European Commission

IRENA
International Renewable Energy Agency

REGIONAL ENERGY TRANSITION OUTLOOK
EUROPEAN UNION

ISBN: 978-92-9260-658-9

Citation: IRENA (2025), *Regional energy transition outlook: European Union* , International Renewable Energy Agency, Abu Dhabi.

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

Acknowledgements

The report was developed under the guidance of Roland Roesch (ex-Director, IITC) and Ricardo Gorini. It was authored by Sean Collins, Milenko Matosic Suárez, Rodrigo Leme, Gondia Seck, Bishal Parajuli and Yuan Sun (IRENA), María Vicente García, Adam Adiwinata, and Pablo Rimancus (consultant).

IRENA would like to also thank for all their support and guidance: Kendall Esmeijer, Andreas Zucker, Sebastian Sterl and Biljana Kulisic (DG ENER); Immavera Sardone, Titas Anuskevicius and Vincent Basuyau (DG GROW); Georgia Kitsaki and her team (DG MOVE); all representatives from participating Member States who took part in the engagement workshop, October 2024.

The report also benefitted from valuable inputs from technical experts: Varvara Aleksic, Simon Benmarraze, Norela Constantinescu, Francisco Gafaro, Chun Sheng Goh, Petya Icheva, Danial Saleem (IRENA), Daniel Carillo and Nicholas Wagner (ex-IRENA).

Publication and editorial support were provided by Francis Field and Stephanie Clarke. Technical review was provided by Paul Komor. The report was edited by Steven Kennedy with design provided by Nacho Sanz.

This report was funded by the European Commission and prepared by IRENA in collaboration with the European Commission and benefited from consultations with Member States.

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International Renewable Energy Agency

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EUROPEAN UNION

FOREWORD

Francesco La Camera

Director-General

International Renewable Energy Agency

The European Union (EU) continues to lead the global energy transition, taking decisive steps to secure its economic and industrial competitiveness, reduce fossil fuel import dependency and enhance energy security. Its commitment to the transition is embodied by ambitious climate targets, as well as landmark policies and plans such as the Clean Industrial Deal, the Action Plan for Affordable Energy and REPowerEU.

End-use sector decarbonisation, however, remains a considerable challenge to progress, owing to slowing electric vehicle adoption, resistance from hard-to-decarbonise industries and limited success in building renovation. Meanwhile, the global climate agenda faces growing headwinds as political shifts threaten to undermine international unity on climate commitments.

The leading role of the EU at the forefront of the global energy transition remains vital, therefore. With renewable energy at the heart of its strategy, the EU seeks to balance energy security, economic competitiveness and climate action, whilst leveraging the strong business case offered by the energy transition, unlocking new market opportunities, driving innovation and attracting investment in renewable energy technologies.

The shift to clean, affordable energy also forms a key pillar of the European Commission's 'competitiveness compass' – a roadmap that seeks to catalyse a new era of dynamic, sustainable growth across Europe.

It is in the context of this drive for a more competitive, decarbonised EU economy that IRENA has produced this regional outlook for the energy transition. Developed in close collaboration with the European Commission and EU Member States, it provides key insights to support the refinement and implementation of the policies and regulations required to achieve a secure, competitive, climate-aligned energy system.

In the coming years, the EU's energy transition goals will depend on: accelerating infrastructure integration and expansion; committing to renewable electrification; and strengthening institutional frameworks for integrated energy planning and implementation, with robust enforcement mechanisms to secure accountability.

Investing in the energy transition within the EU brings clear benefits in terms of security, competitiveness and climate protection. Built around low-cost renewables, the transition can enhance energy independence and deliver affordable and sustainable energy to industry, households, communities and citizens across the EU.

