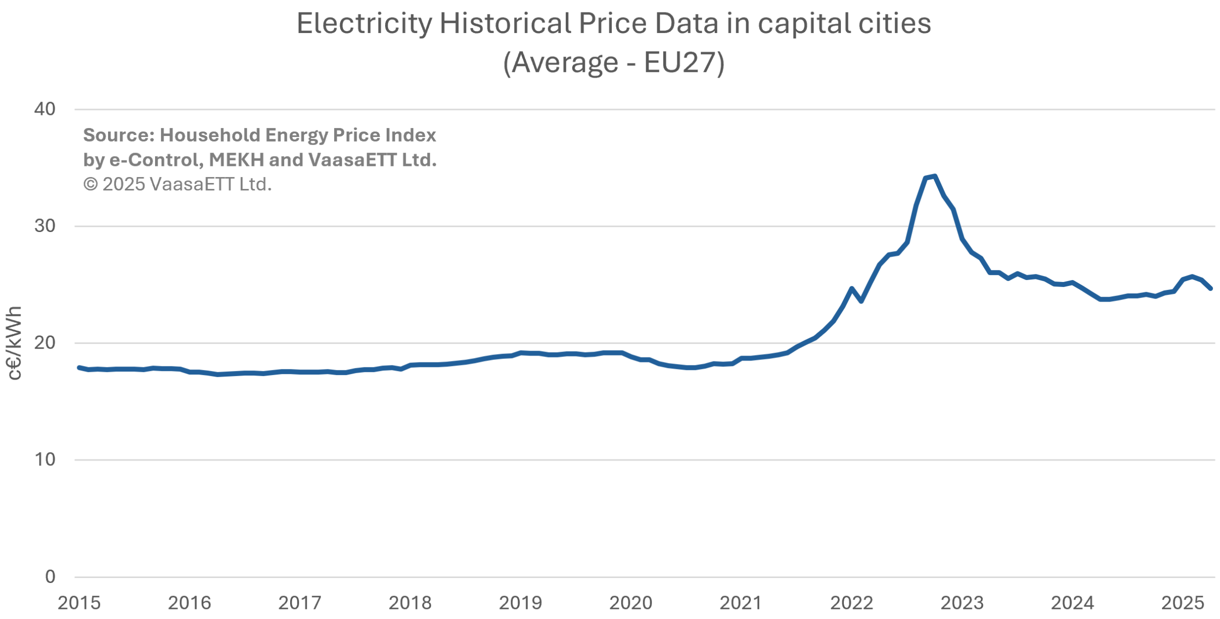
The impacts of the energy crisis

Before the energy crisis, average EU wholesale electricity prices were up to 40% higher than in the US most of the time, yet comparable to prices in Japan and China (EC, 2024j). Even as EU electricity prices continue to recover from their peak levels of 2021 and average day-ahead electricity prices have fallen further in 2024, higher gas (spot) prices after 2021 remain a key factor driving future electricity price formation (EC, 2024m). Understanding these market dynamics is critical, not least because high energy prices can shake investor confidence and fossil fuel import expenditures can weigh heavily on national budgets. These impacts can be greatly diminished by substituting gas and other fossil fuels with renewables in the generation mix and improving energy efficiency.

As shown in Figure 3.7, gas prices rose during 2021 and 2022 due to reduced supply from Russia, geopolitical tensions and rebounding economic activity in the post-COVID period. EU wholesale gas prices increased by more than 3.5 times compared with the historic average, propelling the EU's energy import bill to 4.3% of

EU GDP in 2022 — roughly twice the levels seen since 2014 ([36]) (EC, 2024j). At the same time, high gas prices led also to an unprecedented peak in electricity prices during the second half of 2022, an effect that was compounded by exceptionally low generation from hydro and nuclear power.

Figure 3.7 Average household electricity (above) and gas (below) price data, EU-27



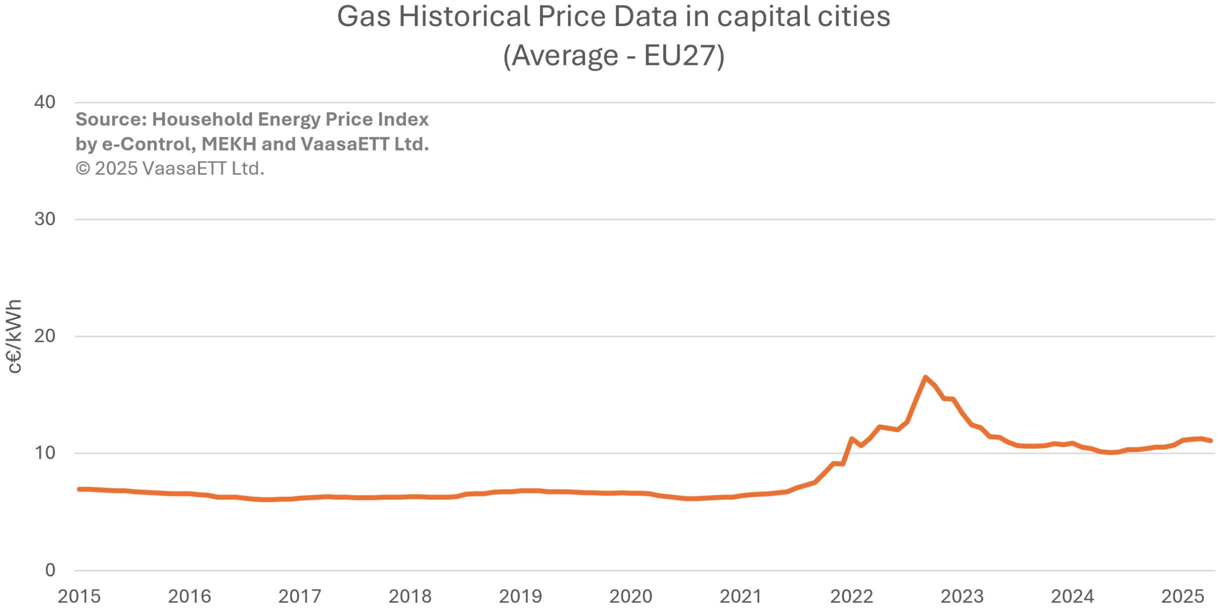


Image source: Household Energy Price Index, 2024. Image data not verified by the EEA.

([36]) Between 2014 and 2020, the EU's energy import bill fluctuated between 1.5% and 2.8% of EU GDP.

The geopolitical instability created by Russia's invasion of Ukraine exposed a major short-term weakness of the EU energy system: its overreliance on imported fossil fuels. Since 2022, the EU has broadly stopped importing more volatile and insecure gas from Russia and started to replace it with more expensive liquefied natural gas (LNG) from other countries, while accelerating the expansion of its own renewable energy (Draghi, 2024). Subsequent attacks on gas pipelines such as Nord Stream or Balticconnector exemplify the importance of establishing resilient critical energy infrastructure, joint projects and increased cross-border planning and cooperation. This will increase renewable energy sources, stabilise energy prices and diversify energy supply (EC, 2023i).

Expected evolution of day-ahead electricity prices by 2030

Electrification can strengthen Europe's industrial sector. Although operating costs are low or close to zero with renewable energy sources, most other costs occur upfront, including indirect expenses to upgrade the transmission and distribution grids. Over time, a focus on renewables will lower the wholesale price of electricity and improve industrial competitiveness, even as high investment levels are necessary in the short term to expand grids and networks and build out flexibilities, for instance.

In 2023, the EU average day-ahead electricity price was EUR 91.7 per megawatt-hour (MWh) ([37]). Average retail prices for EU industrial electricity were roughly the same level as in Japan and two to three times higher than the US (EC, 2024j; ENTSO-E, 2025a). However, by the third quarter of 2024, strong generation from renewables led to a 28% decrease in electricity prices in northern Europe, compared with the same period in 2023 (EC, 2024m, 2024i). This demonstrates the ability of renewable generation sources to replace gas and push down electricity prices.

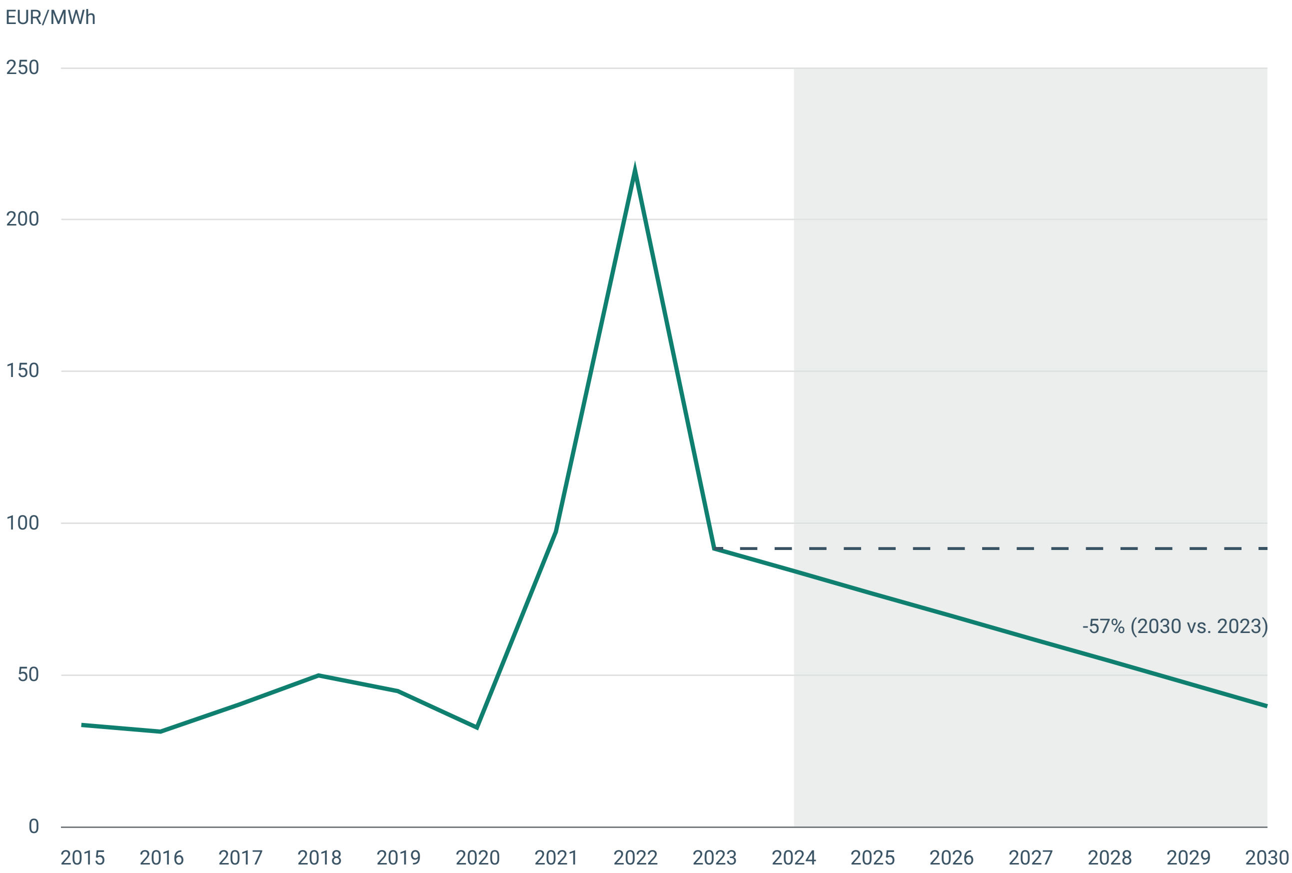
Accelerating the deployment of renewables and improving energy efficiency to meet the benchmark levels for 2030 (EC, 2020c, 2024h) would significantly reduce the hours during which gas peaker-plants must operate as backup generators. By 2030, this would translate into a 57% reduction of the EU average spot electricity price (i.e. 39.9EUR/MWh), compared with 2023 (see Figure 3.8; footnote 33).

If renewables-based electricity grows to benchmark levels set in scenarios for 2030, average annual spot prices would fall in all EU countries and all bidding zones. Among the EU countries, Spain and Portugal would experience the most significant variable generation cost reductions, with decreases of 81% and 77%, respectively, compared with 2023. These declines highlight the effectiveness of renewable energy deployment and market reforms in these regions. Similarly, Ireland and France would see notable wholesale price reductions of 77% and 73%. This underscores the broader benefits of the energy transition across diverse markets.

Most other European market zones are expected to see wholesale price reductions ranging from 40% to 60%, demonstrating widespread cost improvements driven by the shift to a low-carbon energy system (see Figure 3.9). However, certain regions, such as Sweden and Finland already enjoy stable and lower price levels compared with the other EU countries, resulting in less pronounced adjustments of their variable generation costs by 2030. A seasonal price variation is to be expected, with all countries seeing higher average wholesale prices during winter months, in general.

([37]) The day-ahead or spot price is determined by the marginal pricing system, where the most expensive generator needed to meet demand sets the clearing price. This price reflects fuel and operational costs of power plants, carbon pricing, transmission constraints and interconnections. However, it does not include national levies and taxes (e.g. VAT, renewable surcharges, excise duties), which are applied only after the wholesale price and are included in the retail price paid by consumers.

Figure 3.8 **Modelled evolution of EU average day ahead electricity prices by 2030, under assumption that EC benchmark capacity levels for 2030 will be met**



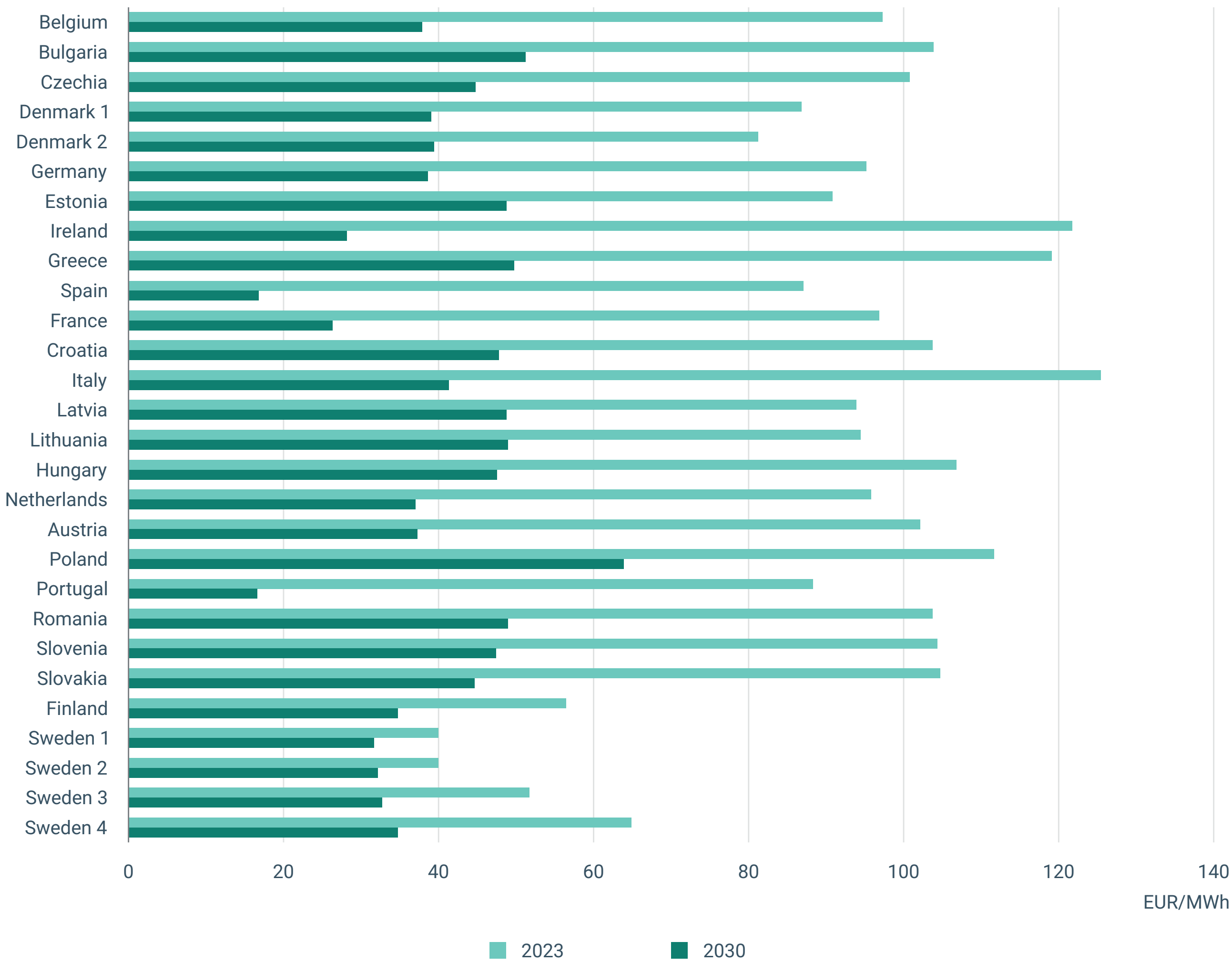
Source: EEA, Rambøll, 2024; EC, 2024d.

Notes: The hourly electricity market model used simulates the grid in 2030 according to the planned and approved interconnections and grid expansions available at the TYNDP 2022 Project Collection. The TYNDP 2024 results were not available at the time of running this scenario in 2024. Importantly, the model calculates the electricity day-ahead price only, based on fuel and operational costs of power plants, carbon pricing, transmission constraints and interconnections. By contrast, taxes and levies (e.g. value added taxes, renewable surcharges, excise duties) determined and applied at the national level and representing a main component of retail prices paid by households are not included in the day-ahead electricity market prices and in the above simulation. The average EU electricity price in 2023, of 91.7EUR/MWh is also the day-ahead price and does not include any national levies and taxes.

Nevertheless, costs related to investments in capacity deployment, grid enhancement, storage build-out and activation of demand response will be considerable in the near term. Europe will need an estimated EUR 350 billion in additional investment per year over this decade to meet its 2030 emissions-reduction target in energy systems alone, alongside EUR 130 billion for other environmental goals (EC, 2021a).

For national policymakers, three key questions emerge: how to distribute these costs across society; how to recuperate the costs without increasing the gap between the prices of retail electricity and fossil fuel commodities (which would dissuade electrification); and how to restructure debt (as necessary) to spread costs over a longer time frame. Much of the level of future retail electricity prices will actually depend on how policymakers will tackle these various cost components.

Figure 3.9 Electricity price difference 2023 to 2030 (REF) across market regions



Source: EEA, Rambøll, 2024.

Energy expenditure in industry and households

On average, energy costs have played historically a modest role in EU industry's total manufacturing costs, accounting for 1.7% of EU industrial production costs in 2019, down from 2.3% in 2010 (EC, 2024j). Following the 2021 energy crisis, the share of energy costs has gone up sizably. Energy-intensive industry sectors have seen rises between 20% to 50%, with increases of up to 90% for the fertiliser sector. This renders certain industries more vulnerable to volatile commodity prices and competition from abroad (EC, 2024j). Nevertheless, in 2023, energy costs for average EU businesses still ranged between 1% and 3% of total production costs; for energy-intensive sectors such as iron and steel, cement, chemicals, glass, clay, ceramics and building materials, as well as pulp and paper, they ranged between 5% and 10% of total production costs (EC, 2025h).

The energy crisis also marked a breaking point in the EU trend for household energy expenditure. This had decreased overall for all income levels over the past decade, yet rose in 2021 and 2022 (EC, 2025h). At the EU level, low-income households spent 7.5% of their budget on energy in 2022 (EUR 1,250), up 0.3 percentage points from 2020 levels. Nevertheless, national household budgets and purchasing powers, building efficiency standards, retail energy prices (including taxes and levies applied nationally) and household energy needs (depending on geographies and level of urbanisation) vary significantly across the EU countries. This variation explains why low-income households spent a considerably higher share of their disposable income on energy in certain countries, compared to others ([38]). Taxes represented two fifths of EU retail electricity prices during the second half of 2019 on average. By second half of 2022, this share fell to 15.5% (the lowest levels since 2008), as policymakers attempted to mitigate rising household expenditures linked to the high gas and electricity prices (Eurostat, 2025).

Even if the financial impact of increasing energy and electricity prices was not overwhelmingly significant for many households, the rise in energy prices has disproportionately impacted the poorest, where energy expenditure takes a substantial share of the disposable income. The growing costs of fossil fuel imports and the rising energy bills have placed additional direct and indirect pressure on both households and industries, underscoring the need for faster structural changes to lower energy costs by 2030. Apart from quickly expanding renewable energy production to limit the transmission of fossil commodity price volatility on energy prices, policies aimed at increasing business productivity, including via stronger signals to conserve energy, can promote effective industrial readjustment to higher energy prices (Chen et al., 2023). A key lesson from current national responses to the energy crisis is the need for more efficiently tailored national emergency relief measures to meet the specific needs of the most vulnerable households (EC, 2025h; Jüngling, E et al., 2025).

Opportunities from continued fast technological learning and cost-reductions

The costs of developing renewable energy sources have fallen significantly, as illustrated in Box 3.1. Generating electricity with onshore wind and solar is now cheaper than with fossil fuels. The offshore wind investment market too is deemed to be competitive in specific locations. Offshore wind project developers have witnessed increased financial pressure lately, following rising costs due to inflation, higher capital interest rates and supply chain bottlenecks. Yet these economic pressures are expected to ease with declining inflation and interest rates. To accelerate progress toward offshore wind targets in Europe, new auction designs may benefit from including considerations for state support and the additional costs developers face, such as grid connection (Energistyrelsen, 2024). Meanwhile, other measures are being rolled out to further lower development costs of offshore renewables, including the coordination of cross-border planning efforts for key energy infrastructure projects, along with collaborative frameworks to leverage joint investments and reach consensus on the equitable distribution of costs (EC, 2024g; CINEA, 2025).

Nuclear power has gained traction recently, as a stable power source that fulfils a role in the future electricity system. The profitability of nuclear power investments is determined by relatively high capital costs and low marginal costs. Lower electricity prices are likely to reduce the operating hours of nuclear power plants to a certain degree. Though as penetration of wind and solar power increases, this will affect the rentability of new nuclear investments. Equally, it will alter the capture prices

([38]) Over 20% and over 15% in Slovakia and Romania, respectively, compared with less than 5% in Finland, Luxembourg, Malta and Sweden. This broadly reflects differences in purchasing power (EC, 2025h; Eurostat, 2025).

for investments in renewable generation through the so-called 'cannibalisation' effect. However, as the cost of renewable generation has fallen sharply, the expansion — especially of solar power — has continuously outpaced projected growth scenarios. In the Netherlands, for example, policies to improve the rollout of roof solar panels, has made the country 'world champion of solar PV'.

Box 3.1

Cost reductions of renewable energy technologies

The rapid expansion of key renewable energy technologies such as solar PV, wind power and batteries have been largely driven by significant reductions in technology costs. These cost reductions have been propelled by intense R&D efforts, industrial scaling of manufacturing processes and market expansion (Chatzipanagi et al., 2023) resulting in remarkable price declines over the past decade.

When considering the levelised cost of electricity (LCOE) - accounting all the costs of electricity generation and expressing it per unit of energy produced - the following cost reductions have been observed, based on a global weighted average:

- For **solar PV technologies**, there was an estimated cost reduction of 90% between 2010 and 2023 (IRENA, 2024).
- For **wind energy**, offshore costs are estimated to have decreased by 63% and onshore wind by 70% over the 2010-2023 period (IRENA, 2024).
- The costs of critical **battery technologies** have also fallen considerably over the last decade. According to Bloomberg data analysed by CETO (Bielewski et al., 2023), battery costs decreased by 79% between 2013 and 2022.

Technologies become more efficient and affordable depending on their inherent characteristics, such as the size, modularity and design complexity (Malhotra and Schmidt, 2020; Way et al., 2022). Costs for many technologies have remained roughly stable (e.g. CCS) or even increased (e.g., nuclear) over recent decades. Wind, solar and battery costs have dropped almost exponentially (c.10% every year) while deployment has increased exponentially (Way et al., 2022). The cost reductions have accompanied the widespread deployment of these technologies, which have consistently surpassed expectations. Projections (including recent ones) have systematically underestimated deployment rates for renewable energy technologies and overestimated their costs, as also shown in the following figure (Xiao et al., 2021; Way et al., 2022).