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ABBREVIATIONS

AI	artificial intelligence
CBAM	Carbon Border Adjustment Mechanism
CCS	carbon capture and storage
CO_2	carbon dioxide
COP	Conference of the Parties
DES	Decarbonising Energy Scenario
DRI	direct reduced iron
DSM	demand-side management
E3ME	Energy-Environment-Economy Model for Europe
EC	European Commission
EJ	exajoule
ENTSOE/G	European Network of Transmission System Operators for Electricity/Gas
EPBD	Energy Performance of Buildings Directive
ETS	Emission Trading System
EU	European Union
EV	electric vehicle
ESCO	energy service company
H_2	hydrogen
GDP	gross domestic product
GHG	greenhouse gas
GJ	gigajoule
Gt	gigatonne
GW	gigawatt
HVDC	high-voltage direct current
ICE	internal combustion engine
IRENA	International Renewable Energy Agency
KPI	key performance indicator
LCAF	lower carbon aviation fuels
LTAG	long term aspirational goal
LPG	liquefied petroleum gas
Mt	million tonnes
$MtCO_2$ eq	million tonnes of carbon dioxide equivalent
Mtoe	million tonnes of oil equivalent
MWh	megawatt hour
NECPs	National Energy and Climate Plans
PES	Planned Energy Scenario
PJ	petajoule
pkm	passenger-kilometre
PV	photovoltaic
PWh	petawatt hour
R&D	research and development
RED	Renewable Energy Directive
RFNBOs	renewable fuels of non-biological origin
SAF	sustainable aviation fuel
TFEC	total final energy consumption
tkm	tonne kilometre
TW	terawatt
TWh	terawatt hour
TYNDP	Ten-Year Network Development Plan
VRE	variable renewable energy
WETO	World Energy Transitions Outlook

Unless otherwise stated, monetary values (EUR) are in constant 2024 euros.

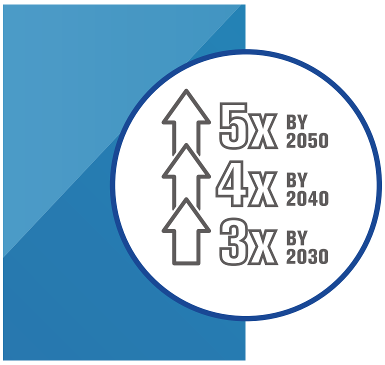
EXECUTIVE SUMMARY

KEY MESSAGES

The European Union (EU) plays a leading role in global efforts to mitigate climate change. Rising carbon dioxide (CO_2) emissions, weakening global climate governance and surging investment requirements necessitate faster and more co-ordinated EU action to propel the energy transition towards net-zero emissions by 2050. The EU's next steps, including its participation in climate and energy transition forums – notably the Conference of the Parties (COP), the Group of Twenty (G20) and the Group of Seven (G7) – will be decisive for the success of Paris Agreement goals.

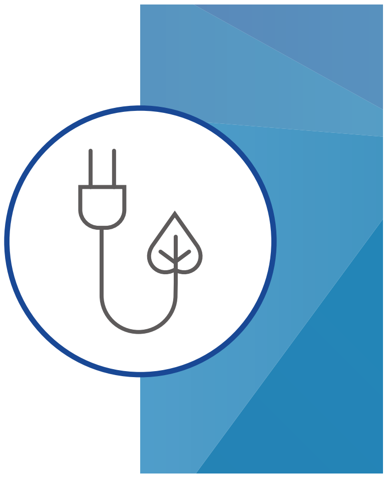
As the European Union strives to advance the energy transition, it must pay close attention to energy price inflation and energy supply security. This is not a reason to slow down, but to ensure the transition is smart, balanced and maintains public support. The pace of implementation of European and international commitments must be balanced with concerns over energy security and affordability through strategic investments and well-managed rollout.

The EU long-term strategy to achieve net-zero emissions by 2050 is already aligned with the Paris Agreement's 1.5°C threshold and backed by appropriate targets for renewable energy, renewable fuel and energy efficiency. Increasing renewables' share in the generation mix would deliver rapid CO_2 emissions reductions while balancing the priorities of energy security, energy efficiency and economic competitiveness. Achieving this will require not only ambition, but faster implementation at all levels. To tap renewables' potential, power sector infrastructure must be expanded and modernised. Innovative solutions, such as sector coupling, energy storage, and smart grids that use digital technologies, can all play a key role in minimising and optimising costs across the energy sector.



Renewable power capacity may potentially triple by 2030, grow by four times by 2040 and by five times by 2050 (vs. 2021). However, this pace of growth is not assured, and it is essential to secure energy system stability even while accelerating renewables' deployment. Protecting power grids and facilities from increasingly frequent, extreme climate events and other risks (including cyber risks) is another priority. Strengthening regional markets, fast-tracking flexibility solutions and promoting cost-competitive innovations in storage are crucial for a resilient and competitive power system.