While different factors might explain this, it can lead to underestimating the future role and levels of deployment of these technologies. This risks policymakers not putting in place the conditions to enable that scale-up and take advantage of them (e.g., grid investment, developing clean-tech skills and electrification of other sectors) (Bruegel, 2024).

If scaling-up the deployment of these technologies continues to drive cost reductions, counter to current thinking, faster transitions could save trillions globally by accelerating these processes (Way et al., 2022).

Recent years have shown that cost declines are not guaranteed, nor linear. The aftermath of the COVID-19 crisis, combined with inflation and rising raw material prices, led to cost increases across all three key technologies. Nevertheless, a return to the downward trend in costs is expected across the different technologies, with the recent IRENA report indicating significant cost reductions for wind and solar power in 2023, bringing the LCOEs of these technologies below alternative fossil fuel-based generation technologies (IRENA, 2024).

Further cost reductions are expected in the coming years, based on further development of current technologies and the deployment of new technologies, such as alternatives for the current lithium-ion batteries. New innovations, at both the solar cell and system levels, could contribute to keeping the high learning rate shown in the past (Victoria et al., 2021). For wind, growth in turbine size may continue to be an important driver of lower lifetime generation costs, offsetting the potential movement towards less-attractive wind sites. Eventually, a floor for clean tech cost reductions will be reached, though currently it is impossible to predict and how low it will be.

Figure 3.10 Future cost projections reported by integrated assessment models (IAM) and IEA studies

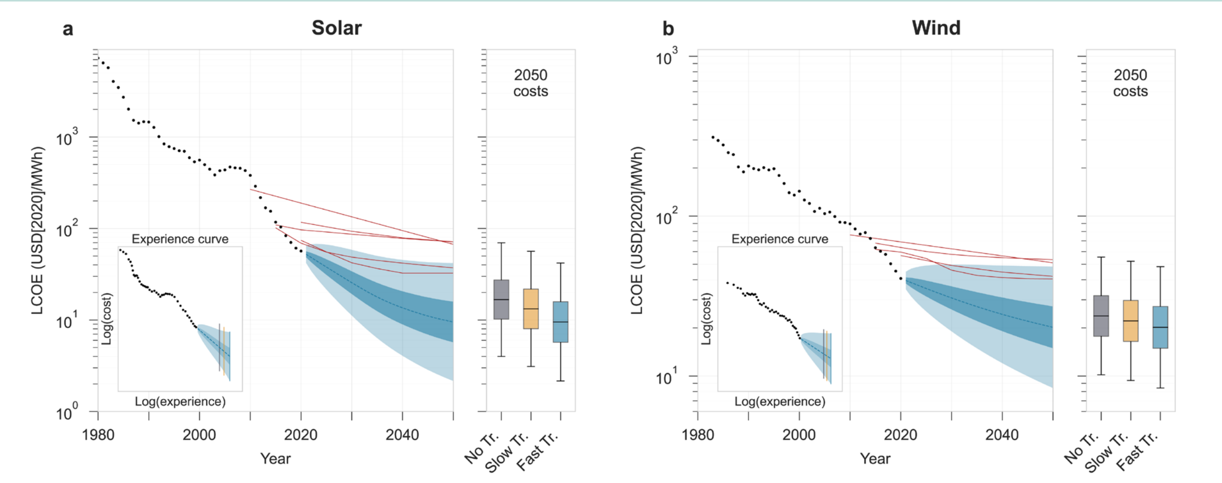


Image source: Way et al., 2022. Image data not verified by the EEA.

The figure shows a selection of past and future cost reduction projections reported by IAMs and IEA studies. The paper documents that historic cost projections were consistently higher than actual historical cost reductions. Moreover, expected cost reduction projections too are significantly higher than the authors' forecast medians. This suggests a likely underestimation of the actual future cost saving potentials of these key technologies.

Identifying future flexibility needs in the EU electricity subsystem

Variable renewable electricity (VRE) sources are expected to dominate the future EU electricity system. To balance supply and demand in real time, non-fossil flexibility resources will be critical. Further digitalisation of the EU electricity system will be essential in optimising network use by enabling a seamless communication between devices and the safe aggregation of flexibility across smart buildings, electric vehicles and battery systems via digital tools (EC, 2022a).

In 2024, Europe experienced a record number of hours with zero or negative day-ahead electricity prices ([39]). This followed high wind and solar PV generation in some regions, coupled with low demand and insufficient cross-border electricity trading (ACER, 2024b; Montel Analytics, 2025). This increased congestion in the EU power grid on occasion, leading to curtailment of renewable electricity supply to the tune of EUR 4 billion in 2023 — a sizable cost for EU operators and consumers (ACER, 2024b). Against this backdrop, progress of the Transmission System Operators in maximising cross-zonal capacity available for electricity trade is deemed too slow. Further market integration and trading are essential for an efficient EU electricity market and a cost-effective energy system transformation (ACER, 2024a, 2024b). To avoid an increase in congestion management costs as VRE deployment accelerates by 2030, non-fossil flexibility resources must more than double by 2030 (EEA and ACER, 2023) ([40]).

Updated EU electricity network codes and guidelines are in place to address possible imbalances in the operation of cross-border power grids. Yet the severe electricity blackout that struck the Iberian Peninsula on 28 April 2025 (and temporarily impacted parts of France) may prompt decisionmakers to introduce additional requirements and stress tests to prevent or minimise potential domino effects across interconnected electricity systems (ACER, 2025; EC, 2025d). Spanish and EU investigations are underway to find the cause of the major imbalances between injections and withdrawals of electricity that day. In general, a stronger, more interconnected network with higher system inertia and good flexibility resources will be better suited to rebalance the system and reduce the risks of future outages (EUI, 2025). Stronger domestic resilience and improved regional coordination remain thereby important in this regard.

Flexibility needs differ in terms of duration (temporal resolution) and are usually grouped as short-term (hourly-daily), mid-term (daily-weekly) and seasonal (monthly-yearly). Policymakers should understand these discrepancies to better anticipate short-term operational challenges, medium-term balancing requirements and longer-term system planning needs. In this way flexibility solutions can be deployed effectively. To better grasp these needs, the EU electricity market framework mandated the European Agency for the Coordination of Energy Regulators (ACER) to conduct a pan-European assessment by mid-2027 (EU, 2024e).

To cover these system needs, policymakers and system operators can leverage four main types of flexibility resources, as illustrated also in Figure 3.11:

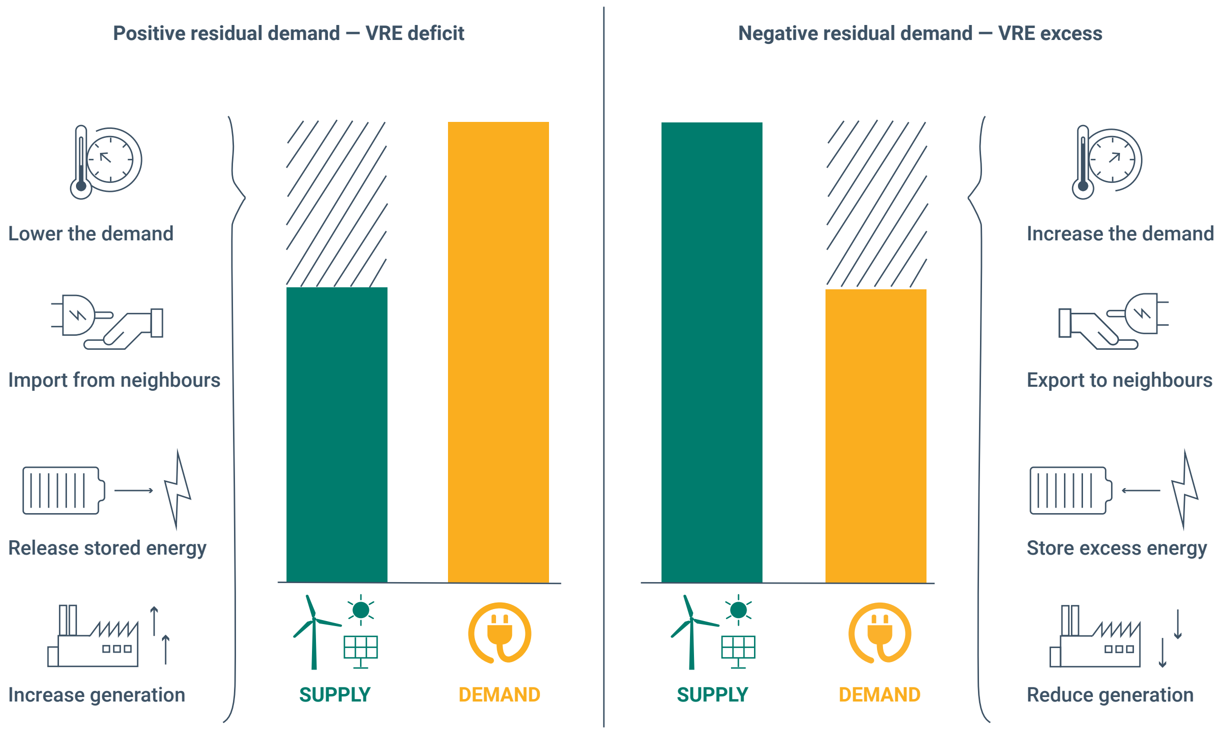
- supply-side flexibility, referring to adapting (dispatchable) power generation to meet varying demands (e.g. backup generation);

([39]) Negative prices are extreme cases of low-price episodes caused by high VRE generation and low demand, for instance during a sunny or windy weekend. In total, 4,838 hours of zero or negative prices occurred in 2024, nearly twice as much as in 2023.

([40]) Curtailments represent 'wasted' electricity loads in the system, such as when excess generation from renewable sources is intentionally reduced or turned off to ensure the balance between supply and demand. For producers, this represents financial losses, while for consumers the foregone benefits of cheap, renewable electricity supply.

- energy storage solutions, capturing and releasing surplus energy to align supply with demand;
- demand-side flexibility (demand response), referring to adjusting consumer energy use to better coincide with energy availability, also employing innovative measures to enhance consumption efficiency;
- flexibility from spatial equalisation, involving the activation of transmission and distribution grids and interconnections to better exploit complementarity local and/or regional supply and demand profiles and smoothen aggregated supply and demand profiles.

Figure 3.11 Main flexibility categories and their deployment for balancing the electricity system



Notes: Flexibility needs cut both ways, as the increased reliance on renewables will create peaks of electricity supply without enough demand and lack of supply with greater demand.

Source: EEA and ACER, 2023.

Wind and solar have complementary generation profiles. Smart coupling therefore offers important opportunities to smoothen and stabilise renewable electricity supply. Together, the intermittency of solar and wind generation is much lower than in a system that relies on only one of these technologies. Finding the local optimum for smart coupling between varying renewable electricity sources will lessen intermittency.

When renewable electricity supply exceeds demand, there are several possible options. Demand could be artificially ramped up, excesses supply could be stored or exported to neighbouring countries and, as an ultimate measures, generation could be curtailed.

In times of renewable electricity shortages, adjusting demand (i.e. demand-response), importing electricity from neighbouring countries, drawing on storages and ramping up dispatchable generation will all help. Under a target-reaching scenario, excess VRE supply can increase to 118TWh by 2030. This highlights the importance of anticipating and addressing future system-wide flexibility needs (EEA and ACER, 2023).

Sharing electricity between neighbouring countries tends to reduce total flexibility needs within interconnected electricity systems, as different weather patterns tend to cancel out existing national fluctuations in supply and demand. Constructing interconnections between regions with complementary weather patterns will, in general, help to smooth variability in supply.

The demand for dispatchable electricity generation — such as from gas — declines towards 2030 if renewable generation capacity increases to meet the 2030 benchmark levels. This development would call into question the business case of flexible generation from gas, as reduced operating hours lead to higher costs per unit. Demand flexibility could thereby become a more cost-effective solution.

Households account for a major share of seasonal electricity demand imbalances, contributing up to 50% of the additional demand during winter months in some countries. The electrification of buildings and passenger transport may exacerbate future imbalances, due to higher electricity demand from BEVs and heat pumps. Empowering households to act flexibly and adjust peak consumption will be key to dampening peak demand by redistributing some of this demand to non-peak hours.

Flexible demand is critical in other sectors too. Production processes should be designed to take flexible demand into account, raising production at times of high electricity availability and reducing it during scarcity times.

The 2022 Action Plan on Digitalising the Energy System established a framework to ensure the interoperability of different systems and enable flexible demand and aggregation from households and businesses in response to system needs. This includes a Common European Energy Data Space (CEEDS), common standards on data exchange, consumer-facing digital tools to help cut or shift demand during peak hours and the provision of real-time consumption data through smart metering infrastructure (EC, 2022a).

Storage is key to increasing flexibility. Next to pumped hydro — which today is essential but faces certain challenges in terms of local geographies — batteries offer a viable non-fossil storage solution. Technology costs for batteries have fallen since 2013 by about four fifths (Bielewski et al., 2023). Although the price-gap between China and EU is slowly closing, price competition is tough. Battery costs are driven mainly by materials, facing specific drawbacks in the availability of REMs (EC, 2025j).

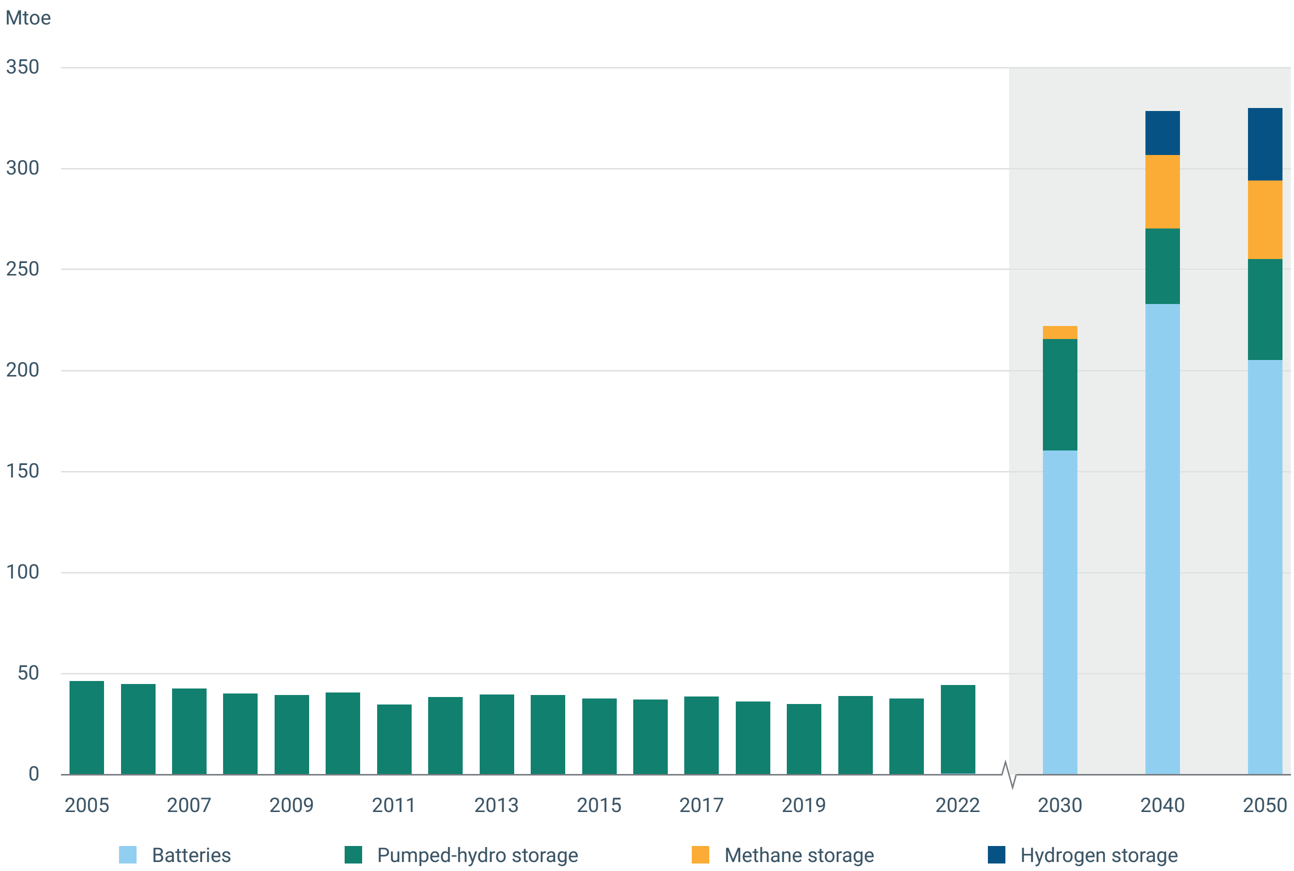
Hydrogen represents another flexibility solution, especially the prospect of using excess low-carbon electricity to produce hydrogen or e-methane and store this for future (seasonal) power supply. Thanks to its versatility, hydrogen will be an essential part of the future energy mix. Many economic sectors are in line to use it. In the longer term, producing green hydrogen is cheaper at excess electricity moments, such as with low-to-negative prices and when renewable supply exceeds demand. Yet in the near future hydrogen will neither be cheap nor abundant. Its cost-competitiveness is under question due to uncertainties in production methods and their respective life cycle GHG emissions, as well as the lack of supporting infrastructure for transport and storage (Johnson et al., 2025). To maximise impacts, national hydrogen strategies will need to carefully plan the most salient hydrogen applications across the energy system, such as in the production of petrochemicals and fertilisers, steel and other hard-to-decarbonise branches, long-distance transport and long-duration energy storage. Applications such as space heating of buildings and fuel cells (with the exception of long-distance transport) are the least strategic and would benefit most from direct electrification (Johnson et al., 2025).

The amount of storage required per country will differ by 2030, depending on the generation mix and the flexibility of demand. The EC benchmarks from the EU Climate Target Path 2030 clearly find a very high expected amount of battery storage by 2030, as illustrated in Figure 3.12.

Promoting the swift deployment of renewable energy and insulating energy costs from gas price volatility through Power Purchase Agreements (PPAs) — through improved financial conditions and standardisation — would benefit manufacturers by providing access to lower and more stable energy prices. Specifically, Member States with a high potential for renewable energy (and therefore lower energy prices), such as Portugal, Spain or Sweden, could hold a competitive advantage. Similarly, EU countries with lower labour costs could eventually emerge as more cost-competitive.

Beyond 2030, when carbon must be replaced with renewable sources, electricity will have to be upcycled to molecules (hydrogen and other e-fuels). Molecules are more easily stored seasonally, meaning such future power-to-X solutions could improve seasonal flexibility across the EU energy system.

Figure 3.12 Electricity stored by technology between 2005 and 2022 and outlook towards 2030, 2040 and 2050



Source: EEA, based on data from Eurostat, 2024a; EC, 2024h.

Empowering prosumers: a key element of the renewable energy transition

Renewable energy prosumers and communities are still in their infancy across most EU Member States. Despite that, a conservative estimate for the EU technical potential for rooftop PV systems amounts to 580GW installed capacity. This could generate roughly 26% the EU's total final consumption of electricity in 2022 (Kakoulaki et al., 2024). As the costs of panels continue to decline, more households will be able to purchase these systems.

Household solar PV systems are usually small-scale, with a relatively high cost per unit of installed solar capacity compared to commercial solar PV parks. However, these systems present two significant advantages. First, accelerating rooftop PV installation could enable EU households, on average, to generate up to 89% of their own electricity demand by 2050 (EEA, 2022b). This hyper-local energy production could reduce some of the strain on energy infrastructure. Even today, almost all citizens or households can participate in a renewable energy cooperative and can become prosumers (directly or indirectly). Second, citizen involvement as prosumers in the energy transition introduces a new, important source of capital for investments in renewable electricity generation and climate mitigation (CE Delft, 2021). This in turn fosters greater public engagement in the energy system transition.

Prosumers often encounter challenges: high initial cost, no available technical know-how and legal barriers for the prosumer model. Governments should enact policies to enable innovation, as emphasised in the REPowerEU plan. These policies should enable the legal model and address technical and financial barriers (EEA, 2022b).

3.1.3 Key actions and recommendations for the electricity subsystem

This section lists some core measures that Member States can take to accelerate the electrification of the energy system.

Carbon pricing can help industrial users, households, transport sectors and other sectors to electrify

Carbon pricing is essential to the electrification of end-use sectors. Carbon prices generate value for low-carbon investments and electrification, while helping to overcome the price parity between fossil and renewable energy sources. The EU ETS1, together with the upcoming Carbon Border Adjustment Mechanism (CBAM), may be sufficient to persuade energy-intensive industrial users to electrify their processes, especially if long-term predictability is provided. For smaller industries, households and transport, ETS2 will be become fully operational in 2027. The system will be comparable with the existing EU ETS but will also cover upstream emissions. With an opt-in, Member States can broaden the scope of the ETS2 with other sectors not yet covered by the EU ETS1, such as horticulture, agricultural machinery and fishing vessels. This could help those sectors to invest in electrification and other low carbon measures.

Accelerating renewable energy investment, deployment and grid expansion

High upfront investments costs remain one of the main challenges to the adoption of renewable electricity, even though variable costs during production are very low. Expanding capacity, network and storage infrastructure requires significant near-term investment. Private capital is available, though business opportunities are often too weak to mobilise sufficient investment in sustainable energy technologies, grids, storages and other solutions that would enhance EU decarbonisation, competitiveness and security of supply. To improve and accelerate the deployment of private capital, Member States can pay more attention to key factors behind successful national de-risking strategies. These include offering tax breaks or differentiated tax brackets for clean business cases and technology assets ([41]) and developing green investment funds — two measures outlined also under the recent EC Clean Industrial Deal (EC, 2025c; ETC, 2025). One specific issue with the increase of solar and wind is that the business case weakens when these sources become the marginal supplier in the merit order. In those cases, electricity prices will be low. Specific policy instruments like two-way contracts for difference (CfDs) can overcome this issue. With a two-way CfD, suppliers will be subsidized in case of low electricity prices and they will pay when prices are high.

Lengthy permitting processes ([42]) can hinder the further uptake of renewable electricity sources and grid expansion. Local issues such as the lack of community acceptance (either due to project proposers ignoring community perspectives or NIMBYism), lack of space and biodiversity restrictions require proper consideration of all interests. Member States can help to align local procedures and invest in better management linked to deployment (social, land use, biodiversity) without compromising environmental conditions (Birdlife, 2025).

Cross-border collaboration can help to create a more cost-effective EU energy system but requires good planning and arrangements between bordering countries (EEA, 2020a). Grid expansion is essential to overcome already noticeable bottlenecks in certain regions — such as in quasi-isolated regions like the Iberian Peninsula — and to accommodate the expected large increase in variable electricity generation. Timely investment decisions in transmission and distribution grids can prevent imminent problems with net congestion. Governments must be clear about their decarbonisation plans (including their long term strategies for 2050 and plans for clean industrial transformation) and the ensuing consequences for grid capacity, expansion and flexibility needs. Increasing electrification will increase certain costs within the electricity subsystem, requiring an efficient use of the available infrastructure. The integration of the national electricity systems can improve the overall efficiency and security and lower total system costs for EU consumers (see 'Coordinated action: key to a more sustainable and secure EU energy system' in Chapter 2.1).

Increased efforts for grid integration and for strengthening (cross-border) transmission and in particular distribution networks are necessary and helpful from a European perspective. Such measures can provide consumers with a wider access to low-cost renewable electricity supply, while creating opportunities to scale up cross-border demand flexibility. For example, by 2030 interconnectors could avoid curtailing as much renewable power as Sweden consumed in 2023. Demand response could lower the need to backup solar and wind generation by the equivalent of Spain's total power consumption in the same year (EEA and ACER, 2023). Even as cross-border interconnections imply a need to solve specific distributional trade-offs between exporting and importing countries, increasing them will lead to additional welfare gains overall for European consumers over the medium term (Heussaff, C., et al., 2025).

([41]) Such as shorter depreciations periods and tax credits for clean technology assets, which allow businesses quickly to offset high initial investment costs (EC, 2025c).

([42]) According to the Draghi report, permitting processes last around six years for onshore wind in most Member States, sometimes extending beyond eight or nine years, while almost no EU country can complete the process within two (or three) years as requested under the recast Renewable Energy Directive. For ground-mounted PV systems, the length of the permitting process varies between one and three or four years, while normally under one year for rooftop PV systems (Draghi, 2024).

Supporting the realisation of key cross-border projects, a EUR 600 million call for EU energy infrastructure projects is running until September 2025 under the Connecting Europe Facility Regulation (Regulation (EU) 2021/1153) and will support co-finance studies and works for Projects of Common Interest (PCIs) and Projects of Mutual Interest (PMIs) (CINEA, 2025).

3.2 Facilitating the transformation of the EU heating system and electrification

In contrast to the EU electricity subsystem, heat is typically produced and consumed locally to reduce transmission losses. There is therefore no unified EU heating subsystem, but rather a large variety of distinct subsystems operated at the building and industrial plant or facility level. Thermal district heating (or cooling) networks are shared by multiple buildings, usually in urban areas. The vast majority of these subsystems still burn fossil fuels (EEA, 2023d).

Historically, the decarbonisation of this subsystem has been slow and mainly focused on substituting fossil fuels with biomass, at times with trade-offs such as impacts on air quality (EEA, 2023d). Decarbonising heat demand from buildings and industry by 2030 will benefit from a more rapid switch to renewable electricity, along with energy and resource efficiency measures and greater demand response. With a few exceptions in some industrial sectors, technical solutions already exist. This implies that slow historic progress is the result of insufficient socio-economic drivers for the transformation (Hansen et al., 2024).

This section explores key drivers to decarbonise heating systems, in relation to their respective opportunities and challenges.

3.2.1 Heat supply and demand across the EU

Factors shaping heat demand today

In 2023, buildings and industry were the two largest heat end-users across the EU. Heating represents most of the final energy demand across these two sectors. The majority of thermal energy needs in buildings is for heating space and water ([43]), while industry demands are mainly for high-temperature processes (see also Box 3.2). Most heat is still produced by burning fossil fuels (especially gas), though biomass also plays an important role in some regions, particularly in Nordic EU Member States and in rural areas across Europe. District heating supplies some of the demand, while electricity (used in boilers, heat pumps and direct heaters) represents a smaller share.

The decarbonisation of heating systems has progressed slower than in the EU electricity system but, overall, there have been considerable changes over the past two decades. Fossil fuel use for direct heating dropped by 28% between 2005 and 2022, while biomass use surged by 58% (see Figure 3.13). District heating decreased by 11%. In recent years there has been a rapid shift towards electricity-based thermal services, especially through heat pumps. This is particularly evident in buildings and is demonstrated by the steep rise in heat pump installations (see Figure 3.15). In industry, electrification of heating needs has been slow, indicating slower progress toward decarbonisation.

([43]) In buildings, when thermal regulation of space and water is performed with heat pumps, it represents an electrification-based solution to decarbonise heating, according to the framework used in this report.

Demand for energy carriers to produce heat declined by 15% between 2005 and 2022. This was driven by heat demand reductions in industry (20%) and in buildings (12%) (see Figure 3.13 (EEA, 2023d)). Efficiency gains in industry led to greater heat productivity over this period, increasing the gross value added (Kovacs and Domonkos, 2024). In buildings, efficiency standards, thermal retrofits and warmer average winter temperatures contributed to the observed decline of final heating needs. This also led to a general decline in energy poverty-related indicators over the past decades, despite demand growing sharply in 2021 and 2022 due to the unfolding energy crisis (EEA, 2024e).

Efficiency improvements and electrification – the fastest way to phase out fossil fuels in heating by 2030

Meeting the 2030 climate and energy targets will require a fundamental shift in the energy mix for heating in both buildings and industry (see Figure 3.13). Two simultaneous strategies are essential for this transition: to increase energy efficiency to reduce heat demand in buildings and industry; and to promote electrification to reduce the reliance on fossil fuels. Electrification comes usually with additional efficiency gains from the high efficiency of heat pumps and upstream renewable electricity sources, from process restructuring and higher flexibility and from better control of electric heating technologies in industrial branches (EEA, 2023c). Yet, electrification must be complemented by coherent policy packages to improve demand side response, strengthen transmission and distribution grids and improve storage potentials across the heating and the electricity subsystems ([44]). Additionally, policymakers must consider setting the foundation for joint European solutions that will become important mainly for larger industrial sites after 2030, such as hydrogen infrastructure and carbon capture, utilisation and storage (CCUS).

Continued efforts to enhance energy efficiency will be crucial. Compared with 2022, overall heat demand should be reduced by 23% in 2030 and by 47% in 2050, according to recent EC decarbonisation scenarios (EC, 2024h). Over two-thirds of the total heat demand reduction would come from the building sector, with reductions in the order of 39% by 2030 and around 53% by 2050, compared to 2022. Public buildings are urged to provide an exemplary role regarding energy efficiency improvements to achieve a 1.9% annual reduction in energy consumption by 2030 as a whole. All public bodies are required to renovate 3% of the total floor area of their public buildings per year to meet higher energy performance standards (EU, 2023a). Energy retrofits that respect circular economy principles can minimise the climate impact of associated material sourcing (EEA, 2024a).

In contrast to buildings, industrial heat consumption is expected to remain relatively stable until 2030, before declining by 36% to 2050, compared to 2022 levels.

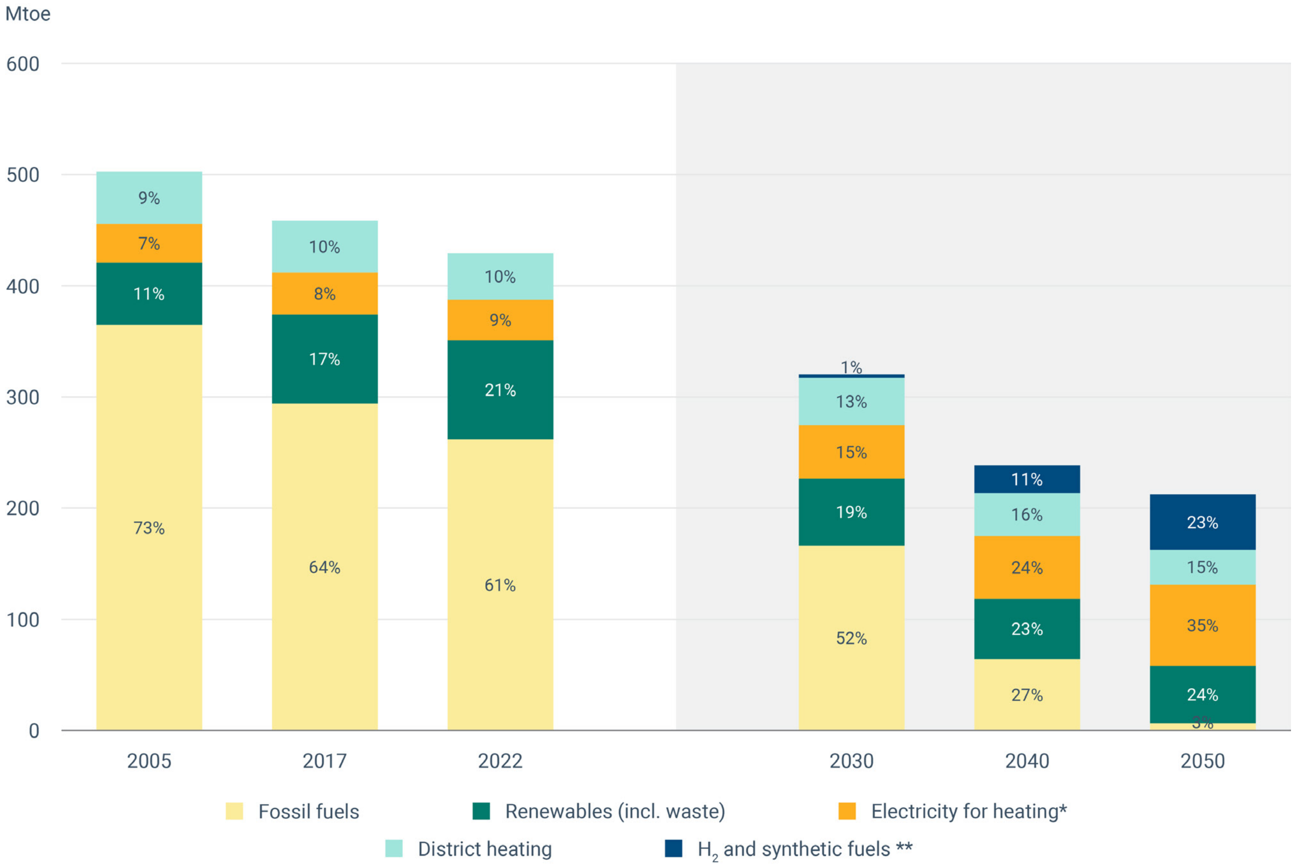
The electrification of heating needs - switching from heating to the electricity subsystem - is projected to increase significantly by 2030 and will be critical for reducing gas and other fossil fuel use. This presents substantial opportunities to replace outdated fossil fuel heating technologies in buildings and industry. Heat pumps could raise the share of electric heating from 9% in 2022 to 15% by 2030

([44]) This could include information campaigns, tools providing more granular consumption signals and flexibility-rewarding price structures addressing user behaviours and mitigating social impacts. These are expected to reduce imbalances between supply and demand in the system, for instance through bi-directional charging of electric vehicles that increases storage potentials, flexible operation of heat pumps and of industrial processes, along with the rapid growth of prosumers that produce and consume their own electricity.

and further to 35% by 2050, making electricity the dominant method for meeting thermal energy needs (EC, 2024h). This additional electricity use also leads to efficiency gains (heat pumps are three to five times more efficient than fossil fuel boilers (IEA, 2023a)) and would be more than offset by the reduction in gas needs. Overall, this would result in a massive drop of final energy demand and GHG and other air pollutant emissions, along with likely financial gains for households by 2030 (see e.g. 'Electrification: a pathway to greater energy system efficiency').

According to the target-reaching EC scenarios, in 2030, the heating mix in buildings and industry would still be dominated by fossil fuels (see Figure 3.13). Yet by mid-century, fossil fuel use must decline by 98% in the mix, compared with 2022, to meet EU climate targets (EC, 2024h). Heating demand and fossil fuel use for heating must also decline between 2030 and 2050. Hydrogen and synthetic fuels should enter the heating mix, reaching a share of 23% by 2050. In addition, the share of district heating would slightly increase (from 13% to 15%) and the share of biomass would grow from 19% to 24%, though in absolute terms these sources would remain relatively stable.

Figure 3.13 **Combined final energy consumption for heating of buildings and industry (estimated values for electricity) and forward outlook**



Notes: This figure shows the energy mix for meeting thermal needs in buildings and industry. It illustrates the gradual switch from the heating subsystem to the electricity subsystem, via electrification.

* Electricity only for water, space and process heating purposes; electricity for other purposes is not included. The calculation is based on historical average values for residential sector (around 9% of total electricity consumption) (Eurostat, 2024b) and for industry (around 5% of total electricity consumption considering process heat and other heating) (Fraunhofer ISI, 2024) and based on EC (2024h) for 2030-2050. This is under the assumption that electricity demand in buildings and industry increases due to electrification of heating and processes ([45]). Electricity for heating includes e.g. electric boilers and heat pumps. Besides heating, a high share of electricity was used for appliances and mechanical energy. Some chemical feedstocks are also produced using fossil fuels, though this is not considered here, as that is outside the direct scope of the energy system.
** Hydrogen and synthetic fuels will mainly be used for industrial process heating.

Source: EEA, based on data from Eurostat, 2024a and EC, 2024h.

([45]) A differentiation of past electricity demand for heating and other purposes is not available from statistics for industry and commercial buildings, but is for households. In the past, the overall share of electricity used for heating was around 5% in industry and around 27% in buildings, according to the EC impact assessment (EC, 2023e). This impact assessment outlines future electricity demand also only as a total so that it remains unclear how much of the electricity is projected to be going to processes, electric appliances or is used for heating. However, the impact assessment finds that electricity consumption must increase 'due to an increased uptake of heat pumps' and that 'industry, agriculture and services show a similar picture' in this regard (Part 3, Section 1.2.2.).

Box 3.2

Heat demand in industry

Industrial heat demand is often split into three categories: low temperature demand of up to 100°C, medium temperature demand between 100 and 400°C and high temperature demand above 400°C (see Figure 3.14). Around 56% of industrial heat demand occurs in high temperature applications in the iron and steel, non-metallic minerals and chemicals sectors. For iron and steel production (aside from primary steel production), high temperatures are needed for secondary production and metal processing, such as iron casting, forging and rolling. Processing of non-metallic minerals, in addition to the production of cement clinker and lime, includes production of glass and ceramics. The third largest high temperature heat demand comes from the production of basic chemicals including ammonia for e.g., fertiliser production, ethylene for plastics and hydrogen production via steam methane reforming.

Medium and low temperature demand accounts for 44% of all industrial heat demand. This demand mainly stems from the production of chemicals. Temperature levels depend on the individual chemical reaction and are typically supplied by steam in highly integrated plants or chemical parks. The paper industry demands process heat mainly at medium temperatures, though also at low temperatures for some purposes such as drying. The production of food and beverages also requires heat at different temperatures, for example in sugar production, the processing of milk, backing and meat production. The remaining 10% — mostly low temperature demand — comes from machinery, transport equipment and textiles (here included under 'other sectors') (JRC, 2012).

Heat at temperatures below 100°C can typically be electrified by using heat pumps. Heat pump technology has also been developed for temperatures above 100°C and, increasingly so, up to 200°C or more. For higher temperatures and more specific processes, other electrification technologies such as infrared, microwaves, induction and electric arc are needed. Some of these technologies are still early in their development.

Figure 3.14 Heat demand by industry and temperature level

Source: EEA, *adapted after JRC* (2012).

3.2.2 Challenges and drivers to decarbonise the heating subsystem

Decarbonising the heating subsystem will be a key test for the EU. Slow historical progress, both in efficiency improvements and electrification, suggests that more efforts are required to remove obstacles across this subsystem and to facilitate solutions from the electricity subsystem, such as heat pumps. While technical solutions to accelerate the transformation of the heating subsystem are available, buildings and industry face unique barriers in transitioning away from fossil fuels.

Pathways to clean and efficient heating in buildings

In buildings, the two main challenges are the slow pace of energy efficiency renovations and the prevalence of fossil fuel heating systems. Currently, only 1% of EU buildings undergo energy renovations each year, with deep energy renovations that deliver highest savings occurring at much lower rate (at 0.2% per year (EC et al., 2019; BPIE, 2021, 2022). The significant reliance on fossil fuels for heating poses the other major barrier. Renewable energy sources have progressed too slowly to reduce this reliance significantly. However, a substantial shift towards electrification — combined with greater integration of renewable and waste heat sources — could help to overcome in the short term some of the limitations of using energy efficiency measures alone (EEA, 2023d).

Improving insulation and building design to mitigate heating and cooling needs, in combination with the installation of heat pump systems, can substitute the demand for fossil fuel-based heating systems in most buildings. This would keep heat pump-related electricity needs at moderate levels. To accelerate the sustainable upgrade of national building stocks and learn to combine better these two strategies, a more rapid and effective knowledge-sharing of good practices across researchers, industry, policymakers and national funding agencies is essential (EEA, 2024a; Barbhuiya et al., 2024).

Policymakers should explore effective subsidy programs and innovative financial schemes, such as 'on-bill systems', de-risking private lending and green loans. Stricter policy implementation would also help (BEUC, 2022). Overall, the annual renovation rate should double and deep renovations should increase fifteenfold by 2030 (i.e. to 3% per year – a level that must be sustained through to 2050) to meet the 2030 EU climate goals and achieve climate neutrality by 2050 (EC, 2024h; BPIE, 2021; EEA, 2024e).

An important task for policymakers is to evaluate the performance and durability of (deep) renovations, to understand how certain retrofits ensure lasting energy savings and more flexible energy demand (Barbhuiya et al., 2024). Efficiency measures alone cannot reduce sufficiently the large amount of fossil fuels used to heat buildings. To speed the integration of renewables in buildings, affordable products that allow a flexible, resilient electrification of heating needs must be scaled up ([46]). The importance of near-zero energy buildings, passive or even energy-positive buildings needs also to be clearly highlighted to consumers (EC, 2024h; BPIE, 2021; EEA, 2024e). Beyond these approaches and the steer from economic policies, information campaigns, education and awareness raising actions are emerging as necessary and effective behavioural measures.

([46]) For instance heat pumps, but also rooftop solar PV modules, energy storage and smart energy management solutions.

Pathways to clean and efficient heating in industry

In industry, the broad variety and diverse temperature requirements of processes across subsectors suggests that tailored decarbonisation pathways are necessary. This includes electrification, CCUS and hydrogen (see Figure 3.13).

The largest emitters within the energy intensive industry sectors of six European countries ([47]) have not yet demonstrated adequate alignment with national and EU decarbonisation policies, while few actual commitments for investment have been taken (Hansen et al., 2024). To be successful, national strategies must be tailored to the needs of industrial subsectors. Some will require multiple decarbonisation solutions, others will have few (Hansen et al., 2024). Despite this complexity, industry electrification emerges as the most feasible short-term strategy for all subsectors. It must increase rapidly by 2030. A summary of key measures to reduce industrial GHG emissions is shown in Annex 2.

Efficient heat pumps can already replace gas in low- to medium temperature heat and steam applications (up to 165°C) ([48]). With technology improvements already underway, output temperatures from heat pumps will increase to 200-300°C by 2035 (MIT, 2024; Xie et al., 2024). For higher temperatures (up to 2,500°C), technologies such as resistance heating, induction heating and electric steam crackers are expected to become viable by 2035. Roughly 90% of the EU industry's current demand for fossil fuels for thermal purposes could be electrified by 2035, which clarifies the importance to decarbonise the electricity subsystem and to accelerate electrification (Fraunhofer ISI, 2024).

In spite of this significant potential, industrial electrification has been stagnant over the past decade. This suggests non-technical obstacles are hampering the diffusion of electric solutions in industry. These could include actual or perceived high capital expenditure (CAPEX) and/or operating expenses (OPEX) of converting to electricity-based heating systems); uncertainty about political priorities and future price developments; and other challenges, such as the significant changes to existing processes when switching from flame- to electricity-based technologies or finding suitable space for new infrastructure on site ([49]). Technical solutions for electrification or the use of hydrogen tend to be plant-specific and generally less advanced.

Some industrial processes also emit GHGs beyond the use of energy. In primary steel production, oxygen is removed from iron ore using coking coal as reduction agent in blast furnaces. Gas and hydrogen can also serve as reduction agents when direct reduction shafts are used. Consequently, switching to renewables-based hydrogen would enable near-zero emissions — primary in steel production — though this step would need an overhaul of primary steel production processes.

The calcination process to create cement and lime also emits CO_2. Switching fuels can reduce energy-based emissions, but avoiding process emissions entirely would require CCUS technologies. However, innovative cement chemistries, such as magnesia-based cement, calcinated clays and alkali/geopolymer binders, offer new pathways to decarbonise or complement traditional cement production (Barbhuiya et al., 2024). For the production of basic chemicals that require carbon and hydrogen as feedstock (e.g. ethylene), fossil carbon can be

([47]) Denmark, Germany, The Netherlands, Norway, Sweden and the United Kingdom.
([48]) This would include, for instance, a large variety of low-temperature chemical processes, plastics, pulp and paper, food processing, drying textiles and shaping metal for parts for vehicles.
([49]) Furnaces, for example, are highly integrated in the specific production process.

replaced with non-fossil carbon from biomass or captured atmospheric CO_2 (Lopez et al., 2023; Rosental et al., 2020). Carbon from chemical recycling could be another source, though it is still fossil based.

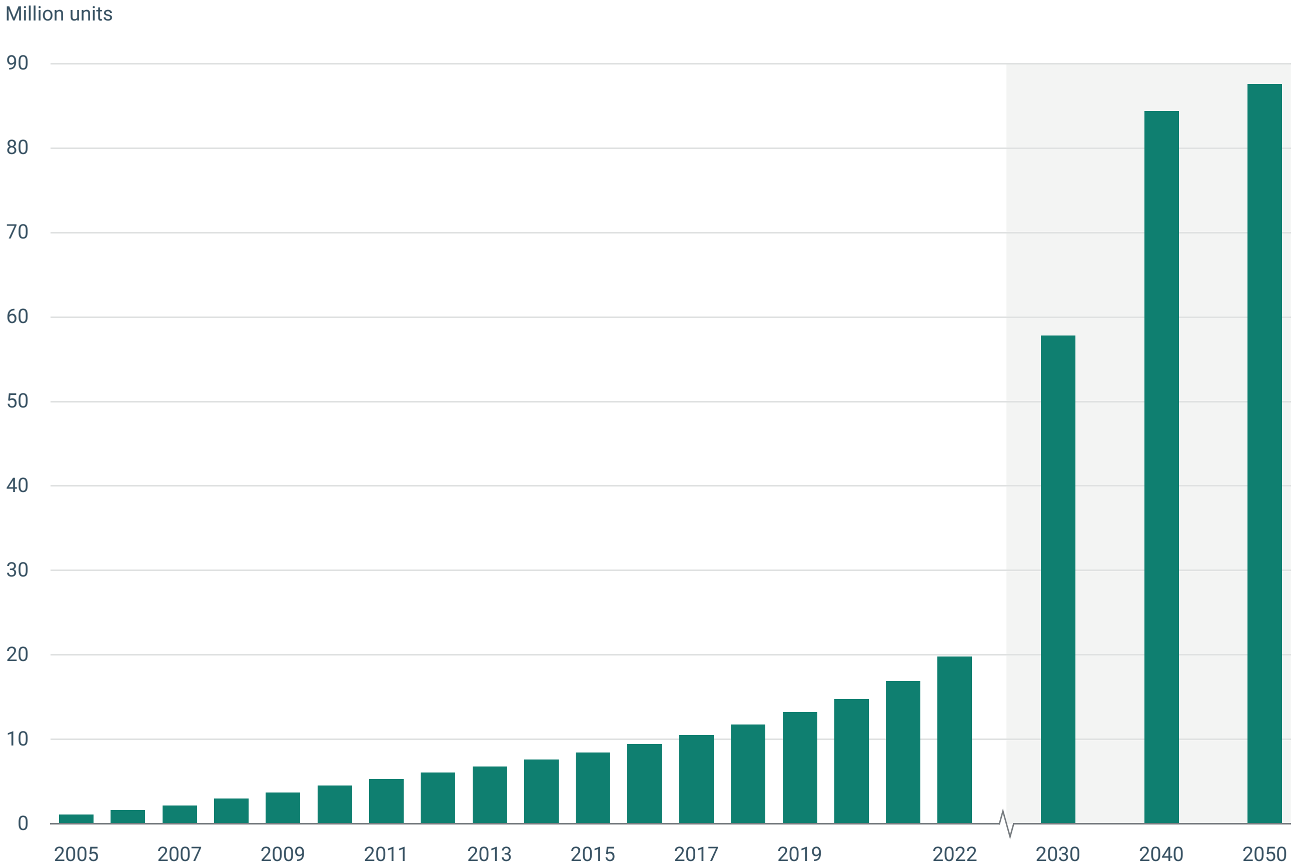
Heat pumps: a solution to accelerate energy-efficient heating and electrification

With electrification, heat pumps will play a key role in any measures to decarbonise buildings and industry heating and cooling needs. Expanding their use is crucial to accelerate the transformation of the heating and electricity subsystems. By transferring thermal energy (both heat and cold) from the environment at an efficiency of 300% to 500% ([50]), modern heat pumps by far surpass the efficiency of traditional heating systems. Not only do they improve the overall efficiency of heating, they also help a growing share of VRE supply to substitute fossil fuels combustion for heating and they unlock demand flexibility (Johra, 2022; Nyers and Nyers, 2023). Nordic European countries are currently leading in per capita adoption of heat pumps, revealing that these technologies work efficiently in relatively colder climates too (Rosenow et al., 2022). While the efficiency gains of heat pumps can drop considerably during extreme cold spells, these time-limited impacts can be mitigated by boosting the thermal efficiency of buildings and (in some cases) retaining or installing backup heating systems (Rosenow et al., 2022; Rob et al., 2024). Ongoing innovations promise to fast-track the development of heat pump systems for use in very cold climates (IEA, 2024d).