Implementing the energy transition at the right pace across Member States is a key challenge and the phasing down of fossil fuels needs to accelerate. The EU is not on track to meet its short-term renewable energy and emissions targets for 2030.[1] Furthermore, the European Commission's mid-term 2040 climate target (to reduce net emissions by 90%) will only be achieved with additional measures in Member States. Presently, national implementation across sectors, technologies and energy carriers is lagging. Stronger governance and differentiated responsibilities are needed. Disparities in decarbonisation action among the Member States may require extra efforts from some countries to compensate for lags in others.



Investing in clean energy and modern infrastructure is key to keeping electricity affordable. As renewables expand, wholesale prices tend to fall, reflecting lower operating costs and reduced exposure to fossil fuel price swings. By 2050, a fully decarbonised system can provide greater price stability, but this requires targeted investment today. Beyond grids and flexibility, policy makers must prioritise a broad portfolio of investments - scaling up renewable generation, advancing storage technologies, upgrading market design, and modernising infrastructure - to ensure long-term affordability and resilience. Delaying these investments may engender long-term costs and insecurity – early action is both strategic and cost effective.

[1] *Under the revised Renewable Energy Directive, the EU aims for renewable energy to constitute at least 42.5% of its gross final energy consumption by 2030, with an aspirational goal of reaching 45%, while the "Fit for 55" package targets a minimum 55% reduction in emissions below 1990 levels by 2030.*

Good governance and enforcement are needed to guide the energy transition. Integrated and co-ordinated energy planning at the EC level can also help in prioritising actions, allocating resources and co-ordinating enforcement across Member States. The current EU model of a central strategy with national implementation would benefit from becoming more agile and better aligned at the regional level, given the acceleration required for 1.5°C compatible decarbonisation, competitiveness enhancement and energy security assurance.

Legislation, including policies, regulations, decisions and recommendations, may need to be enhanced to help steer economic structures and value chains towards less carbon-intensive sectors, more sustainable consumption patterns, and more responsible consumer behaviour. Therefore, shifting the economic structure of the European Union towards greener sectors can support emission reduction targets. In addition, achieving net zero by 2050 will require the widespread adoption of the best available energy-efficient technologies across all sectors, as well as a highly efficient use of resources in both production and consumption. This structural shift should be accelerated with a stronger legislative and financial push across multiple levels.

EU industrial policies and plans – such as the Net-Zero Industry Act and the Clean Industrial Deal – are key to aligning competitiveness and security. Strengthening trade and inter-bloc co-operation can also play an effective role in cutting emissions while raising energy security and economic competitiveness. While the industrial policy on minimum local content helps regional industrialisation, key areas and sectors may benefit more from trading with regions and countries that have natural competitive advantages, such as abundant natural resources and competitive renewable sources. Balanced trade and diversified suppliers increase energy security and avoid the risk of disruption of value chains. Europe's industrial decarbonisation should therefore be matched by strategic external partnerships and diversified supply chains.

Further development of regional energy integration within the European Union is an effective, cost-competitive measure to accelerate emission cuts. Effective integration requires a holistic approach, from physical infrastructure to markets and governance, tapping into the best renewable resources and the most productive areas across Member States. However, grid congestion and the need for significant grid expansion – from north to south and east to west – pose critical challenges. A more integrated EU energy market will also support lagging Member States and ensure a fairer, faster transition overall. Expanding and reinforcing transport, grid infrastructure, energy markets, permitting and co-operation on transition investments are enablers of an effective energy transition implementation package.

In addition to reducing emissions, the EU energy transition enhances energy security and competitiveness, while also delivering socio-economic benefits including jobs, welfare and health improvements – provided the right policy frameworks are in place at both national and EU levels.

KEY FINDINGS

The European Union's efforts to achieve the Paris Agreement comprise a portfolio of actions across different sectors and energy carriers, which requires effective energy planning and co-ordination of implementation. Renewable generation powering deep electrification, combined with strong energy efficiency measures, and complemented by fostering biomass and hydrogen derivatives utilisation, are the key drivers for achieving net zero by 2050. However, implementation gaps persist and need to be urgently addressed to stay on track.