Across the EU, the number of electric heat pumps has increased more than seventeenfold since 2005, from 1.1 million units to 19.8 by 2022 (see Figure 3.15). According to EEA estimates, this growth has reduced the consumption of gas and oil in heating by 75Mtoe and 37Mtoe, respectively, by 2023. The co-benefits of this included strong reductions in associated GHG and air pollutant emissions across heating systems, according to EEA estimates (-82MtCO_2, -260 kilotonnes (Kt) sulphur dioxide (SO_2), -194kt of particulate matter ($PM_{2,5}$, PM_{10}), -238Kt nitrogen oxides (NO_X) and -47Kt volatile organic compounds (VOCs) (EEA, 2023c).

([50]) The Coefficient of Performance (COP).

Figure 3.15 **Stock of heat pumps in buildings between 2005 and 2022 and outlook towards 2030, 2040 and 2050**



Source: EEA, based on data from EC, 2024h, Eurostat, 2024a and EHPA, 2023.

Despite this progress, current efforts fall short of delivering the optimal deployment target of 57.8 million units by 2030, as outlined in the EU Climate Target Plan for 2030 (EC, 2020c). Achieving this target would require an eightfold increase in the average annual rate of heat pump deployment.

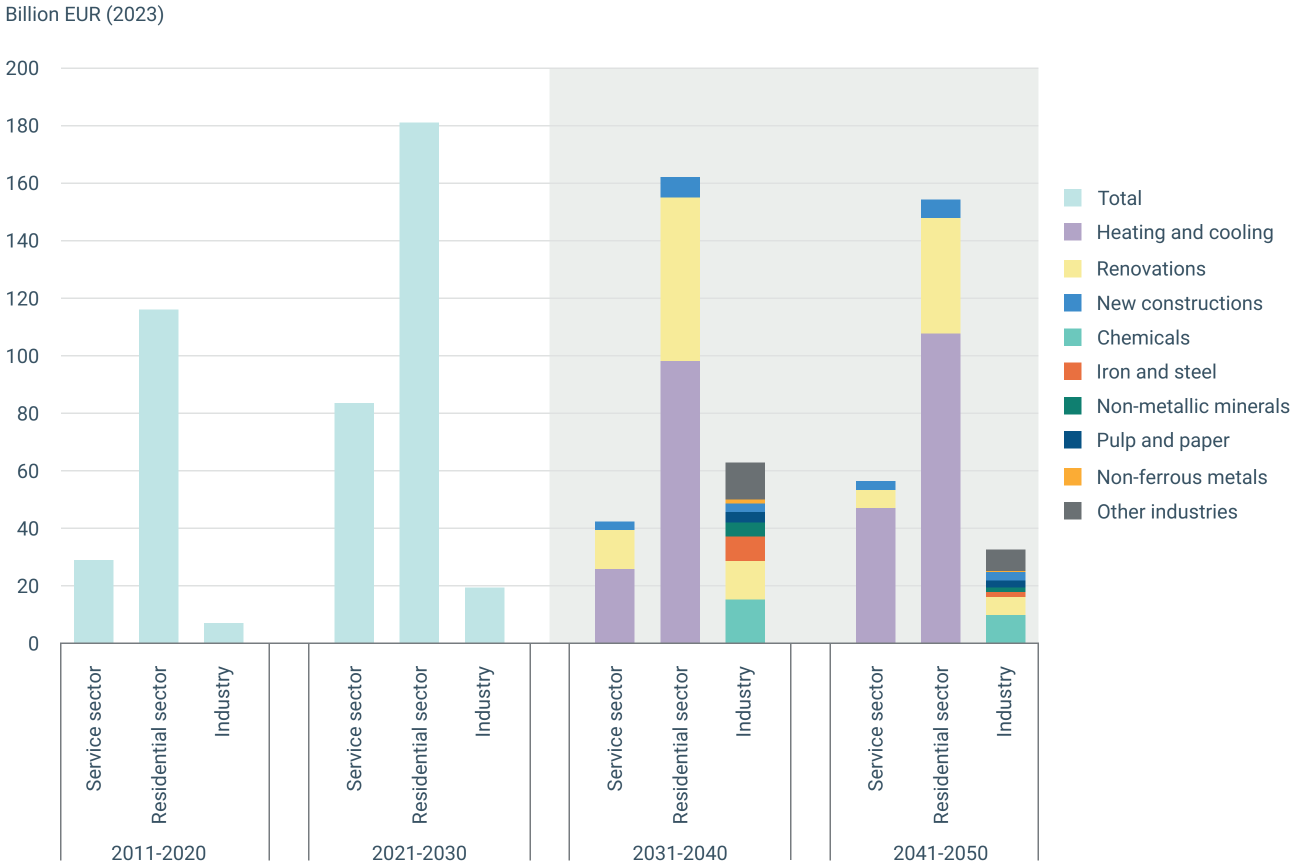
Substantial funding is key to drive electrification of heating needs and efficiency improvements

Electrification often requires considerable upfront investment, as do a switch to renewable energy sources and improvements to energy efficiency. Across the private sector, as in industry, investment cycles are somewhat faster and quick to respond to price signals, than in buildings owned by individual citizens, where different aspects may support or hinder the decision to invest (EEA, 2023a).

Annual investment needs for buildings are around EUR 265 billion, EUR 204 billion and EUR 211 billion (in 2023 prices) for the periods 2021-2030, 2031-2040 and 2041-2050, respectively (see Figure 3.16). This is significantly higher than historic investments (EUR 145 billion, for 2011-2020). The residential sector will require the most investment due to the larger size of the building stock and its lower efficiency and responsiveness in general, compared to the service sector. Most funding will need to be directed toward replacing existing heating and cooling systems with more climate-friendly alternatives. The investment needs in the service sector follow a similar distribution.

The technical lifetimes of industrial production plants are between 15 and 30 years and investments represent a strong commitment to a specific location. The EU's industrial production park is ageing, echoing low investments over the past few decades. The reasons underpinning this low investment include uncertainties about project costs, profitability and energy and infrastructure availability (such as access to renewable and waste heat networks, or hydrogen). This has resulted in significant reinvestment needs, which must now target net-zero compatible technologies to avoid locking in fossil fuel-based industrial heating systems (Agora, 2020). For the period 2021-2030, the expected annual investment need is around EUR 20 billion (measured in 2023 prices). This rises significantly thereafter to EUR 60 billion per year (see Figure 3.16).

Figure 3.16 **Annual investment needs for heating systems in the service sector, residential sector and industry between 2011-2020, 2021-2030, 2031-2040 and 2041-2050**



Notes: 2022-2030 data calculated for EUR 2023 from EUR 2019 data using baseline (2011-2020) data.

Source: EEA, based on data from EC, 2020c, 2024h.

Obstacles to scaling up clean heating and efficiency improvements

Decarbonising heating across both buildings and industry faces overlapping economic, social and technical challenges. To make solutions actionable, they must be tailored to specific local contexts (EEA, 2023d). Key concerns include economic factors, especially the perceived financial risk associated with long-term profitability of investments in energy efficiency retrofits and heating system replacements. High upfront costs — such as capital expenditure (CAPEX) in industry or bank loans for homeowners — combined with operational costs, can render such options less attractive today in many circumstances than continuing with the use of fossil fuels, such as gas in buildings and in energy-intensive industry branches. This is often compounded by an aversion to taking on debt and the complexity of managing organisational and technical challenges.

Many European municipalities are currently planning to transform their heating infrastructure for buildings. By renovating the building stock — in combination with the deployment of low to middle temperature district heating (25-50°C) from combined heat and power (CHP) plants — previously unused waste heat sources can be used in the medium term. This includes also thermal energy from industrial or service sector processes, deep geothermal sources or heat pumps. For instance, temperature differences in sewage and seawater can be extracted in modern district heating and cooling networks. Moreover, large heat pumps paired with low temperature heating needs can achieve higher performance values, offering significant energy saving potentials for buildings. When operated flexibly, they also facilitate the integration of VRE sources. This lowers the demand for fossil fuel use in CHP plants, reducing thereby GHG emissions (Mathiesen et al., 2023).

The transformation of local infrastructure can also create uncertainty for households about their future access to district heating or gas networks. This can delay decision-making about investing in decarbonising solutions. Familiarity with current technologies and recommendations from installers and contractors play an important role in this regard. Most consumers ([51]) stick with the same heating technology they previously used, which underscores the need to train installers and motivate homeowners to switch from inefficient fossil gas boilers to more efficient homes equipped with renewable energy systems (HARP, 2021). Next to the information gaps about the financial benefits of replacing heating systems and implementing energy efficiency renovations, administrative complexities and challenges in accessing financial support often deter investment further.

Knowledge of the clear economic and technological benefits, a personal commitment to energy efficiency and peer influence within industry can all help drive people toward more sustainable solutions. Behaviourally-informed policy design can help decisionmakers better address the non-financial motivations behind homeowners' decisions to invest. This helps them to support different population groups — including vulnerable households — with tailored solutions. Comprehensive data collection and insights into behavioural factors remain therefore essential for improving policy effectiveness (for more detail see EEA, 2023a).

In residential buildings, ensuring that the needs of vulnerable households are understood and met is critical throughout the energy system transformation. Low-income families may lack the financial resources to afford energy-efficient upgrades and heating system replacements. If unattended, these economic

([51]) According to the EU-funded HARP project, almost three quarters of the assessed consumers in France, Germany, Italy, Portugal and Spain make their decision this way.

barriers can perpetuate energy poverty and widen the gap between the affluent and marginalised. Economic instruments that recycle and redistribute taxes and carbon price revenues, combined with information campaigns to raise awareness about the broader health, environmental and socio-economic benefits of heat decarbonisation, can significantly improve the living conditions of vulnerable households and support their efforts to decarbonise (Emmerling et al., 2024).

The specific effects of these policies vary depending on existing factors. These include age, income, a rural or urban location, employment circumstances and (to a lesser extent) gender and household size and composition. Certain households face multiple disadvantages and may be particularly vulnerable to cost effects of climate policies, while others may benefit (EEA and Eurofound, 2021). The EU SCF was set up to help vulnerable groups at risk of energy poverty to contribute to the societal transformation (EC, 2024l).

Industrial production plants require regular reinvestment cycles due to their typical 15-to-30-year lifespans. Many conventional plants in energy-intensive industries will reach the end of their technical lifetime by 2030 (Agora, 2020). While this suggests high investment is required, it presents an opportunity to transform energy-intensive industries and invest in decarbonised production methods. By driving innovation and securing investments in decarbonised solutions, these industries can start to prepare now to maintain and improve their competitive edge for the medium to long-term.

In certain industries, OPEX can be more critical for decarbonisation than CAPEX. This includes integrated high-temperature processes that require biogas, hydrogen, e-fuels or the deployment of CCUS technologies. So in a broader context of industrial heat decarbonisation, investment needs may shift from plant-specific costs to the demands of overarching energy supply and infrastructure, especially for energy-intensive industries that will require large quantities of clean electricity, hydrogen and CO_2 transport infrastructure beyond 2030 (see Figure 2.11).

One example of the challenges faced by industrial investments is the European CO_2 transport network to support CCUS technologies. The system will need to handle 50MtCO_2 by 2030 and 250Mt by 2050, at an estimated cost of EUR 9.3 to 23.1 billion (EC, 2024k). For that, up to 19,000km of pipelines, shipping routes and other infrastructure will be needed by 2050. The rapid construction of such critical infrastructure introduces high investment uncertainties for businesses that dependent on its success. While financial support during the development phase can help, policy coordination across borders is critical to ensure the integration of demand, supply and infrastructure roll-out — such as in the planning of the European Hydrogen Backbone (EHB) initiative. Fiscal decisions — how governments plan, structure and repay their spending over time — are also key. These must be carefully planned and executed to allow the finance of larger upfront infrastructure investments without triggering immediate fiscal strain (ETC CE, 2024). In order to be effective and ensure intergenerational equity, these strategies should consider not only how to finance initial infrastructure developments, but how to ensure costs are spread over longer time frames to avoid excessive impacts on the initial users (ETC CE, 2024).

Box 3.3

Overcoming challenges to industrial decarbonisation in Europe

A multifaceted approach is needed to accelerate the EU clean industrial transformation. Yet there are also common challenges and solutions:

Securing a clear CO_2 price signal under the EU ETS1 and supporting it with additional financing tools, where needed

- Industrial investment decisions require stable and predictable CO_2 price rises for the long term, with allowance prices reflecting necessary investment levels. Without such signals, carbon pricing may induce only marginal emission reductions (Nilsson et al., 2021). Upholding clarity and underlying ambitions is therefore key to ensure consistency and long-term security for investments.

- Different sectors are at different stages of maturity regarding alternative production pathways (see also Annex 2). This development timeline may not align sufficiently with the functioning of the EU ETS1, which tends to incentivise the cheapest decarbonisation measures first. To overcome this asymmetry, additional financing mechanisms — such as the EU Innovation Fund, the future EU Industrial Decarbonisation Bank (as announced in the Clean Industrial Deal (EC, 2025b)) and other possible measures, such as industrial Carbon Contracts for Difference (CCfDs) — may be necessary to foster innovation and deploy low-carbon technologies across all industrial sectors.

Ensuring affordable clean energy

- Clean industry technologies require non-fossil energy carriers, such as renewable electricity, biogas as well as hydrogen or synthetic fuels. Uncertainty about the development of these alternative energy carriers, especially about the cost of electricity, increases the aversion to invest in clean industrial technologies. Next to power purchase agreements (PPAs), supportive instruments include also public debt management strategies to spread the cost over longer time frames. This lowers short-term burdens on initial users and ensures intergenerational equity, as future infrastructure users and taxpayers benefitting from today's investments bear a fair part of the costs (ETC CE, 2024).

- Further incentives will be needed to match the growing variability between solar and wind supply and currently inflexible industrial loads. The operation of the grids must be improved, including to pass short-term pricing signals, for this purpose.

- Beyond developing the EU electricity grid, the European backbones for hydrogen and CO_2 grid infrastructure ought to be agreed. This will create a clear EU-wide vision of where the first electrolysers could be installed (e.g. in regions with high clean electricity and water potentials), as well as of the realistic costs to transport hydrogen and CO_2 to key demand and storage sites.

- The regulatory framework for hydrogen should be clarified in the near term, even though the hydrogen market is expected to take off more slowly. This could improve the EU Hydrogen Bank's approach to incentivising production.

Levelling the international playing field with CBAM

- To prevent carbon leakage and encourage global decarbonisation, the EU is gradually introducing the Carbon Border Adjustment Mechanism (CBAM) in conjunction with the EU ETS1. EU producers may face higher export prices in international markets, which would require further scrutiny to safeguard competitiveness.

- International climate clubs with harmonised carbon pricing and shared trade rules, along with green product standards, can help level the playing field and balance the cost of industrial decarbonisation.

- 'Green leakage' refers to the relocation of energy-intensive production, such as ammonia, methanol and steel making, to regions with cheaper, more abundant renewable energy supply. Reducing EU energy and electricity costs, market fragmentation and uncertainty regarding long-term investments is key. Improving the rates of R&D and innovation, especially in AI, robotics and ICT, will help to raise industrial productivity further.

Closing the investment gap

- While mobilising private capital is essential and finance is widely available, investing savings into stocks and venture capital is less common across the EU, compared with other world economies. This represents an obstacle for closing the green investment gap.

- Some public funding could be deployed more efficiently through harmonised and simplified subsidy allocation mechanisms across the EU. For instance, this could concern expanding the EU Hydrogen's Bank's auctions-as-a-service model, along with more competitive, predictable auction rounds.

The decision to invest in clean industrial technologies is primarily driven by the final prices of energy carriers (including grid fees, taxes and CO_2 prices) and the efficiency of the new production methods. Policymakers can dispel investment uncertainties by improving the gas-to-electricity price ratio in the short run and providing stable policy frameworks for the longer term. At the EU level, carbon pricing mechanisms and their associated, broader frameworks to safeguard the global competitiveness of EU industry (see Section 3.3.3) will remain the primary drivers of this evolution. However, additional EU and/or national measures could be helpful to support a swifter electrification. For instance, Member States could adjust tax rates for consumers that use electricity in conjunction with particular technologies to decarbonise heating or transport (see also Chapter 3.3) (EC, 2025j).

At present, the expansion of energy infrastructure — including for hydrogen and CO_2 networks — is financed by grid fees, state subsidies and also the Important Projects of Common European Interest (IPCEIs) (EC, 2024a; IPCEI, 2023). While most industrial investment must come from the private sector, stronger initial public financial support could be needed, for instance for key cross-border infrastructure networks.

To boost the competitiveness and decarbonisation of energy-intensive industries in the EU — and address the challenges outlined in Box 3.2 — the EC adopted the Communication on the Clean Industrial Deal (EC, 2025b) in 2025. This initiative seeks to move beyond traditional siloed approaches, to take a comprehensive, value chain approach to support EU industry.

Leveraging demand side flexibility for a more cost-effective and secure energy system transition

Leveraging flexibility across the energy system — including supply, demand and storage chains for electricity and heating — is essential to reduce overall energy system costs as electrification is rolled out to more and more end-uses. By easing pressure on the grid and lowering the need for backup generation, demand side flexibility ensures a more efficient and resilient energy system. Today however, industrial facilities and buildings remain largely underused in this regard.

A harmonised approach is necessary to connect and aggregate flexible loads from industry, heat pumps and storages while ensuring grid stability; and there is ample room for the Member States to tackle regulatory barriers and restrictions in the design of their electricity markets and system operation services (ACER, 2023). These obstacles are in the way of a more flexible and system-integrated operation of technologies and the roll-out of smart meters, grid automation equipment and energy management systems. Ultimately, this prevents sufficient information and price stimulation from reaching consumers (Agora, 2021, 2022).

In buildings, home heating will be one of the largest sources of demand flexibility by 2030, followed by smart charging of BEVs (see also Chapter 3.3) (RAP, 2024). Although this flexibility is dispersed across many buildings, a coordinated approach is needed to unlock the full potential and enable broad participation in demand response (EC, 2021f). Flexibility in hot water systems, for example, varies significantly (up to fourfold) based on occupant behaviour and smart controls. In certain cases, intelligent systems can boost flexibility by up to 25% or even more (Balint and Kazmi, 2019; NIST, 2021). In a recent study in southern Sweden, flexible heat pump systems installed in one million single-family homes reduced net electricity demand by 4-7 gigawatt-hours (GWh), with an immediate power decrease potential of 1.6GW estimated at an outdoor temperature of -5°C — equivalent to 7% of the country's plannable power (Nalini Ramakrishna et al., 2024). Flexible heat pump systems also offer economic benefits for most users, with annual profits in Germany varying from EUR 17-85 for single-family homes to EUR 123-692 for larger multi-family residences (Marijanovic et al., 2022).

Demand-side flexibility in industry can be facilitated through thermal storage (power-to-heat), heat pumps and electric boilers. These technologies can generate, store and release process heat and modify production rates and electricity grid-usage in response to market signals (Fraunhofer ISI, 2024). Such flexibility helps industry reduce operational costs and participate actively in electricity markets, shifting consumption away from expensive peak hours (Kögel et al., 2024; Hasanbeigi et al., 2024). Energy-intensive branches such as primary steel making, base chemicals or metals often require constant high-temperature heat, limiting their flexibility. Yet hybrid systems that combine heat pumps and electric boilers with fossil fuel backup plants, or integrate them with heat storage systems, or opt for new technologies (such as direct reduction in iron and steel making) can offer temporary flexibility and strategic benefits for decarbonisation (Agora, 2022; Kögel et al., 2024).

One major barrier to expanding industrial flexibility is the predominant grid charge structure that favours high, constant electricity use rather than flexible consumption. Grid fees are partially based on peak demand and promote continuous operation. By contrast, adjusting grid charges to reflect time-of-use and incentivising the coordinated ramp-up of heat pumps and electric boilers could largely address this issue (Agora, 2022).

Applying circular economy to enhance building decarbonisation

Decarbonising buildings over their life cycle requires also broader efforts to improve resource efficiency and use sustainable materials. The construction phase usually accounts for around 20-25% of the total GHG emissions of a building's life cycle, including the emissions from industrial processes. Material choices are therefore important (EEA, 2023b; ADEME, 2025). Renovation is more sustainable than new constructions, requiring up to 80 times fewer materials to achieve comparable outcomes. It significantly lowers embodied carbon emissions from the production of building materials, such as cement, steel, bricks, tiles and plastic-based construction materials. Using recycled or low-carbon materials, such as reclaimed wood, recycled metal or low-carbon concrete can further minimise environmental impacts (EEA, 2023b, 2024a).

Incorporating circular economy principles in building materials enhances sustainability and reduces waste. Reusing materials from demolished structures, prioritising durable and locally sourced products and designing buildings for easy disassembly all lead to a lower demand of primary materials upstream, from industry. Innovative materials, such as bio-based insulation and carbon-storing wood products, provide further opportunities for reducing embodied carbon. By focusing on material efficiency and responsible sourcing, the building sector can significantly cut life cycle GHG emissions across all value chains (EEA, 2023b; WorldGBC, 2019). Beyond these measures, maximising the efficient usage of buildings over time can systemically reduce GHG emissions and energy demand linked to the occupancy of buildings.

3.2.3 Existing policies

EU and national policy instruments to transform the heating subsystem

The Fit for 55 package is central to the goal of reducing GHG emissions by 55% by 2030, with key measures targeting buildings and industry. The EU has since implemented and revised a series of policy instruments to promote the decarbonisation of the buildings sector.

The EU ETS1 incentivises the cost-effective and technology-neutral reduction of GHG emissions by setting a steadily shrinking cap on total emissions from large industrial installations. These emissions typically belong to the electricity and the heating subsystems. Participants are free to trade allowances and implement appropriate solutions for to lower their emissions, such as improvements in energy and resource efficiency, conversions to cleaner energy sources, or change of industrial processes. The ETS2 will soon extend carbon pricing to buildings, road transport and additional sectors not covered by the current EU ETS1, by requiring fuel suppliers to purchase allowances for their GHG emissions. The aim is to stimulate investments in non-fossil energy technologies and building renovations. To avoid carbon leakage to regions with less stringent emission regulation, the current benchmarking system under the EU ETS1 will shift gradually to the EU's CBAM until 2034.

The Energy Efficiency Directive (EED) and Energy Performance of Buildings Directive (EPBD) set ambitious targets for reducing energy use and promoting building renovations. These policies guide Member States in stimulating private investment and define clear standards for energy performance. Recent updates have scaled back some original ambitions however, particularly for zero-emission buildings (ZEB) and minimum energy performance standards (MEPS). In 2025, the Commission will introduce a delegated act designed to encourage financial institutions to boost funding for building renovations (EEA, 2023b).

The Renewable Energy Directive (EU/2023/2413) reinforces targets for heating and cooling (Article 23) as well as for district heating, incorporating measures like the utilisation of waste heat and cold and broader integration across the three main energy subsystems assessed in this report (EC, 2023c).

Member States are required to submit national energy and climate plans (NECPs), which serve as roadmaps for meeting targets by 2030 on emission reduction, renewable energy and energy efficiency. The plans must also define stable pathways towards climate neutrality by 2050 (long-term strategies; LTS) (EC, 2019). At the time of writing, most NECPs have been updated to align with new challenges and meet new EU-strategic targets under REPowerEU. Their full implementation would bring the EU much closer to meeting the joint climate and energy targets for 2030 (European Parliament and Council of the European Union, 2018; EC, 2019, 2022c, 2025f). Since 2014, EU countries have also developed long-term renovation strategies (LTRS) to decarbonise the building stock by 2050. These strategies now include National Building Renovation Plans, which are aligned with NECPs and must include national targets and financial frameworks (EU, 2018).

EU and national support mechanisms

The EU Modernisation Fund is funded by revenues from the EU ETS1 and is expected to mobilise EUR 48 billion by 2030 to accelerate the modernisation of energy systems across 13 lower-income EU countries ([52]). This includes renewable energy and energy efficiency investments, storages, energy networks and the reskilling of workers. With a budget of around EUR 40 billion (2020-2030), the EU Innovation Fund will finance more expensive, innovative decarbonisation technologies for which the EU ETS1 carbon price does not provide sufficient incentives (EC, 2025e). The planned Industrial Decarbonisation Bank will reinforce this funding, providing EUR 100 billion to decarbonise EU industry through innovative low-carbon technologies.

The IPCEI framework supports first-of-a-kind hydrogen projects across Member States, aiming to bridge the gap between national and EU level support. The newly established SCF aims to mitigate the regressive impacts of the ETS2 on vulnerable groups and support a socially fair transition. Funding for Member States is conditional on national plans that outline longer-term strategies and measures to prevent adverse effects on the most vulnerable groups in society, while rolling out decarbonisation (EC, 2024l). The SCF will be mainly funded via ETS2 revenues, with some co-financing from Member States. Recent studies emphasise the significant potential of national policies that redistribute revenues and taxes to reduce social inequality. These measures can help to mitigate the regressive impacts of climate mitigation and energy transition policies on vulnerable households (Emmerling et al., 2024).

At the national level, Member States are adopting various policy schemes that address the social risks, fairness and public acceptability of energy renovation. Many offer grants and subsidies for building renovations, energy efficiency improvements and renewables-based heating systems based on income level — or target specific buildings, such as social housing. Earmarking revenues from carbon pricing mechanisms enhances transparency and acceptability while reducing emissions. EEA and Eurofound, 2021 provides more information about successful national programs aimed at modernising buildings and improving energy efficiency in social housing.

Several Member States have introduced support programs to reduce emissions in industry. These programs aim to de-risk investments in clean technologies, often through CfDs that incentivise low-carbon energy production. Additional schemes to promote industrial emission reduction, investment in transformative technologies and to mitigate economic and infrastructure risks are currently under consideration by several EU countries.

National fuels and electricity taxes, though complex and varied, are crucial instruments for promoting fuel switching across the economy. While these taxes aim to offset the economic challenges of converting to clean heating sources, they

([52]) Beneficiary Member States are Bulgaria, Czechia, Estonia, Greece, Croatia, Latvia, Lithuania, Hungary, Poland, Portugal, Romania, Slovenia and Slovakia.

do not yet sufficiently encourage investments in clean technologies, such as heat pumps and electrification, in most countries. The broader climate, environment and health benefits of such conversions are, arguably, not enough to overcome the interlinked obstacles discussed above, to drive a faster decarbonisation of the EU heating subsystem.

3.2.4 Key actions and recommendations for the EU heating subsystem

About a third of gross available energy consumption can be attributed to the EU heating subsystem (see Figure 2.2). Accelerating the transition in this subsystem is likely to require national policy mixes which implement and complement the broader EU framework, meeting specific needs of households and industry — two fundamentally different economic sectors. Heat in the residential and service sectors is used primarily for space heating, while thermal energy in industry is mostly used in energy-intensive basic industries. Since most of this heat currently comes from fossil sources, renewables-based electricity presents a significant opportunity for change. Cross-cutting efforts to improve energy and resource efficiency must also be scaled up.

Technological solutions to reduce fossil energy consumption in the residential sector are relatively clear. A strong emphasis on energy-efficient renovation can drastically reduce heat demand. Prioritising the renovation of old building stocks and addressing the building envelope (outer shell) would not only lead to significantly improved energy efficiency, but also enhance living conditions and lower energy bills — often for vulnerable groups in society. The remaining heat demand should be met as much as possible with non-fossil sourced heat. Heat pumps display exceptional performance levels in well-insulated buildings. Their increased deployment and connection to a decarbonised electricity system are essential by 2030.

Similar approaches, such as using industrial heat pumps for low-temperature processes, electrification and a focus on overall energy and resource efficiency, can significantly reduce industrial demand for fossil fuels under the EU heating subsystem, even as electricity demand will go up. The industrial sector faces a major challenge to radically rethink production processes by incorporating new technologies, for example, in the steel and chemical sectors. This involves a shift toward innovative solutions that can reduce dependency on fossil fuels and align with sustainability goals.

In the short term, improving the gas-to-electricity price ratio and developing a skilled workforce are critical to overcome challenges and accelerate progress. Beyond 2030, reducing heat demand further will require an even more holistic approach. Expanding the lifespan of existing buildings, increasing the intensity of building use, increasing the circularity of building materials and industry processes, making full use of flexibility solutions, such as chemical and thermal storage, and building out the agreed pan-European foundation of critical industrial infrastructure (such as for hydrogen and CCUS) will enable a cost-effective transition.

The following measures can be considered necessary on Member State level:

Correcting price signals to foster the decarbonisation of the EU heating subsystem

Historic progress in reducing GHG emissions from heating is considered to be too slow overall. This progress has been partly attributed to stricter energy efficiency standards for new buildings, enhancements in the energy performance of existing buildings, efforts to switch heating systems to renewable energy sources, such as biomass and heat pumps, and milder winter temperatures due to climate change.

Aligning tax rates for energy carriers to promote electricity over fossil fuels is key to stimulating the decarbonisation of the EU heating subsystem (ECA, 2022; ECNO, 2024a). Fossil fuel subsidies, including the recent financial support introduced in 2021 in response to the energy crisis, should be phased-out as soon as possible. In 2023, fossil fuel subsidies across the EU accounted for 34% of total energy subsidies, significantly higher than those for renewable energy sources.

Targeted policies, such as tax incentives and subsidies, can address negative social impacts and ensure a fairer, more effective shift toward climate neutrality. The EU is still working to find a compromise on the Energy Taxation Directive. But Member States can already revise their own tax systems to eliminate exemptions and reduced tax rates for fossil fuels compared with renewables-based electricity, instead basing taxation on carbon intensity. This may also give an upward push for the EU to provide a common and aligned energy tax framework (EEA, 2023f; Baert, 2024).

The EU ETS1 remains the main economic instrument to incentivise emission reductions in industry at the EU level. It is technology agnostic and leaves the choice of decarbonisation strategies to the respective players in industry. However, planning security is essential for these actors to invest in new production technologies with long technical lifetimes. Whereas ETS1 cap reductions for the upcoming years have been communicated, some regulatory uncertainties remain. The inclusion of negative emissions and CCUS poses risks to certain projects, particularly in markets with few certificates.

The effective implementation of carbon leakage protection, through CBAM, is equally important to safeguard the competitiveness of EU exports. Policymakers should remain committed to developing an effective framework and maximising planning security.

Targeted incentives and innovative deployment strategies

Adequate and effective funding will steer the buildings sector towards an expansion of renewable heating systems and greater energy efficiency. There is a pressing need to refine financial strategies to maximise their impact and secure additional public funds. Policymakers must create more targeted and accessible incentives, while diversifying funding sources beyond EU allocations. Potential avenues for funding include green bonds, public-private partnerships, carbon pricing revenues, national investment banks, tax incentives, crowdfunding or reallocated fossil fuel subsidies (Xu, 2020).

Funds should be redirected toward renewable energy alternatives; grants and incentives for energy-efficient renovations prioritising low-income households; and investments in workforce training to support energy efficiency measures and clean heating systems. Subsidy schemes should focus on low-income and vulnerable households and businesses, to assure a just transition (ECNO, 2024b). Prioritising the renovation of the least efficient buildings, while making new ones climate-neutral, will maximise the impact of energy efficiency measures in the short term. Retrofitting buildings in the lowest energy efficiency class can also help fight social exclusion, considering the correlation between energy inefficient buildings and energy poverty (Streimikiene and Kyriakopoulos, 2023; Vurro et al., 2022; Mafalda Matos et al., 2022). While the SCF offers a new mechanism, further addressing the issue of a socially-just transition could equally guide the use of other EU funds to ensure an equitable transition to a greener EU economy.

Carbon pricing and infrastructure planning will enable investments in most clean technologies, while other few technologies will require more support. Green lead markets are an example of an instrument enabling a pull-effect that can enhance this transformation. While the cost of decarbonisation is relatively high on a basic industrial product level (such as for crude steel), it is considerably smaller on the final product level (e.g. a vehicle) (Agora, 2024). Green lead markets can be initiated through public procurement or through the introduction of mandatory quotas.

Some new technology still needs to be developed. Electrified high temperature heat generation and hydrogen applications are less advanced and are expected to remain more expensive in the short and medium term, despite increasing CO_2 prices. To overcome initial challenges, support schemes such as the EU Innovation Fund or national schemes (e.g. SDE++ in the Netherlands or CCfDs in Germany) could be used to target better the development of near-zero emission technologies, focusing on technologies that can be competitive in the long term.

For a fuel switch towards renewable electricity and hydrogen, industrial electricity demand must rise substantially by 2030, incorporating also opportunities for demand response and flexibility, to integrate renewables efficiently. While cost incentives stimulating flexibility in the electricity market do exist also in the short term, grid fees ought to be harmonised and adjusted to incentivise a more grid-friendly demand from final consumers. Most current grid fee structures are suited for baseload consumption, providing insufficient incentives to activate demand response. Stronger incentives for flexible electricity consumption, local energy storage, along with a grid-friendly operation of green hydrogen production and use in industry will enable a more efficient electrification of industrial heat demand.

The fuel switch towards electricity, hydrogen and CCUS also requires expanding or constructing the supporting infrastructure. By coordinating supply, demand and infrastructure planning domestically and across the borders, policy makers can support these efforts and set the base for a more efficient development and use of this key infrastructures. Whereas the cost of infrastructure should be covered by those using it, additional support could accelerate progress in the shorter term. Renewed measures seeking to addressing some of these challenges were recently included in the EC competitiveness compass (EC, 2025a).

Considering behaviour in addressing the non-financial barriers to investment in building renovation

Information and awareness raising are two main policy tools for addressing the non-financial barriers to investment. Tailored information support provided in a timely and targeted way can ease the decision-making process of concerned individuals or businesses, decrease uncertainty and make financial support more appealing. These strategies can ensure that policies are not only technically sound, but also socially accepted — with greater impacts. However, decisionmakers must be aware of main differences in consumers profiles, such as tenants, homeowners or persons living in multi-apartment buildings. Behavioural drivers may vary, including a consumer's motivations, values, intentions, needs and lifestyle.

Homeowners, for instance, are more likely to act on advice regarding energy efficiency renovations when it comes from trusted sources. Often, recommendations from personal connections, such as friends and family, exert a stronger impact on a homeowner's decisions than information from official sources such as public awareness campaigns. Additionally, peers, including neighbours and members of the homeowner's community, play a key role in shaping what is viewed as desirable investments and behaviour. Advice from professionals, such as installers and contractors, generally carries more weight only after the homeowner has already decided to proceed with certain renovations (EEA, 2023a). Thus, administrators and policy makers designing information and awareness campaigns, one-stop-shops and other support systems should pay attention to the individual profiles and behavioural dynamics to design more effective strategies.

More broadly, policymakers can also promote a more circular use of building materials with low embodied carbon content, to reduce life cycle GHG emissions from buildings; or also seek to encourage a more efficient use of the existing building stock, for instance through measures seeking to optimise room and hot water temperatures or to improve occupancy rates.

Ultimately, more comprehensive packages of measures could be needed to promote the clean transformation of the EU heating subsystem. Such packages should consider restrictions on the use of fossil fuel-based appliances in new buildings, setting minimum energy performance standards (MEPS) for existing buildings, introducing CO_2-based taxation of heating energy sources and developing robust frameworks to monitor and evaluate building performance (IEA, 2022; EEA, 2023d; ECNO, 2024b).

3.3 Supporting a more rapid transformation of the EU transport subsystem

3.3.1 Transport energy supply and demand

Factors shaping transport demand today

The transport and mobility subsystem is equally a key economic sector. Historically, fossil fuels such as oil and coal have dominated energy supply in transport. However, this subsystem has undergone several transformative episodes, such as the shift from coal to electricity in rail transport. Despite these shifts, fossil fuel-powered road vehicles, ships and aircraft have formed the backbone of global transport and mobility since the 20th century (Delbeke and Vis, 2019). The sector has driven significant economic growth, and climate change. The prevalence of fossil fuels across most transport modes ([53]) is due primarily to their high energy density and storage potential. A complex infrastructure now exists to support their consumption.

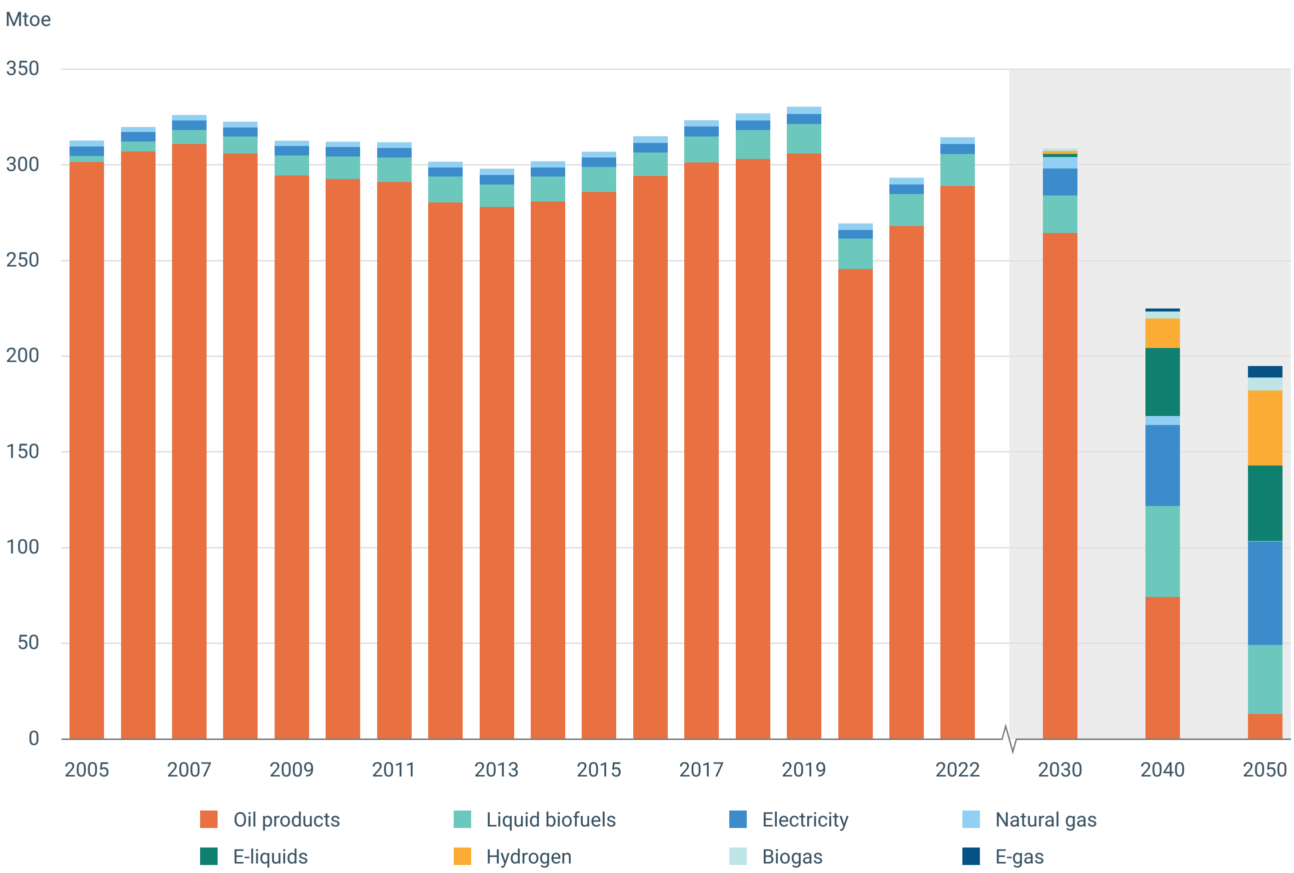
Road transport, aviation and shipping still largely rely on oil and its derivatives, making fossil fuels the primary energy source across all modes, as illustrated in Figure 3.17.

The decarbonisation of transport hinges on energy efficiency improvements, modal shifts to walking, cycling or public transport, and the widespread adoption of technologies such as BEVs, hydrogen fuel cells (primarily for long-distance transport and less so for passenger vehicles) and sustainable biofuels. Limiting GHG emissions from this subsystem to reach the 2030 and 2050 climate targets will require transport energy demand to fall and the fuel mix to shift away from fossil fuels towards clean electricity (EC, 2020a; see Figure 3.18).

According to the forward-looking benchmarks used in this report, oil products need to fall by 8.4% between 2022 and 2030 to meet these EU targets. Electricity must grow in parallel to compensate a third of the reduction of oil products. Liquid biofuels and natural gas, along with small contributions of biogas, e-liquids and hydrogen should deliver a third of the oil reduction. Oil products should decline by 96% by 2050, compared to 2022. This signifies a complete shift from oil products today to other energy carriers, mainly electricity, followed by e-liquids, hydrogen and liquid biofuels in 2050 (see Figure 3.17).

([53]) In 2022, fossil fuels accounted for a 93% share of the total energy supply to EU transport (Eurostat, 2024e).

Figure 3.17 Transport energy consumption per fuel type between 2005 and 2022 and outlook towards 2030, 2040 and 2050



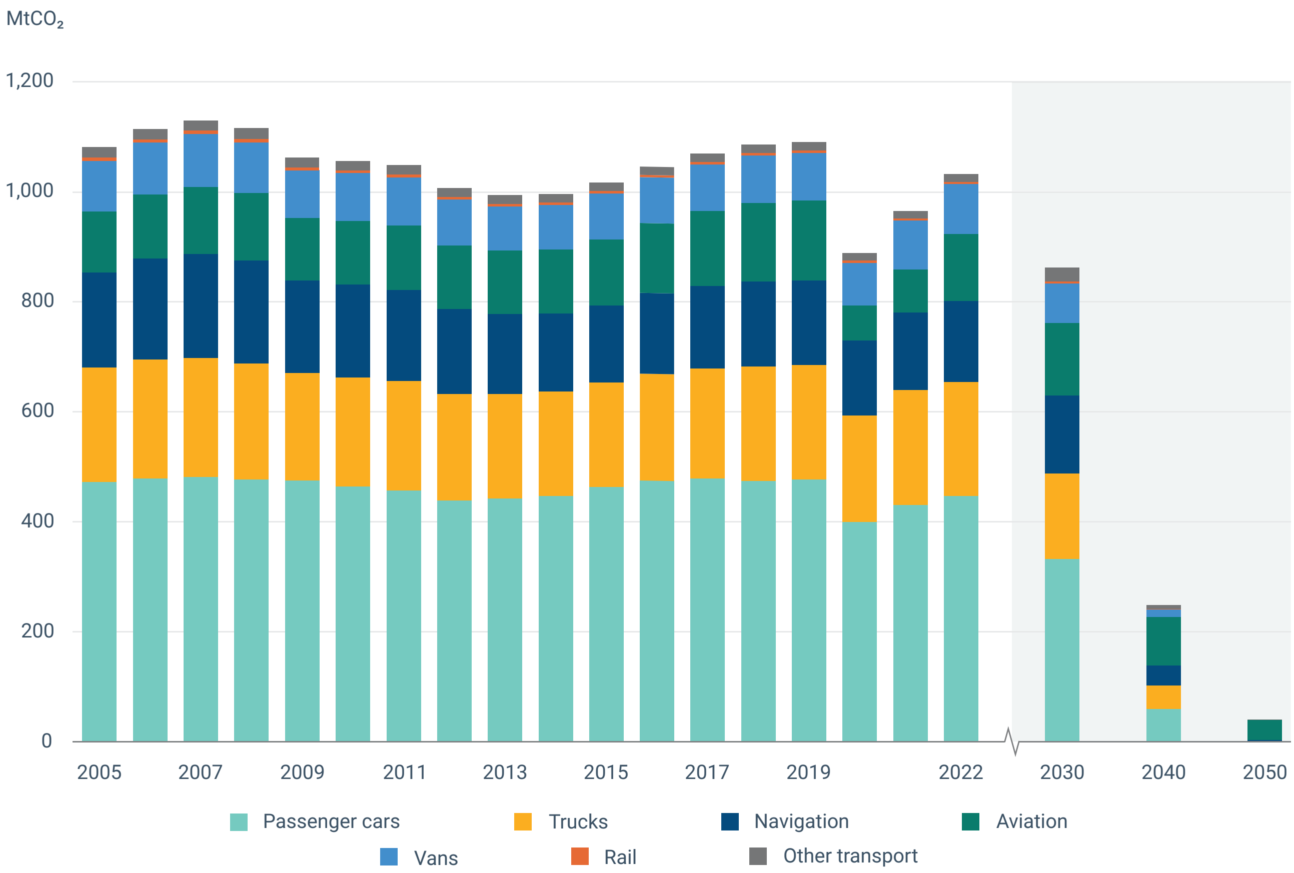
Note: This figure shows the energy mix for meeting demand in transport. It illustrates the gradual switch from the transport subsystem to the electricity subsystem, via electrification.

Source: EEA, based on data from Eurostat, 2024a and EC, 2024h.

Electrification and efficiency improvements — the fastest way to meet the EU climate and energy benchmarks by 2030 and reduce oil import dependency

The shift to alternative energy supplies is critical to reducing GHG emissions in the sector, as illustrated by scenarios across various modes of transport (see also EEA, 2024m). Transitioning from fossil fuels to renewable and low-carbon energy will cut emissions significantly, predominantly from road transport. The increased adoption of BEVs and renewable energy sources is expected to drive a major reduction in emissions between 2022 and 2030 from passenger cars (26%), vans (21%) and trucks (25%) (see Figure 3.18) (EEA, 2024m).