The *key performance indicators* and the *key actions for net-zero energy transition* depicted below summarise the goals to be achieved in each of these avenues. Two scenarios are shown; the Planned Energy Scenario (PES) is the primary reference case for this study, providing a perspective on energy system development based on current energy plans and policies implemented at the European and Member State level. The Decarbonising Energy Scenario (DES) includes alternative pathways towards reaching the targets and aspirations set by the European Commission to combat climate change, enforce energy security and enhance competitiveness. The gap between the two scenarios illustrates the scale of additional effort and ambition needed.

Table S1 Key performance indicators for the EU27 energy transition

	HISTORICAL	PLANNED ENERGY SCENARIO			DECARBONISING ENERGY SCENARIO		
	2021	2030	2040	2050	2030	2040	2050
KPI.01 RENEWABLES (POWER)							
Renewable energy electricity generation (TWh/yr)	967	2 254	2 920	3 538	2 271	3 312	4 253
Renewable energy share in electricity generation (%)	36%	71%	75%	78%	70%	82%	88%
Renewable energy installed capacity (GW)	491	1 246	1 717	1 993	1 247	1 919	2 456
Renewable energy share in installed capacity (%)	52%	79%	86%	87%	79%	88%	91%
KPI.02 RENEWABLES							
Renewable energy share in gross final energy consumption (%) [1]	20%	39%	56%	70%	43%	69%	85%
Renewable energy share in final energy consumption (%) - direct only[2]	10%	15%	17%	17%	16%	17%	17%
Modern use of bioenergy[3] (EJ)	6.0	8.1	8.7	8.5	8.0	8.5	7.6
KPI.03 ENERGY INTENSITY							
Energy intensity improvement rate (%)	1.8%	2.5%	2.3%	2.0%	3.2%	2.8%	2.4%
KPI.04 ELECTRIFICATION IN END-USE SECTORS (DIRECT)							
Electrification rate in TFEC (%)	22%	30%	46%	56%	33%	52%	64%
KPI.05 CLEAN HYDROGEN AND DERIVATIVES							
Production of clean hydrogen[4] (Mt)	< 1	1.7	7.6	14.2	1.9	9.6	19.2
KPI.06 CCS, BECCS AND OTHERS							
CO_2 captured from CCS, BECCS and other removal measures (Mt)	< 10	49	98	121	45	96	116

1 *Please refer to the considerations for calculating the share of renewable energy in final energy consumption and in gross final energy consumption, as outlined in note 5 of page 24..*

2 *Direct renewable share includes direct use of renewables (bioenergy, solar and geothermal).*

3 *Modern use of bioenergy excludes traditional uses of biomass in inefficient stoves and open fires. It includes modern bioenergy use in final energy consumption, international bunkers, transformation centres' own use and non-energy uses.*

4 *Clean hydrogen includes hydrogen produced through electrolysis and biomass gasification, as well as blue hydrogen. The shares of clean hydrogen over total hydrogen production in 2030, 2040 and 2050 are 25%, 73% and 94% in the PES and 29%, 80% and 98% in the DES. These total quantities are notably lower than those assessed in the European Commission Impact Assessment Report for the 2040 Climate Target Communication.*

Notes: BECCS = bioenergy with carbon capture and storage; CCS = carbon capture and storage; CO_2 = carbon dioxide; EJ = exajoule; GW = gigawatt; KPI = key performance indicator; Mt = million tonnes; TFEC = total final energy consumption; TWh = terawatt hour.