Figure 3.18 **Direct CO_2 emissions from transport by mode between 2005 and 2022 and outlook towards 2030, 2040 and 2050**

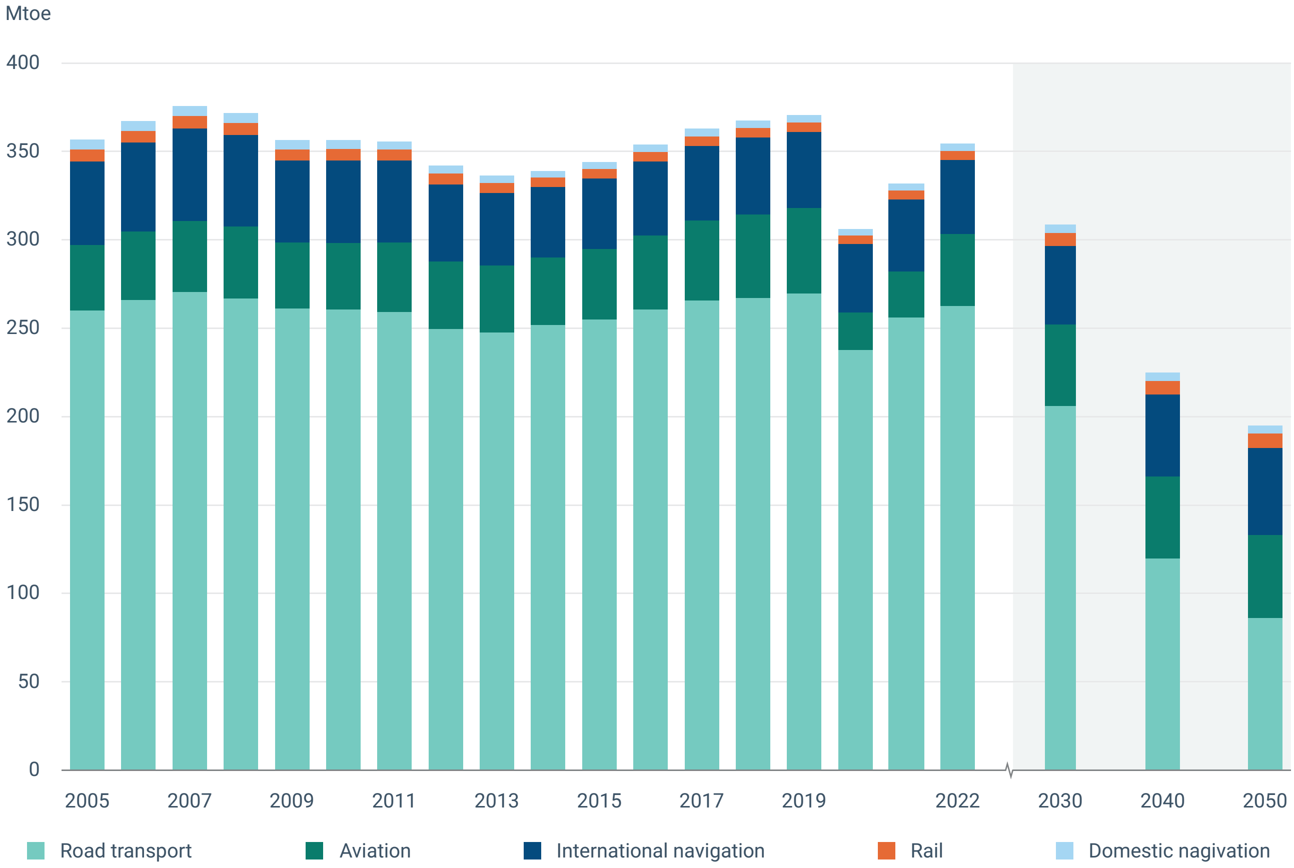


Source: EEA, based on EEA, 2024d and EC, 2024d.

The reduction of energy consumption and switch to cleaner fuels would not negate the expansion of the sector: overall, transport activity can still increase up to 2050 (see 'Electrification and efficiency improvements — the fastest way to meet the EU climate and energy benchmarks by 2030 and reduce oil import dependency'). The fuel switch and associated gains in energy efficiency would lead to an estimated 16% reduction in CO_2 in 2030, compared to 2022 (from 1,015 to 833Mt). Road transport (including passenger cars, heavy goods vehicles and vans) would still make up the largest share of 2030 transport emissions at around 67%, followed by navigation with 17% and aviation with 16%. Emissions are projected to drop significantly by 2040, with a decrease of 75% (to 240MtCO_2) compared to 2022, according to the Commission benchmark scenarios (EC, 2024c). Some residual emissions would remain across all transport modes in 2050, with aviation producing the highest — but negligible — amount of CO_2.

Oil products would still amount to 86% of transport energy consumption by 2030, but with a sharp decline to 36% in 2040 and to 7% in 2050. Electricity would grow from around 5% in 2030 to roughly 18% in 2040 and 28% in 2050. The remaining energy use in 2050 would split between hydrogen and e-liquids (around 21%), liquid biofuels (around 19%), biogas (3.5%) and E-gas (around 3%).

Figure 3.19 Final energy consumption in transport between 2005 and 2022 and outlook towards 2030, 2040 and 2050



Source: EEA, 2024h.

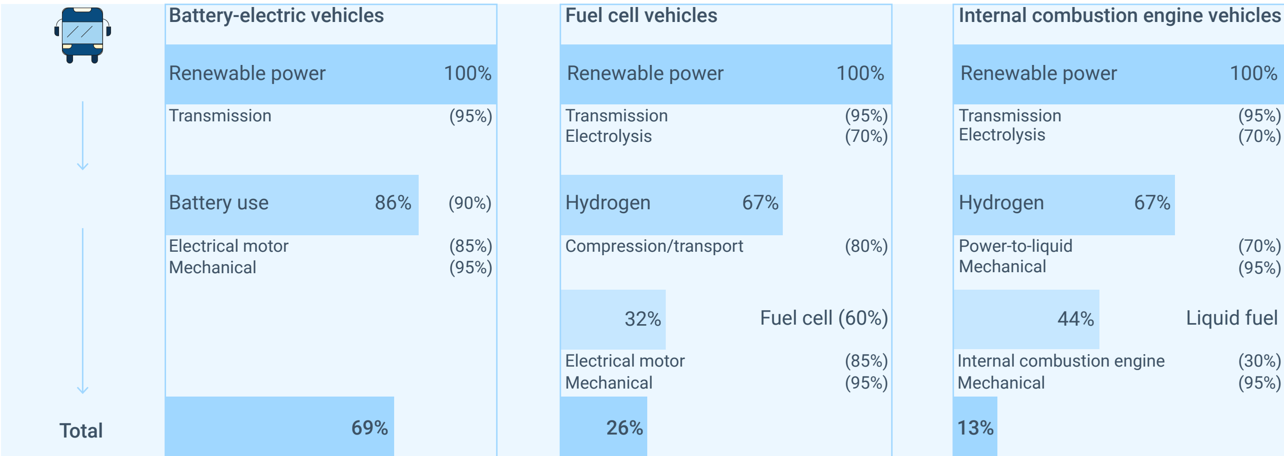
As shown in Figure 3.19, most energy demand stems from road transport, which has to decrease significantly by 2030. Transforming the EU energy system in line with EU targets for 2030 and beyond requires foremost the electrification of road transport (EEA, 2024n; Eurelectric, 2024; EC, 2024c). For instance, Eurelectric estimates that electricity, as share of energy consumption by passenger cars, must rise to around 31-33% by 2040 and 60-70% by 2050 to facilitate the EU energy system transformation. In road transport, this shift would arise from the increasing adoption of battery electric vehicles (BEVs), which should make up 57-58% of the EU's car stock by 2040 and 79-80% by 2050. According to the Commission's recent benchmark scenarios, the electrification of the overall transportation sector needs to increase from around 2% in 2022 to 5% in 2030, 19% in 2040 and 27-28% by 2050 (EC, 2024c).

Long-distance aviation and maritime transport are more difficult to electrify due to technical reasons (EC, 2020a). This includes the longer development cycles of technologies such as sustainable aviation fuels and hydrogen-powered vessels. A reliance on long-haul journeys and international competition further complicates the transition of this subsector (EUROCONTROL, 2023). By contrast, urban waterway transport can be potentially revolutionised with electric (hydrofoil) ferries (Ringsberg, 2023; Sæther and Moe, 2021; AP, 2024; Rivero, 2025).

Efficiency of battery electric vehicles (BEVs)

BEVs have demonstrated significantly higher energy efficiency compared to internal combustion engine (ICE) vehicles, converting around 69% and up to 90% of the electricity they use into motion (Agora, 2018a; Hjelkrem et al., 2020). In contrast, ICE vehicles lose a substantial amount of energy as heat throughout the transformation process, leading to a total well-to-wheel (WtW) efficiency of only 13% (see Figure 3.20) (Agora, 2018).

Figure 3.20 Well-to-wheel energy efficiency



Note: Individual efficiencies are indicated in parentheses. Multiplied together, the individual efficiencies yield the overall cumulative efficiencies in the boxes.

Source: EEA, adapted from Agora, 2018.

BEVs are expected to achieve cost parity of purchase prices with ICEs across all light-duty segments by 2027 (T&E, 2021). Reduced battery costs, innovations in vehicle design and the development of specialised production lines for BEVs will all enhance their market competitiveness (LeasePlan, 2022; EEA, 2024j). In parallel, average electricity prices across all EU countries are expected to fall if the EU electricity system is decarbonised in line with EU benchmarks set by the 2030 EU Climate Target Plan (see also 'Current and near-term evolution of EU electricity prices and energy expenditure', in Chapter 3.1.2). In the EU, adoption of electric vehicles increased rapidly between 2020 and 2023: 23% of newly registered passenger cars were electric during this period. BEVs represented 15% of total new car registrations, while plug-in hybrid electric vehicles (PHEVs) accounted for 8% (EEA, 2024j). In 2024, however, the share of BEVs in new car registrations declined by roughly one percentage point compared to 2023 (EEA, 2025b).

Battery electric trucks are also growing more cost-competitive, with the potential to replace existing heavy goods vehicles. The total cost of ownership is projected to match diesel trucks across most vehicle classes by 2030 (ICCT, 2023). Lower operational expenses, particularly for fuel and maintenance, would help to offset higher upfront costs. However, achieving the necessary reduction in direct CO_2 emissions from heavy-duty vehicles requires expanding decarbonisation efforts thirtyfold by 2030, which highlights the necessity of further policies for this segment (see Figure 3.18).

3.3.2 Challenges and drivers to decarbonise the mobility subsystem

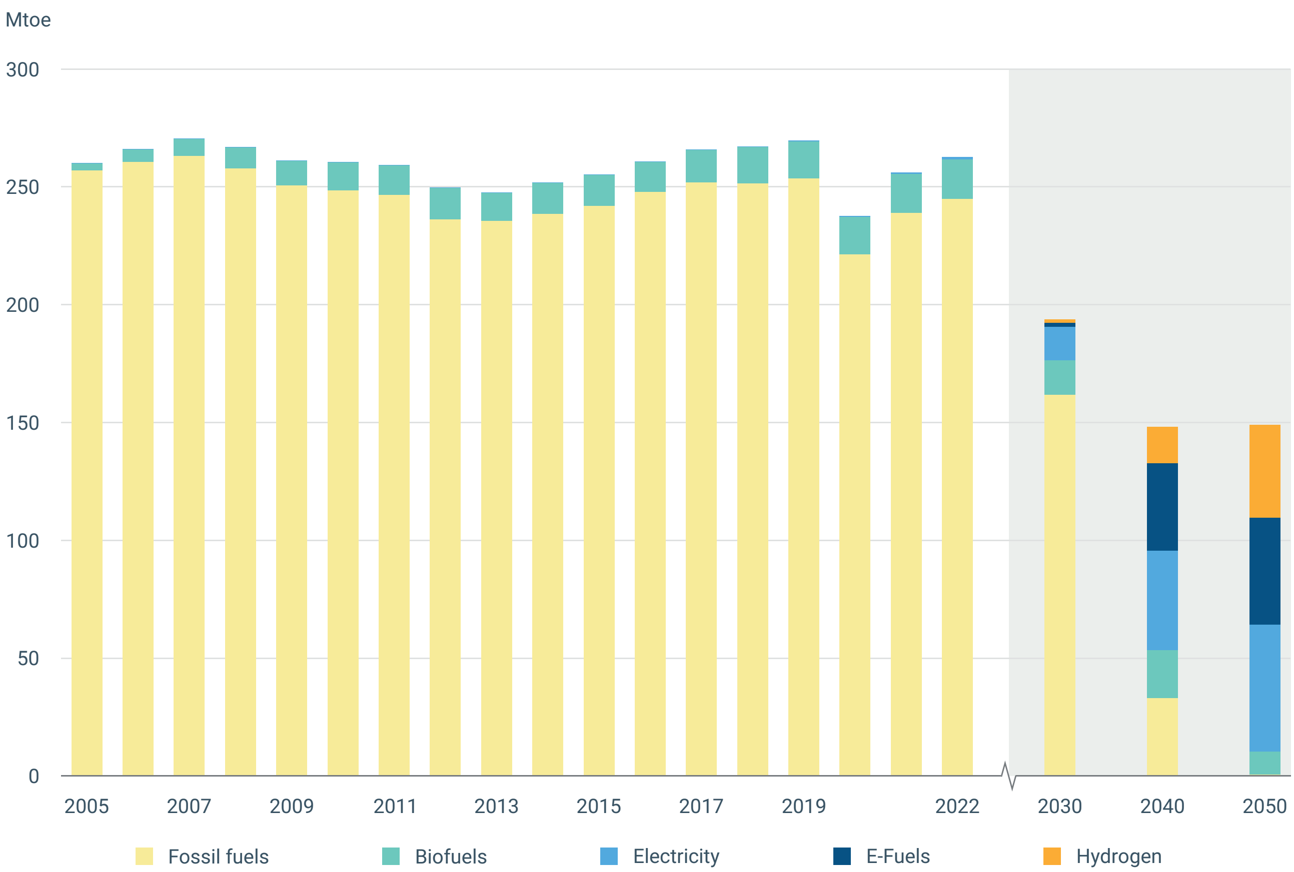
Energy efficiency and savings enabled by the electrification of road transport

Depending on assumptions about fleet type, efficiency and composition, electricity demand for transport in 2050 could vary substantially, from 800 to 2,000TWh (Krause et al., 2024). However, the shift from ICEs to BEVs can boost the energy efficiency of road transport vehicles substantially (see Figure 3.20). This recommends the electrification of road transport as key strategy to increase energy efficiency and lower GHG emissions in transport, particularly as BEVs and hydrogen fuel cell technologies — the latter mainly for long-distance transport — become more wide-spread.

Figure 3.21 shows how the decline in fossil fuel consumption due to electrification would reduce also the overall energy consumption of road transport in 2030 and beyond, while overall transport activity would still increase by 20-30% up to 2050 (EC, 2020c, 2024h).

Even as the electrification of passenger vehicles is increasing across the EU, this trend needs to accelerate particularly in passenger road transport, the most dominant transport mode (EEA, 2024j, 2024k; ECNO, 2024a). The annual uptake of zero-emission passenger vehicles has to rise eightfold to reach climate targets set in the EC's Sustainable and Smart Mobility Strategy (ECNO, 2024b; EC, 2021e).

Figure 3.21 Final energy consumption of road transport by energy carrier between 2005 and 2022 and outlook towards 2030, 2040 and 2050



Source: EEA, based on Eurostat, 2024a and EC, 2024h.

Smart energy management strategies are important to alleviate the impacts of road transport electrification on peak electricity demand

One challenge with the electrification of road vehicles will come from the increase in power demand, especially during peak hours. This may increase imbalances between supply and demand across the electricity grid. As the shift to BEVs accelerates and electrification spreads across several transport modes, the growing reliance on electricity could strain the grid, especially in cities during high demand periods (Hartvigsson et al., 2022).

Managing peak load demand becomes even more critical as electrification expands to include not only private vehicles but also public transport fleets, freight and potentially maritime and aviation sectors. Without optimisation strategies, charging patterns for BEVs could lead to spikes in power consumption, particularly through fast-charging infrastructure (Hartvigsson et al., 2022).

Smart energy management, along with the expansion of renewable power sources and grid infrastructure will need to be prioritised to ensure a balanced and sustainable energy system as transport is electrified. Innovative energy management technologies can optimise how and when energy is used and reduce demand peaks. Dynamic sector coupling through vehicle-to-grid (V2G) communication technologies lets BEVs act as mobile batteries. This bidirectional energy flow can help to stabilise the grid, aligning charging patterns with peak renewable electricity generation and returning electricity to grids during periods of very high demand. Similarly, dynamic pricing signals can encourages BEV owners to adopt smart charging practices during off-peak or low-price hours, reducing the overall pressure on the grid (EEA, 2022c, 2022d; Elia Group, 2020).

Figure 3.22 illustrates the potential impact of BEV charging on residual load. It also indicates how smart charging and V2G technologies — by shifting and reducing peak electricity demand — can significantly ease the strain on energy infrastructure as the deployment and integration of BEVs into the grid accelerates. Together, V2G and smart charging could help ensure that rising electricity demand from a growing BEVs fleet does not overwhelm the grid as Europe pushes through the widespread electrification of transport.

Figure 3.22 **Impact of battery electric vehicles (BEVs) on residual load for Belgium and Germany in 2030**

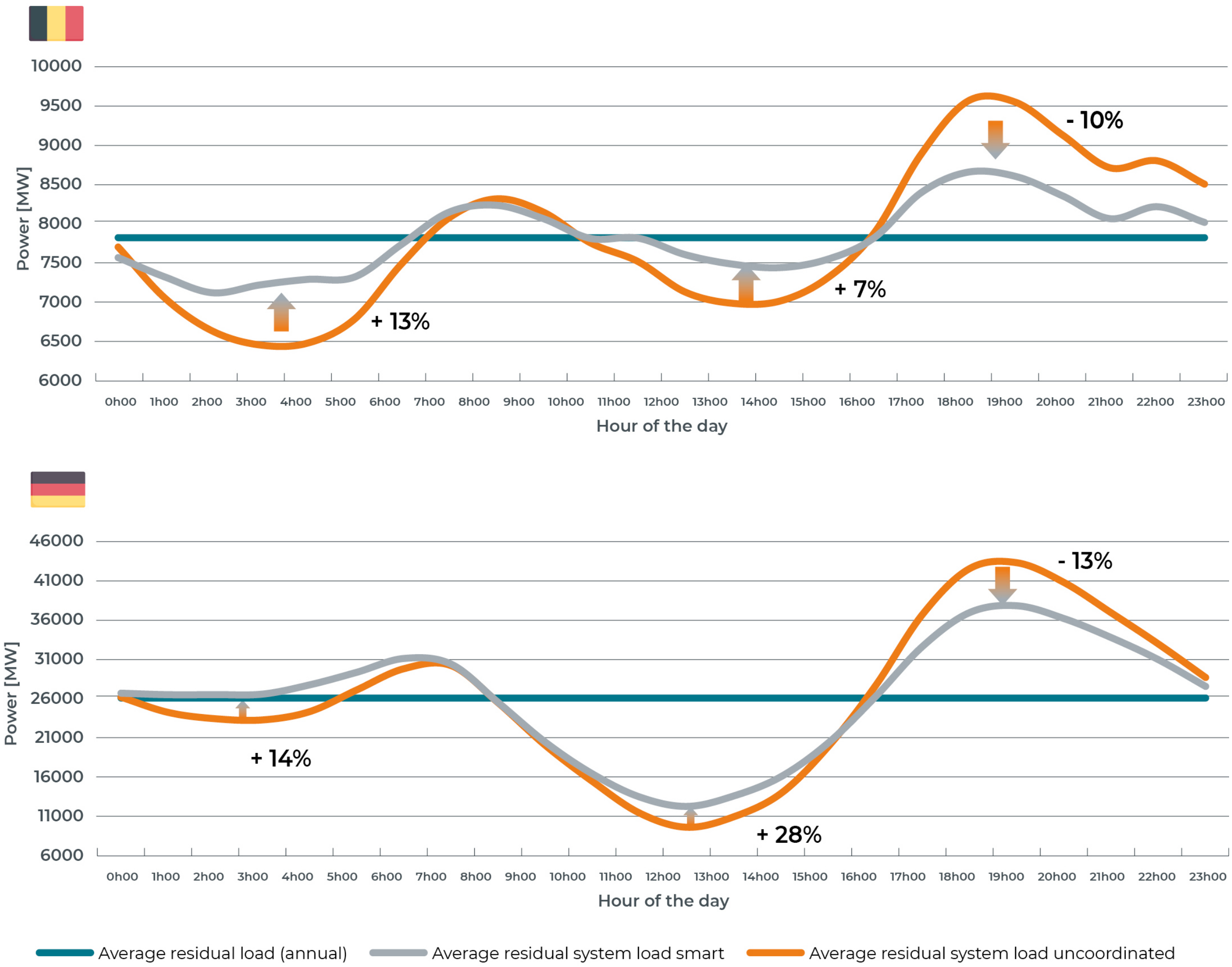


Image source: Elia Group, 2020. Image data not verified by the EEA.

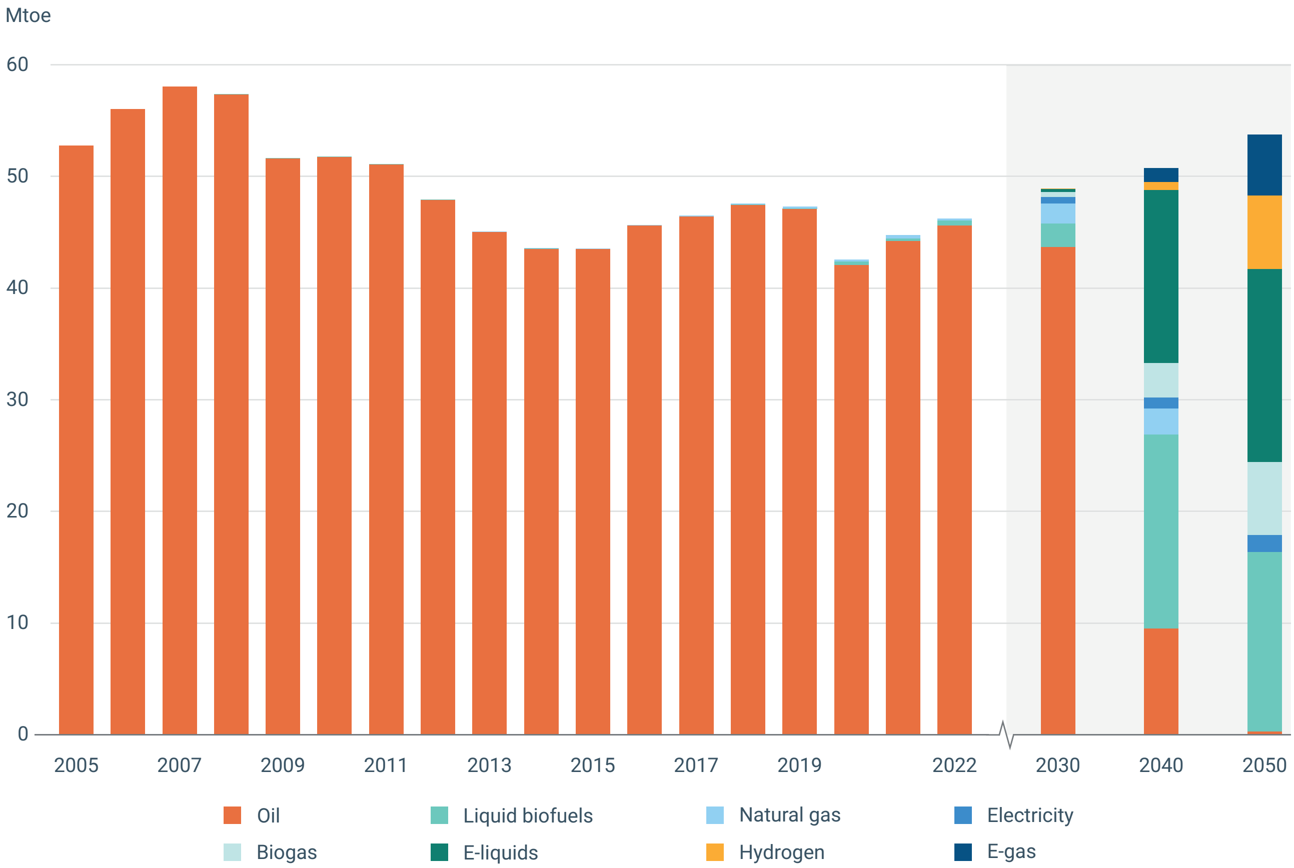
Cycling, walking and collective transport must grow faster to address growing transport volume

Shifting to a fully electrified fleet will reduce emissions. Yet this will not tackle the issues of growing transport volume, increased electricity demand and road congestion. A modal shift from passenger road transport to active mobility (cycling, walking) and collective transport modes could mitigate the negative impacts of excessive mobility, while simultaneously reducing overall energy demand for transport, especially in urban areas (EEA, 2024n). Not only does active, non-motorised mobility come with lower energy needs, it also brings substantial external cost savings due to its positive impact on health, society and the environment. According to Pisoni et al. (2022), these savings can amount up to EUR 15 billion annually when 10% of car trips are replaced by active modes of transport.

Challenges and opportunities to drive a fuel switch in maritime and aviation transport

Currently, a small proportion of maritime transport relies on renewable energy sources, such as hydrogen and ammonia. Perspectives for these low-emission alternatives are mixed. There are challenges related to production, infrastructure and scalability, which hinder widespread adoption. The inclusion of maritime transport in the EU Emissions Trading System (EU ETS1) further supports these efforts by incentivising emissions reductions across this sector (Trinomics, 2023).

Figure 3.23 Final energy consumption in navigation by energy carrier between 2005 and 2022 and outlook towards 2030, 2040 and 2050



Source: EEA, based on Eurostat, 2024a; EC, 2024h.

Final energy consumption in aviation increased by 10% between 2005 and 2022, with a large drop in 2020 and 2021 due to the COVID-19 pandemic. Sustainable aviation fuels (SAF) ([54]) are still not widely used; kerosene remains the preferred fuel type. Advanced biofuels provide short-term benefits, but synthetic fuels may be more favourable in the long term due to their preferred resource efficiency during production, such as for water and energy use. Prioritising synthetic fuels whenever direct electrification is not possible could be more practical in aviation, due to the significant costs of any transition toward sustainable biofuel (Scheelhase et al., 2019).

([54]) Meeting criteria set by the Renewable Energy Directive (RED, Directive 2018/2001/EU), SAF include synthetic aviation fuels from renewable hydrogen and captured carbon, as well as advanced and other aviation biofuels and recycled carbon aviation-fuels. When accounting for the contribution of SAF in transport, the ReFuelEU Regulation differs from than the RED by also allowing low-carbon aviation fuels produced from nuclear energy (EU, 2023f). Emissions of pollutants from the aviation sector have increased considerably over time, with air pollutant emissions linked to the combustion of SAF comparable to fossil fuel-based jet fuels (EASA, 2025).

Investment needs for stimulating the transition towards decarbonised transport

Beyond managing peak power demand in the electricity subsystem, decarbonising the transport subsystem will require investment in vehicles and refuelling infrastructure. For road transport, vehicles investments must rise by around 17% between 2021-2030, compared to 2011-2020, with a 10% increase in passenger cars and 46% in trucks, according to Commission benchmark scenarios (EC, 2024h). While early investments set a foundation, future investments should grow significantly from EUR 130 billion in 2016-2020 to around EUR 220 billion per year by 2026-2030. This will support the complete decarbonisation of all transport modes, particularly the hard-to-abate sectors such as aviation and maritime (Urban et al., 2024).

Investments in recharging and refuelling infrastructure are needed to build widespread, reliable and accessible networks across all modes of transport – especially as electrified and hydrogen-based transport becomes more prevalent (EC, 2020a; Singh et al., 2024). The previous baseline target for a 60% reduction in transport GHG emissions by 2050 required an additional EUR 2 billion per year. The much more stringent target — a 90% reduction by 2050 — now requires an estimated EUR 3 billion per year in additional investments in EV charging infrastructure (Klaaßen and Steffen, 2023). These funds will be essential for expanding fast-charging networks along highways, urban areas and rural regions, to accommodate the growing number of BEVs. Grid upgrades will be necessary to manage the higher electricity demand associated with the mass adoption of BEVs and higher frequency of fast-charging, ensuring the infrastructure is robust enough to support a low-carbon future for transport. Without these upgrades, bottlenecks in energy supply and access to charging infrastructure could significantly slow the transition to clean transport (Singh et al., 2024). As shown in Figure 3.24, the number of charging stations is increasing across the EU. Through the Alternative Fuels Infrastructure Regulation (AFIR), requirements for recharging facilities in road transport are established at the EU level to drive the expansion of charging infrastructure (EU, 2023d).

The inland navigation segment too requires further policy measures to give up on dominant diesel fuels and reduce GHG emissions. Solutions to decarbonise this segment do exist and range from hydrogenated vegetable oil or liquid biogas fuels to replace diesel in ICE vessels, to battery-electric vessels equipped with swappable battery containers and vessels powered by fuel cells running on compressed hydrogen and methanol. However, targeted interventions will be needed if vessel operators or owners are to invest in these more expensive energy carriers and technologies (Karaarslan, S. and Quispel, 2023).

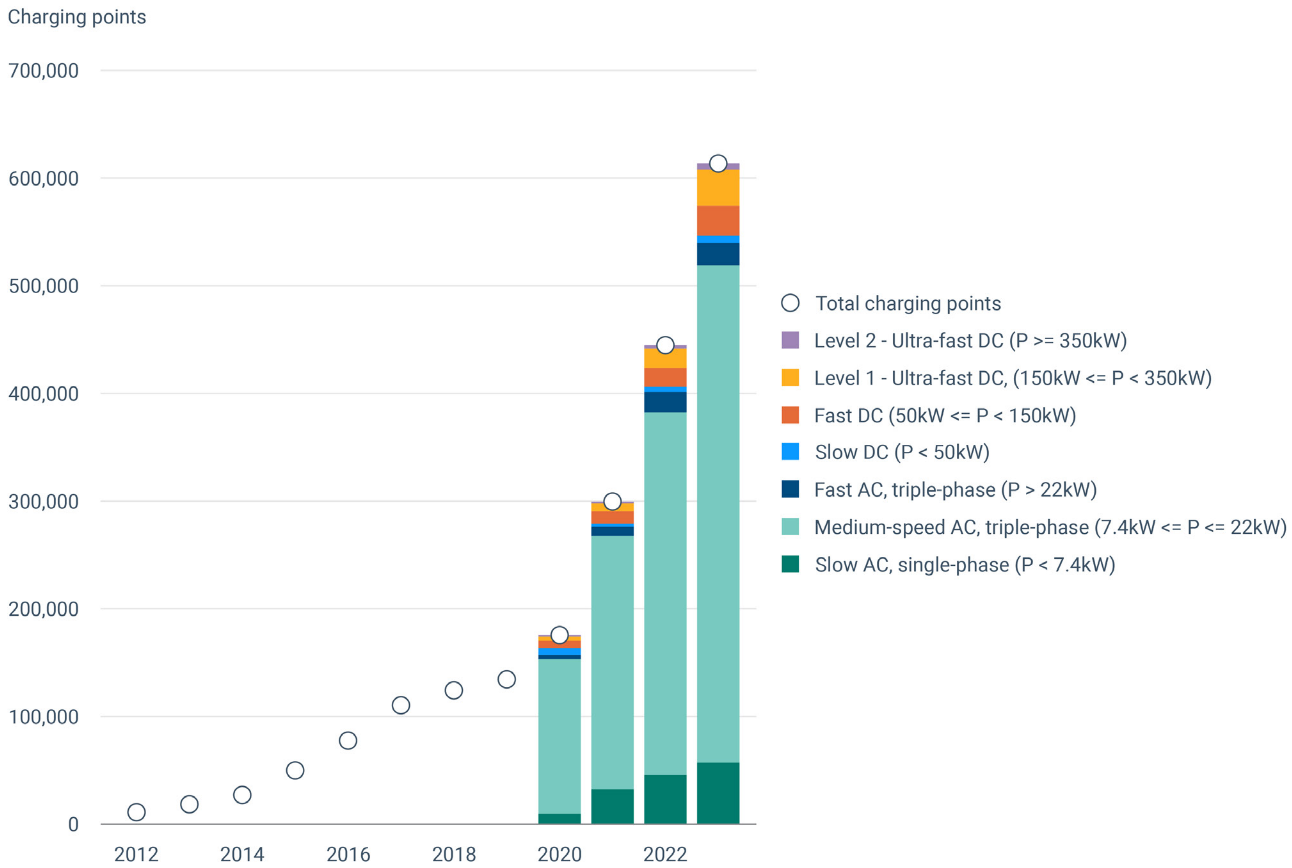
Additionally, AFIR mandates core Trans-European Transport Network (TEN-T) ports to provide one on-shore power supply (OPS) to passenger and container vessels of over 5,000 gross tonnage (GT) already by 2025, expanding OPS comprehensively to inland ports by 2030 to support the shift towards electrification, with charging possible while vessels are docked.

Only 35% of TEN-T ports currently have some OPS installed, the latter not necessarily being AFIR-compliant (EEA, 2024n). This points to a significant space for expansion to meet environmental goals and reduce emissions from maritime transport. Maritime and inland navigation also requires investment for the adoption of advanced biofuels and — in the long term — refuelling infrastructure for alternative fuels. The FuelEU Maritime Regulation highlights the need for large-scale investments in refuelling and recharging infrastructure in ports, along with the electrification of short-sea shipping routes (EU, 2023d). Furthermore, significant financial resources are required to decarbonise large ocean-going vessels. This is a particularly challenging sector. Retrofitting or replacing these ships to shift from conventional heavy fuels to sustainable alternatives is capital-intensive and technologically complex, underscoring the high investment needs (T&E, 2018).

Significant funding is needed in aviation for the development and scaling of SAF, as well as for advancing hydrogen-powered and electric aircraft technologies. These are all currently at low technological readiness levels. With limited progress made last decade, a rapid acceleration in SAF production and use would help to meet the EU's climate goals (EC, 2020a). The aviation industry faces long development cycles and high technological barriers, but the ReFuelEU Aviation regulation is expected to spur investments by setting mandates for SAF usage, thus driving innovation and market readiness for zero-emission aviation technologies to enable decarbonised air travel (EU, 2023f). Similarly, airport infrastructure will require upgrades, including the development of electrified ground operations and hydrogen refuelling stations for ground operations (Yusaf et al., 2024).

Public transport across most of the EU is mostly a resounding success. Yet, rail infrastructure stands out as one of the most significant areas that will need increased investment: an additional EUR 25 billion per year are needed to facilitate a faster shift to this mode of transport. However, insufficient progress was made in the 2010s, particularly in cross-border rail connectivity and high-speed rail development (Klaaßen and Steffen, 2023). The new climate targets, which aim

Figure 3.24 Publicly available charging points by type of charger in the EU



Source: EEA, 2024n.

to cut transport emissions by 90% by 2050, demand a rapid scaling-up of rail infrastructure to absorb more passenger and freight traffic. This would reduce the carbon footprint of long-distance and regional transport (EEA, 2021).

3.3.3 Existing policies

The overarching EU policy framework for decarbonising transport

The EU is aiming to decarbonise the transport subsystem in line with the EGD and the 2050 climate objective, which target a 90% reduction of transport-related GHG emissions compared with 1990 levels. The EC's Sustainable and Smart Mobility Strategy (EC, 2020a) encourages a 25% rise in inland freight from road to rail and short sea shipping by 2050. Passenger transport efforts are geared towards promoting more sustainable modes, particularly rail. Meeting these targets requires simultaneous changes across the EU transportation and electricity systems, including efficiency improvements and speedier rollout of renewable electricity, low-carbon fuels, zero-emission vehicles and necessary refuelling infrastructure. The Fit for 55 package sets regulations for road, maritime and aviation transport to help decarbonise this subsystem (EC, 2023a, 2023d). To strengthen signals for decarbonising transport (including for example the possibility to reduce trips and trip length) a separate EU ETS2 will cover road transport emissions from 2027, while the initial EU ETS has been expanded to include shipping emissions from 2024. Both systems work by setting a carbon price to stimulate cleaner technologies and generate additional revenues for decarbonisation ([55]).

EU policies aiming to reduce GHG emissions in road transport

To reduce GHG emissions from road transport, the EU has introduced successive CO_2 performance standards for cars and vans (Regulation (EU) 2019/631). These set fleet-wise limits for manufacturers and penalise excess emissions.

For heavy-duty trucks, EU emission performance standards mandate a 15% reduction in average CO_2 emissions by 2025 for certain types of new trucks, compared with 2019-2020 levels (EU, 2019). The Fit for 55 package sets newer GHG reduction targets of 45% for 2030, 65% for 2035 and 90% for 2040. It also broadens the requirements for medium lorries, city busses, coaches and trailers. All new city busses must be zero-emission by 2025 (EC, 2021d).

AFIR mandates minimum recharging points for electric vehicles to support the uptake of zero emission vehicles. Linked with the uptake rate of for electric and hydrogen-powered vehicles, it also sets minimum recharging points across major highways and urban areas, to facilitate a systemic shift from fossil fuel dependency towards decarbonised road transport alternatives (Regulation (EU) 2023/1804).

EU policies aiming to decarbonise maritime and aviation transport

([55]) The extended EU ETS applies to vessels of 5,000GT or above and covers voyages within the EU and on international routes to and from EU ports. It will mandate shipping companies to initially pay for 40% of their GHG emissions in 2025, rising to 100% by 2027 (EU, 2003; Carbon Market Watch, 2023). The ETS2 establishes a separate emission trading system with its own carbon price that applies to companies supplying fossil fuels for road transport. The full implementation of the ETS2 will occur in 2027, with a monitoring phase starting in 2025. The aim is to reduce emissions by 42% by 2030. Auction revenues will be used for climate initiatives and to support vulnerable groups (EC, 2023b).

Alongside EU ETS carbon pricing frameworks, the FuelEU Maritime Regulation targets a reduction of average GHG emissions by at least 2% by 2025 and 80% by 2050, compared to 2020 levels (EU, 2023d). It prompts the use of sustainable fuels, including advanced biofuels, hydrogen and potentially emerging technologies such as methanol and ammonia, along with investments in OPS in ports for the activities at berth of certain vessel categories (EU, 2023d).

By contrast, the decarbonisation of inland navigation is not addressed with dedicated EU policy measures to reduce GHG emissions. This segment is addressed indirectly, via more general provisions under the Renewable Energy Directive. To increase policy coverage and coherence, Member States can also opt-in this segment under the EU ETS2.

Similarly to the FuelEU Maritime Regulation, the ReFuelEU Aviation regulation requires EU airports to gradually increase the share of SAF from 2% in 2025 to 70% in 2050 (EU, 2023f). It also mandates specific targets for synthetic fuel blends from 2030 onward (1.2% of SAF, representing 0.07% of total aviation fuel, must be synthetic by 2030, rising 35% of SAF by 2050, the equivalent to 24.5% of total aviation fuel).

3.3.4 Key actions and recommendations for the transport subsystem

Reducing fossil fuel dependency of passenger road transport through electrification

While average national and EU electricity prices may fall by 2030 if the EU electricity system is decarbonised along with current EU targets, current electric vehicle adoption rates are insufficient to reach the optimal transport electrification targets set for 2030. This indicates a need for near-term policy intervention to drive the uptake of sustainable alternatives further, beyond existing EU support through the AFIR (Seibert et al., 2024).

Policymakers can stimulate this through tax breaks, subsidies and purchase premiums to increase the electrification of the passenger road vehicle fleet (ECNO, 2024a). Such initiatives can be especially beneficial to address the upfront cost disparity between BEVs and conventional vehicles, improving the affordability of decarbonised, more energy-efficient alternatives. Establishing low-emission zones in line with the EU's CO_2 performance standards on cars and vans (EU, 2023c) can create a direct incentive for individuals to transition to cleaner alternatives, to avoid access limitations or additional fees associated with conventional, fossil fuel-dependent vehicles.

Promoting a modal shift from passenger road transport to sustainable, active travel modes

While technology may bring some solutions, further reductions in energy demand hinge on supportive policies that manage overall transport demand and promote a shift towards more sustainable, active modes, alongside public transport.

To simulate such a modal shift, seamless transfers between public transport and active modes such as walking, cycling and micro-mobility should be ensured through the development of integrated multimodal networks. For instance, mobility hubs that offer bike-sharing and e-scooter services near public transport stations can enhance first- and last-mile connectivity and overall convenience, but only if parametrised correctly to ensure these vehicles replace regular car trips rather than active transport modes, have an enhanced longevity and are maintained with renewable energy and efficient logistics (OECD, 2021; Kazmaier et al., 2020; ITF, 2020;

EEA, 2019e). As pointed out in Chapter 3.3, active mobility comes with several benefits for society and the environment, while also leading to potential cost savings.

Additionally, to stimulate a modal shift towards active modes, policymakers can enhance the attractiveness and convenience of sustainable transport alternatives by discouraging private car ownership when alternatives are available. This includes stimulating ride-sharing schemes and integrating transport modes, while keeping these affordable alternatives to passenger road transport (OECD, 2021).

Accomplishing a modal shift for freight by leveraging investments in more rail and waterborne transport

The EU's Sustainable and Smart Mobility Strategy underscores the urgent need for a modal shift in freight transport as part of its broader goal to achieve climate neutrality by 2050 (EC, 2020a). Road freight — currently dominant in Europe — is a major contributor to greenhouse gas emissions, air pollution and road congestion. Shifting freight from road to rail and waterborne transport can significantly reduce these negative externalities ([56]).

Recent research suggests subsidies and grants are the most effective policy instruments for promoting a modal shift torailtransport (Takman and Gonzalez-Aregall, 2024). The Connecting Europe Facility (CEF) and TEN-T network are prime examples of successful EU level tools that have provided the necessary infrastructure investments in rail and waterborne transport (EU, 2024d). To stimulate a modal shift on a national level, policymakers could use taxation and regulation measures, as well as financial incentives designed to benefit low-carbon transport alternatives (Beil and Putz, 2023).

Addressing peak load and power demand from increased transport electrification through innovative energy management and dynamic pricing models

The decarbonisation of transport, especially road, will cause electricity consumption to rise (Krause et al., 2024). To mitigate the challenge of peak load demand from the electrification of transport, innovative energy management technologies should be incentivised and grid flexibility improved. These innovative energy management approaches can optimise energy use patterns and flatten peak power demand. Relevant tools include the integration of V2G technology, along with smart-charging mechanisms, as highlighted in Section 3.3.2.

Successful implementation will require a regulatory framework that provides granular signals to consumers and encourages the deployment of V2G systems. This can enable BEVs to act as decentralised energy storage, feeding electricity back into the grid during peak demand periods, for example. Revision of the current national electricity network tariffs and electricity taxation regimes — that often render negative the business case for electrification — along with targeted subsidies, tax credits or grants for V2G applications could accelerate integration, enhancing grid flexibility and resilience, particularly when renewable energy sources are more scarce.

([56]) It should be noted that inland navigation and shipping may face higher future risks of disruption or low efficiency, due to the risk of more recurrent draughts caused by climate change. To overcome such challenges, logistics services need to invest in appropriate climate adaptation measures.

([57]) For instance, critical peak pricing — meant to reflect increased system costs during 'critical peak' events, or peak time rebates — remunerating customers if they reduce consumption during designated peak periods.

Dynamic pricing models should be promoted further to encourage smart-charging behaviours. Time-of-use pricing, real-time rates or other dynamic tariff structures ([57]) could be tried out more broadly to optimise when BEVs charge. This would ensure energy consumption is aligned with periods of low demand or high renewable energy supply and contribute to the balance of electricity loads.

Research and development (R&D) in smart grid technologies, along with public-private partnerships can support advances in grid management, further easing the integration of electric transport. Coordinating energy and transport sector policies will ensure these technologies can be scaled and integrated effectively, overcoming challenges surrounding peak load and power demand.

Incentivising research and development to support decarbonisation in both maritime and aviation transport

The decarbonisation of both the maritime and aviation sectors is crucial to meeting long-term climate goals, particularly as both industries currently rely heavily on fossil fuels. To achieve the EU targets set through the FuelEU Maritime Regulation and the ReFuelEU Aviation Regulation, the development and adoption of low-emission technologies and alternative fuels in the sectors is to be driven at a national level (EU, 2023d, 2023f).

Specifically, in the maritime sector, a transition away from fossil fuels will be essential for meeting the targets outlined in the FuelEU Maritime Regulation, as highlighted in Section 3.3.3. However, challenges related to the scalability and infrastructure for alternative fuels (such as hydrogen, methanol, electricity, ammonia) must be addressed. To overcome these barriers, Member States should incentivise R&D in these fuel technologies by offering grants and fostering public-private partnerships. In parallel, the regulatory framework should be strengthened, with more ambitious short-term targets to ensure steady progress towards the 2050 goal. Available tools for policymakers include grants, procurement and tax reform to further incentivise decarbonised shipping (ITF, 2023).

Specifically, policymakers can prioritise funding and regulatory frameworks that incentivise the development of ports capable of refuelling ships with alternative fuels. This will be key to ensuring alternative energy sources are accessible across major shipping routes. This allows for substantial investment in port infrastructure, which is necessary to support the widespread use of low-emission fuels across the entire EU.

Aviation emissions have grown significantly over the past few decades (EASA, 2025). The transition to SAF presents a major opportunity for the sector to reduce its carbon footprint. However, SAF-related emissions of air pollutants are broadly comparable with those of fossil fuel-based jet fuels. Current limitations on the scalability and availability of SAF also suggest a need for substantial investment in R&D. Policymakers are recommended to ensure development and innovation in SAF, by working with fuel producers to scale up production. Sustained investment in R&D will be critical to advance fuel technologies further, ensuring that both SAF and synthetic fuels become more cost-effective and accessible over time. Given the costs associated with biofuel production, synthetic fuels should be prioritised from the outset (Scheelhase et al., 2019). Policymakers can support this shift by offering financial incentives and subsidies to airlines that adopt synthetic fuels early, accelerating the transition towards decarbonisation. Policymakers are also encouraged to establish intermediate targets to keep the sector on track, to scale up production and meet 2050 targets.

4 A balanced approach: targeted actions within comprehensive policy frameworks to reform the EU energy system

Renewable energy-based technologies can now outcompete the largest part of the incumbent fossil fuel commodity chains, mainly in electricity but increasingly so in heating and transport. This marks a new phase in the transformation of the EU energy system, where accelerated change is possible across Member States.

On the heels of the transformative policies of the EGD, including a European Climate Law that sets Europe on the pathway to climate neutrality in fewer than 30 years, Europe's new policy agenda sets competitive decarbonisation, innovation and security (including strategic supply) as the key priorities for the coming years. All three dimensions of the EC's 2025 Competitiveness Compass address the EU energy system transition. This transformation has become a strategic necessity in the face of geopolitical tensions and to promote sustainable economic growth (EC, 2025a). Reinforcing these efforts, the Clean Industrial Deal and the Action Plan for Affordable Energy aim to enhance strategic EU decarbonisation efforts and lower energy costs for EU citizens and businesses (EC, 2025c, 2025b).

4.1 Main insights

A rapid electrification of demand can greatly improve the overall efficiency of the EU energy system ([58]), lower emissions of GHGs and air pollutants and reduce national fossil fuel import bills. According to this report, it could also reduce significantly the variable cost component of electricity prices, with the potential to improve by 2030 national and EU competitiveness and energy supply independence. In interplay with efforts to promote energy and resource efficiency, circularity and broader sustainable production and consumption patterns across society, this will help to mitigate system inertia and enhance synergistic effects and responses from across all sectors (Geels et al., 2023).

Improvements in energy efficiency were not as widely discussed during the recent gas price crisis, though successful EU and national energy efficiency policies taken before 2022 helped to avert a more critical fallout. This highlights the necessity to boost efficiency and circularity efforts further by 2030. Policymakers have accessible levers to accelerate the current transformation through renewables (propelled by innovations and cost reductions in solar, wind and battery storage), electrification (replacing fossil fuels in buildings, transport and across many industry branches) and energy and material efficiency improvements.

Yet the present level of investment is insufficient to achieve many, if not most of the EU energy transformation benchmarks for 2030. Finding new means to boost public and private funding is paramount to close investment gaps during

([58]) Electric technologies are most often more efficient than their fossil fuel counterparts, as was shown in Chapter 3 with the example of heat pumps and electric vehicles.

this decade, accelerate deployment of renewable energy capacity and reward consumers when improving energy efficiency and flexibility. Moreover, regulators should anticipate future scenarios and deploy resources ahead of needs — such as infrastructure bottlenecks and system flexibility requirements. This will require a stronger focus on electricity transmission and distribution grids, interconnections and demand response from industry, electric vehicles and heat pumps — all enabled by digitalisation of the energy system. Aligning tax rates for energy carriers to promote electricity over fossil fuels is equally important in the short term to promote electrification and renewable energy deployment. Currently, high taxes on electricity increase bills and the current structure of taxation in many countries does not disincentivise the use of fossil fuels over electricity (EC, 2025b).

Greater cooperation and coordination between national regulators can help with optimally planning, upscaling and utilising key infrastructure, including flexibility resources, across EU borders. This also means strengthening cross-border planning to account for the specific vulnerabilities of 'quasi-isolated' or 'peripheral' EU regions. Further integrating national energy systems will maximise the advantages of diverse energy mixes, fostering innovation, competitiveness and productivity. It will also smooth the transition to a renewables-dominated EU energy system and help avoid a subsidy race between Member States. Implementing the Carbon Border Adjustment Mechanism (CBAM) to correct international carbon pricing disparities will help industrial transformation, even as national circumstances will differ. Beyond these more generic principles, the following insights are deemed important for a successful national implementation:

4.2 Policy insights for accelerating the transition within energy subsystems

Bolstering renewable generation capacity in **the electricity subsystem**, while sending stronger electrification signals to end-users in the short term, could increase synergistic effects for the energy system transition. This underscores the importance of near-term investments in supportive infrastructure and the phasing-out of subsidies for fossil fuels. Fundamental changes are expected in electricity supply (more intermittency) and use (increased electric loads from buildings, industry and transport). A stronger push is therefore needed to double EU flexibility resources through grids, demand response and storage. A faster roll-out of supportive standards on data management and device interoperability — enabled by grid digitalisation and AI — would increase opportunities to cut the cost of power networks through optimised electric loads, by aggregating demand response from buildings and electric vehicles securely, with dynamic pricing.

The **heating subsystem** would benefit from more rapid electrification too. However, measures to enhance energy efficiency — particularly through the retrofit of least-efficient buildings and the adoption of clean industrial processes — are equally important. This calls for less prescriptive policies that can help users to determine optimal balances between various solutions. Heat pumps are key to the phase out of fossil fuels. National efforts could focus on revising energy taxation, phasing out fossil fuel subsidies, prioritising electrification and introducing targeted incentives and robust funding strategies to incentivise investment in energy efficiency retrofits, encourage innovation and support vulnerable consumers.

The **transport subsystem** stands to gain from accelerated electrification and the transition to clean fuels, along with shifts to more sustainable and active transport modes. National measures could consider subsidies or tax adjustments to reduce the upfront cost disparity between electric and conventional vehicles, particularly for low-budget BEVs and trucks. Equally important is further investment in seamless transfers between public transport and active modes such as walking, cycling and micro-mobility, as well as rail and maritime transport infrastructure. R&D for efficient and clean fuels, particularly for shipping and aviation, remains important to enable progress beyond 2030.

4.3 Further key insights to accelerate the energy system transition

Building trust through reliable policymaking

Reliable and supportive policymaking is crucial to build trust, reinforce the appetite of investors and guide national energy transformations — necessities highlighted also in the Draghi report on EU competitiveness (Draghi, 2024). Consistent short-term signals must align with longer-term planning to foster confidence in the commitment to sustainable change. Robust national frameworks, reliable support mechanisms and the strategic development of key energy infrastructure across borders will reduce uncertainty and encourage investment. This in turn will ensure that industries, companies and private consumers can plan with confidence for longer time horizons (IEA, 2022; EEA, 2023a).

The current EU framework that includes the NECPs, LTSs and the associated monitoring system can enhance information exchange across actors and countries and improve national and EU policy efforts. These tools can enhance the alignment of short-term actions with long-term goals, increase national and EU level consistency, promote regulatory stability and facilitate the emergence of optimal blueprints for key EU infrastructure, reducing the uncertainty for all stakeholders (EC, 2020a; Singh et al., 2024; EEA and ACER, 2023).

To accelerate the ongoing transition, policymakers must go beyond techno-economic solutions and address also non-financial barriers that may be overlooked in practice (Geels et al., 2023). Such obstacles can be diverse and complex: ranging from ineffective public communication strategies and low energy literacy across society; to vague, non-transparent or non-digitalised administrative processes; inadequate spatial planning procedures (including overly-restrictive zoning requirements for solar and wind deployment); or insufficient public resources to manage permitting applications.

These obstacles can hamper even the most well-funded policies. The simplification of administrative procedures based on existing best practices is an effective strategy that does not compromise on environmental integrity. Similarly, personalised guidance to consumers from trusted sources tends to be more effective than generic public campaigns. This suggests information strategies and public support should be targeted to reach and engage citizens most effectively. Designing policies from a community- and user-centric perspective is key to successful implementation. This includes prioritising citizen needs and well-being, while including people in the decisions that affect them. For instance, segmenting consumers based on their attitudes, values and behaviours and communicating more effectively about co-benefits of investing in climate, nature and health protection can help community engagement and ensure broader social acceptance of policies fostering energy system transformation (EEA, 2023a, 2024g). In addition, for reconciling long-term sustainability thinking with short-term policymaking, national policymakers could: create and outline a clearer hierarchy of energy transition policy goals; strengthen national administrative capacity for swifter, more effective policy implementation; shift public support to areas that can accelerate industrial and societal transformation; and prepare the ground for a just and inclusive societal transition (EEA, 2024g).

Working with comprehensive policy mixes to align signals along all energy system components

In general, balanced and comprehensive national policy mixes will succeed better than overly prescriptive policies in driving a socially cohesive and efficient transformation of the energy system. For instance, future measures should seek to secure supply chains for key resources and materials, as well as supporting renewable energy expansion, accelerated electrification and increased flexibility. Mitigation policies considering social impacts and inclusive approaches are called upon to address socio-economic disparities, support reskilling efforts, ensure energy affordability and increased transparency and targeted public support (see also 'Supporting a socially-just transition') (ECNO, 2024b). This will require a better integration of insights from the social sciences and humanities into all levels of policymaking.

Global evidence from two decades suggests, inter alia, that signals sent by pricing policies work well with businesses. Yet complementary measures are needed to address the behaviour of individuals and households when making choices about buildings and transport (Stechemesser et al., 2024). Policymakers should prioritise known sector-specific best practices that complement and do not distort existing EU frameworks, such as the EU ETS, rather than increasing national policy quantity per se. Individual consumers' decisions about building and transport are significantly influenced by behavioural non-monetary factors and short-sighted decision-making. Pricing should be combined with other instruments to achieve the greatest impact. To accelerate emission reductions in these areas, broader incentives, especially targeting adoption decisions taken by consumers remain important (e.g. insulating building envelops, replacing heating systems or vehicles) (Stechemesser et al., 2024; Alt et al., 2024).

Supporting an informed and socially-just transition

The transformation of the energy system will provide more sustainable, affordable and reliable energy to consumers, even as distributional effects and their management are necessary in the short term (Heussaff, C., et al., 2025). To enable a socially just transition, policies must help all citizens — especially vulnerable groups at risk of being disproportionally affected — to contribute positively to the energy transition. On the one hand, this will require measures that redistribute energy system costs in time and between different users. On the other, it presupposes also a continuous public dialogue at various levels to help identify and solve trade-offs and raise the energy literacy of citizens.

Measures leading to price increases for some energy carriers and charging the time of energy use are necessary to incentivise efficient system operation (Heussaff, C., et al., 2025). However, they also tend to disproportionately affect the finances of lower-income households, which can jeopardise the effectiveness of climate policies (EEA and Eurofound, 2021). At the EU level, the SCF is designed to finance measures and investment for supporting vulnerable households and other actors particularly negatively affected by the price impact of the ETS2. The fund will be fed by revenues from ETS2 and contributions from Member States. Member States are to develop specific Social Climate Plans by June 2025, to outline specific measures that mitigate the social impacts of the ETS2. The SCF is a crucial component of the ETS2. Plans can focus on targeted structural investment measures for energy efficiency in buildings as well as low-emission mobility options.

At the national level, effective strategies to reduce energy poverty and promote a just transition include building renovation grants and programmes — such as Lithuania's state-sponsored apartment modernisation efforts and the Energiesprong initiative in the Netherlands (EIB, 2024; CINEA, 2024; Energiesprong, 2024). Some governments also reinvest carbon tax revenues into energy efficiency measures for low-income households, helping to mitigate the regressive impacts of these climate and energy policies. Additional targeted interventions include subsidies for the energy upgrade of social housing, discounts for energy-efficient appliances and dedicated support for vulnerable groups. Achieving a socially just transition requires coordinated, systemic action that combines investments in renewables, electrification and energy efficiency with innovative financing mechanisms and well-designed policy packages (EEA and Eurofound, 2021).

Equally salient are inclusive governance procedures — engaging stakeholders early to foster a more genuine and meaningful public participation — and transparent public dialogue programmes. This includes targeted public campaigns to increase the energy literacy of individual consumers. If properly designed and implemented, communication strategies can increase the local acceptance of new projects and help households maximise benefits from actively participating in the energy transition (CAN, 2025). They can also address misconceptions and misinformation that could be amplified by geopolitical anxieties, as demonstrated recently by the Iberian blackout (Euronews, 2025; ProtoThema, 2025). A 2024 report identified misinformation as second-highest global risk after the risks of climate change, given the propensity of social media algorithms to promote controversial and divisive content and the high volume of posts and messages reaching final users on a daily basis (World Economic Forum, 2024; see also Box 2.1). Additional efforts may be necessary to tackle this imbalance, discourage manipulation and increase the credibility and transparency of online information.

Skills and jobs are essential for the energy transition

Transitioning to a cleaner EU energy system and a greener EU economy entails fundamental changes to industry structures and employment. These will bring unique regional and social implications. Although overall employment levels are expected to remain relatively stable, significant job losses are anticipated in emission-intensive sectors not able to decarbonise, while new opportunities will emerge in low-emission sectors (OECD, 2024). While the ETS2 policy framework is necessary to ensure decarbonisation signals are passed uniformly across heating and transport systems, national policymakers should anticipate how best to use new and existing revenues. This will socialise costs while considering transition difficulties for vulnerable groups. For instance, the most affected social groups (e.g. households at risk of energy poverty or rural communities with insufficient opportunities to adapt in the short term) could be supported through the EU Solidarity Fund, European regional funds and national policies that proactively address industrial transformation and support labour market transitions.

Given the strong union presence in these sectors, tripartite negotiation and dialogue will be essential. Workers with low to medium qualifications often face significant challenges when retraining for new roles or industries, making targeted support essential. National policies to address this challenge could include initiatives like paid training leave and specialised qualification programmes to equip workers with skills relevant to emerging sectors, such as clean technology manufacturing. Strengthening 'skills intelligence' by improving insights into current and future skills demands across EU regions and sectors is equally critical. Achieving this will require collaboration with industry stakeholders, local governments and social partners to identify transferable skills and region-specific labour market needs. Additionally, tying support for businesses to social conditions, particularly through public procurement and industrial policies, could serve as a valuable mechanism to support labour market transitions (Hassel et al., 2024).

List of acronyms

ACER	EU Agency for the Cooperation of Energy Regulators
ADEME	Agence de l'environnement et de la maîtrise de l'énergie
AFIR	Alternative Fuel Infrastructure Regulation
AI	Artificial Intelligence
BECCS	Bioenergy with Carbon Capture and Storage
BEUC	European Consumer Organisation
BEV	Battery Electric Vehicle
BPIE	Buildings Performance Institute Europe
CAN	Climate Action Network
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCfD	Carbon Contracts for Difference
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CEEDS	Common European Energy Data Space
CEN	Comité Européen de Normalisation
CENELEC	Comité Européen de Normalisation Électrotechnique
CEF	Connecting Europe Facility
CER	Critical Entities Resilience Directive
CfD	Contract for Difference
CINEA	European Climate, Infrastructure and Environment Executive Agency
Climate-ADAPT	European Climate Adaptation Platform
CO_2	Carbon Dioxide
CRM	Critical Raw Materials
CSO	Central Statistics Office
CTP	Climate Target Path
DAC	Direct Air Capture
EASA	European Union Aviation Safety Agency
EC	European Commission / European Council
ECA	European Court of Auditors
ECB	European Central Bank
ECNO	European Climate Neutrality Observatory
EEA	European Environment Agency
EEB	European Environmental Bureau
EED	Energy Efficiency Directive
EGD	European Green Deal
EHP	European Hydrogen Backbone
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
EP	European Parliament
ESABCC	European Scientific Advisory Board on Climate Change
ESPR	Ecodesign for Sustainable Products Regulation
ETC	European Topic Centre

ETC CE	ETC Circular Economy and resource use
ETC CME	ETC on Climate Change Mitigation and Energy
ETS	European Trading System
EU	European Union
EU DC CoC	EU Code of Conduct for Data Centres
EUCO	European Council
EUCRA	European Climate Risk Assessment
EV	Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GT	Gross Tonnage
GW	Gigawatt
H2	Hydrogen
HARP	Heating Appliances Retrofit Planning
IA	Impact Assessment
IAM	Integrated Assessment Models
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
IRENA	International Renewable Energy Agency
IRP	UN International Resource Panel
ITF	OECD International Transport Forum
JRC	Joint Research Centre
Ktoe	Kilo-tonnes of oil equivalent
KWh	Kilowatt-hour
L&D	Loss and Damage
LCOE	Levelized Cost Of Electricity
LNG	Liquefied Natural Gas
LTRS	Long-Term Renovation Strategy
LTS	Long-Term Strategy
LULUCF	Land Use, Land-Use Change and Forestry
MEPS	Minimum Energy Performance Standard
Mt	Megatonnes
Mtoe	Million-tonnes of oil equivalent
NECP	National Energy and Climate Plan
NIMBY	Not In My Back Yard
NOx	Nitrogen Oxide
OECD	Organisation for Economic Co-operation and Development
OPEX	Operating Expenses
OPS	On-shore Power Supply
PCI	Project of Common Interest
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
PMI	Project of Mutual Interest
PPA	Power Purchase Agreement
PtX	Power-to-X
PV	Photovoltaics
R&D	Research & Development

RAP	Regulatory Assistance Project
REF	Reference
REM	Rare Earth Metals
RES	Renewable Energy Sources
SAF	Sustainable Aviation Fuel
SC1	High Ambition Scenario
SC2	Low Ambition Scenario
SC3	Partial Achievement Scenario
SCF	Social Climate Fund
SDE++	Stimulation of sustainable energy production and climate transition
SO2	Sulphur Dioxide
SUV	Sport Utility Vehicle
T&D	Transmission and Distribution
T&E	Transport & Environment
TEN-E	Trans-European Network for Energy
TEN-T	Trans-European Transport Network
TNC	The Nature Conservancy
TtW	Tank-to-Wheel
TWh	Terawatt-hour
TYNDP	Ten-Year Network Development Plan
UN	United Nations
UNEP	UN Environment Panel
V2G	Vehicle-to-Grid
VAT	Value-Added Tax
VOC	Volatile Organic Compound
VRE	Variable Renewable Energy
WEF	World Economic Forum
WtW	Well-To-Wheel
ZERO	Zero Emission Building

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Annex 1 Energy system progress assessment tables

Progress overview for key EU energy system indicators

Table A1.1 visualises how close specific energy system indicators are to reaching 2030 energy system benchmarks. Progress is measured by comparing the rate of change needed to meet the 2030 benchmarks with the actual growth trend seen over the last six years. Based on this comparison, progress is classified into the following categories:

On track	The necessary change is being met or exceeded.
Almost on track	The necessary change is only slightly faster than current trends.
Somewhat off track	Progress is slower, but the target is still achievable with moderate improvement.
Considerably off track	Significant acceleration is needed to meet the target.
Wrong direction	The trend is moving away from the target.
Not known	Insufficient/no reference data to assess the trend.

Source: EEA, based on EC, 2020c, 2024h and Eurostat, 2025.

Table A1.1 Indicator clustering according to five progress categories

System / State	On track	Almost on track	Somewhat off track	Considerably off track	Wrong direction	Total
Energy system (high level indicators)	**4**	**7**	**2**	**9**	**10**	**32**
GHG emissions from energy consuming sectors		2	1	2		5
Net greenhouse gas emissions			1			1
Gross available energy		1				1
Gross available energy by fuel	2	1		3	4	10
Final energy consumption — total				1		1
Final energy consumption by fuel	2	1		1	2	6
Final energy consumption by sector		2		2	1	5
Net fossil fuel imports by fossil fuel type					3	3
Electricity subsystem indicators	**2**		**2**	**11**	**4**	**19**
Electricity generation					1	1
Electricity generation by energy carrier	1			2		3
Electricity generation from renewables				1		1
Final electricity consumption					1	1
Final electricity consumption by end-use sector				2	2	4
Net installed capacity				1		1
Net installed capacity by energy carrier	1		1	1		3
Net installed electricity storage; new fuels production capacity				2		2
Net installed renewable capacity				1		1
Stored electricity (batteries, hydrogen, methane, pumped hydro)			1	1		2

Heating subsystem indicators	**11**	**6**		**11**	**22**	**50**
Stock of heat pumps in the residential and services sector				1		1
Consumption of gaseous fuels in the gas network					1	1
Energy consumption in industry by fuel	1	3			3	7
Final energy consumption in industry total		1				1
Final energy consumption in industry by sub-sector	4			2	4	10
Final energy consumption in residential sector total				1		1
Final energy consumption in residential sector by application	2			1		3
Final energy consumption in the residential sector by fuel	2	1		3	2	8
Final energy consumption in the services sector total		1				1
Final energy consumption in the services sector by energy carrier	2			1	4	7
Final bioenergy demand by sector and scenario				2	5	7
Final non-energy consumption in industry by fuel					3	3
Transport subsystem indicators	**6**	**2**	**1**	**10**	**15**	**34**
Direct CO_2 emissions from transport total		1				1
Direct CO_2 emissions from transport by mode	1	1		1	4	7
Energy consumption of road transport by fuel/energy carrier				3	2	5
Energy consumption of aviation by fuel/energy carrier				1	1	2
Energy consumption of domestic navigation by fuel/energy carrier	1			1		2
Energy consumption of international navigation by fuel/energy carrier	1		1	1		3
Energy consumption of rail by fuel/energy carrier				1	2	3
Final energy consumption of transport by fuel/energy carrier	3			1	2	6
Final energy consumption of transport by mode (vehicles, flights, etc)				1	4	5
Total	**23**	**15**	**5**	**41**	**51**	**135**

Notes: Progress indicators were calculated as the ratio between the annual absolute change required to meet the 2030 target (based on the average of EC scenarios S1 and S2) and the annual absolute growth trend observed over the past six available years of historic data. Depending on the ratio, the indicators were assigned to one of the following categories: 'On track' (ratio: 0–1; dark-blue highlight), 'Almost on track' (ratio: 1–1.5; light-blue highlight), 'Somewhat off track' (ratio: 1.5–2; yellow highlight), 'Considerably off track' (ratio: >2; orange highlight) and 'Wrong direction' (ratio: <0; dark-red highlight). Classification could not be calculated for four indicators due to insufficient historical data: FEC by fuel (hydrogen), FEC by fuel (synthetic fuels), Gross available energy by fuel (hydrogen) and GHG emissions (industrial removals). The 'Considerably off track' categorisation was determined through a review of scientific literature.

Source: EEA, based on EC, 2020c, 2024h and Eurostat, 2025.

Annex 2 Key measures to reduce industrial emissions

Multiple technological approaches are available to achieve significant reductions in GHG emissions within the industry sector. As the broad category of 'industry' encompasses a wide range of subsectors — each with distinct technologies and market conditions — reduction strategies ought to be tailored to subsector needs. The following table attempts to provide a synthetic, non-exhaustive overview of main reduction levers for industrial GHG emissions, clustered by resource (including energy) inputs, efficiency, technological change as well as end-of pipe and external solutions.

Implementation measures	Potential applications	Status	Challenges for scaling up	Overcoming the challenges
		Material efficiency		
• Recycling of products at the end of life • Reduction of primary production and extraction • Circular economy	• All industrial sectors	• Less mature than energy efficiency: • Circular Economy Action Plan (COM(2020) 98 final) • Clean Industrial Deal (COM(2025)85 final), including the commitment to develop a circular economy act by end-2026	• Requires a new layer of industrial applications competing with primary production incumbents • Product quality assurance • Diversity of goods and inputs • Uncertainties regarding quantified contributions (e.g. recycling potentials) and regarding assumptions of fundamental changes in consumption and production	• Improved waste management • Standardisation of products and inputs • New actors and flows of recycling materials will need to be aligned
		Energy efficiency		
• Improvements of existing processes in terms of energy demand • Remains important as new technologies are deployed	• All industrial sectors	• Energy Efficiency Directive (EU/2023/1791) sets out principles and targets, which are then implemented by national authorities	• Commonly applied • Energy efficiency commonly translates to reduced operating costs • Third party certification exists	• Continued expansion of knowledge base, strengthening energy efficiency networks on exchange

Implementation measures	Potential applications	Status	Challenges for scaling up	Overcoming the challenges
Alternative production technologies				
Industrial heat: • Fuel switch to heat pumps, electric boilers and alternative fuels	• Heat pumps are most efficient and suitable for temperatures below 200°C: paper, food, some chemicals • Other technologies reach higher temperatures	• High technology readiness level (TRL), but limited deployment, in particular of industrial scale heat pumps • If economically attractive, could be deployed rather quickly	• Electricity price uncertainty in view of renewable expansion • Technical constraints of facilities	• Reliability of electricity, other energy and CO_2 prices • Successful demonstration plants • Instruments to bridge the investment gap
Direct electrification: • Replacing fuels in furnaces or other applications	• Commonly for higher temperatures, e.g. ceramics, glass, some chemical processes (e.g.: steam cracker), etc.	• Limited deployment • Only induction furnaces are common • Demonstration plants exist	• Electricity price uncertainty in view of renewable expansion Research and experience from upscaling demonstration plants	• Same as above
Decarbonised gases: • Hydrogen or alternatives, replacing fuels in furnaces or other applications	• Fuel switch from natural gas • Primary metal industry (alternative reduction agent, very high temperatures), glass, ceramics, chemical processes (integration with feedstock)	• Limited deployment • Research stage and first pilot systems	• Cost and availability of clean hydrogen • Technical constraints of facilities • Research and development	• As above • Also, support of H2-production and demand to incentivise market and provide reliability • Building up an infrastructure by repurposing or building new pipelines and import hubs
Decarbonised gases: • Feedstock decarbonisation	• Switch from natural gas • Mainly in the chemical industry • Closely linked to a circular economy	• Very limited to no deployment	• Cost and availability of clean hydrogen • New production pathways in the chemical industry (switch to methanol-to-olefin route)	• As above • Also, research and development for alternative production routes which apply decarbonised alternatives
• Biomass as energy carrier or feedstock	• In theory all industries •Current users are paper and food industry, which process biomass and use waste • In combination with CCS to generate negative emissions	• Widely established	• Limited availability of sustainable biomass • Competing for usage with other sectors, with possible implications on land carbon stocks, biodiversity and air pollution	• Limited availability cannot be overcome • Upholding sustainability requirements to avert negative effects • Choosing other sustainable levers
Carbon Capture and Use (CCU) and Carbon Capture and Storage (CCS)				
• Capture of hard to abate emissions, typically process emissions to be stored underground or in long lived products	• Seen as main reduction lever for process emissions, e.g. in calcination, as in cement, lime, some others • Could be used for energy emissions as well	• High TRL, with first pilot plants for underground storage in North Sea • Storage in products under discussion • Industrial Carbon Management Strategy (COM(2024) 62 final)	• Costs of capturing • Lack of infrastructure for transportation and storage • Increased public acceptance • Regulation for CCU • Limited experience on storage	• Successful pilot projects • Regulation of cross-border transport • Planning and building the infrastructure
Negative emission technologies				
• Last resort, emissions are compensated in other sectors	• Energy use of biomass in combination with CCS • Applications outside industry subject to research	• Early research ongoing • Accounting of negative emission not established	• Sustainability and effectiveness need to be ensured	• Research of technological options • Regulation and accounting need to be established

As shown in Section 3.2.2, the transformation levers for industrial decarbonisation solutions have been mapped out. The electrification of process heat generation will be the key lever for this transformation by 2030.

Other technologies, such as hydrogen and CCUS, will play a small yet critical supporting role by 2030. This is particularly relevant in those industrial sectors that are more difficult to decarbonise and has some applications in transport (e.g. shipping). These technologies require further incentives to be tested at the commercial scale.

European Environment Agency

Renewables, electrification and flexibility
For a competitive EU energy system transformation by 2030

2025 — 135pp. — 21 x 29.7cm

ISBN: 978-92-9480-728-1
doi: 10.2800/4558900

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TH-01-25-022-EN-N
doi:10.2800/4558900