Box S1 Key actions for the net-zero energy transition

SECTOR / TECHNOLOGY	BY 2030	BY 2040	BY 2050
Total final energy consumption	Reduce total final energy consumption to 750 Mtoe (30.3 EJ), reflecting efficiency gains and early fuel switching.	Decline further to 581 Mtoe (23.4 EJ) as electrification and renewables dominate across sectors.	Reach 493 Mtoe (19.7 EJ), driven by widespread efficiency, electrification, and fuel substitution.
Renewable share in gross final energy consumption	Raise the renewable share to 43%, driven by accelerated electrification and direct renewable use.[1]	Scale up to 69% as renewables become the dominant source across power, heat, and transport.	Reach 85%, marking a near full transition to renewables in final energy use.
Wind and solar	Deploy at least 1 100 GW of new wind and solar capacity, with corresponding grid expansion, to bring total renewable capacity to 1 247 GW.	Increase wind and solar capacity to nearly 1 800 GW, integrating significant system flexibility, raising total renewable capacity to 1 919 GW.	Expand wind and solar capacity to almost 2 300 GW, achieving a 91% renewable share in total power capacity, and bringing total renewable capacity to 2 456 GW.
Storage and flexibility	Deploy at least 45 GW of battery storage capacity.	Integrate over 230 GW of battery storage and enhance system flexibility.	Integrate over 240 GW of battery storage into a flexible power system with deeply embedded sector coupling.
Heat pumps	Install 51 million heat pumps in buildings; scale at 7% annual growth.	Install 76 million heat pumps in buildings.	Install 87 million heat pumps in buildings.
Industrial electrification	Increase electricity share from 31% (2021) to 41%.	Increase electricity share to 51%.	Electrify 61% of industrial energy use.
Buildings efficiency[2]	Improve energy efficiency by 2.6%/year via retrofits (vs. 2021).	Improve efficiency by 2.1%/year via retrofits (vs. 2021).	Improve efficiency by 1.9%/year via retrofits (vs. 2021).
Electric vehicles (EVs)	Deploy 100 million EVs[3] (from 5.8 million in 2021[4]) and expand charging infrastructure.	Deploy 275 million EVs.	Deploy 335 million EVs.
Hydrogen and its derivative fuels	Prepare framework for regional hydrogen hubs and large-scale electrolysis.	Expand hydrogen pipelines and produce 10 Mt of clean hydrogen.	Produce 20 Mt of clean hydrogen[5] with industrial uptake hydrogen and its derivative fuels; establish global hydrogen trade routes.
Carbon capture (CCS/BECCS)	Pilot CCS/BECCS projects capturing 44 $MtCO_2$ per annum, focusing on industrial demonstrations.	Scale capture to 84 $MtCO_2$ per annum, with CO_2 transport and storage infrastructure.	Capture 99 $MtCO_2$ per annum, achieving net-negative emissions.

[1] *Please refer to the considerations for calculating the share of renewable energy in final energy consumption and in gross final energy consumption, as outlined in the page note of Section 1.2, Chapter 1.*

[2] *The retrofit rate for each decade is relative to year 2021 and refers to the rate needed to achieve the specific target (energy consumption and emissions) in each decade if the EU would only want to achieve the specific target in the respective decade. For example, if only the targets in 2050 would be relevant, then the retrofit rate needs to be 1.9% relative to 2021.*

[3] *EVs include electric and plug-in hybrid cars, motorcycles, buses, and light- and heavy-duty trucks.*

[4] *The number of electric vehicles in 2021 include cars, buses, light and heavy-duty trucks (ACEA, 2024b).*

[5] *Clean hydrogen includes hydrogen produced through electrolysis, biomass gasification, and blue hydrogen. The shares of clean hydrogen in total hydrogen production in 2030, 2040, and 2050 are 25% (20% electrolysis, 2% biomass, 3% blue), 73% (55% electrolysis, 2% biomass, 16% blue), and 94% (81% electrolysis, 1% biomass, 11% blue) in the PES. In the DES, clean hydrogen shares reach 29% (23% electrolysis, 4% biomass, 3% blue) in 2030, 80% (58% electrolysis, 4% biomass, 19% blue) in 2040, and 98% (80% electrolysis, 3% biomass, 14% blue) in 2050.*

Notes: Indicators presented in the table correspond to the Decarbonising Energy Scenario. GW = gigawatt; EVs = electric vehicles; Mt = million tonnes; CCS = carbon capture and storage; BECCS = bioenergy with carbon capture and storage; CO_2 = carbon dioxide; EJ = exajoule; Mtoe = megatonnes of oil equivalent

The pace of implementation of new renewable technology investments and penetration is falling short of what is required to meet the targets set for 2030, 2040 and 2050. Total energy consumption by 2030 is expected to decline by 20% and 23%, respectively, compared to 2021 in the two scenarios that underpin this report. Final energy consumption is expected to reach 764 million tonnes of oil equivalent (Mtoe) and 723 Mtoe in the PES and DES, respectively, from 950 Mtoe in 2021, due to growing energy efficiency and structural changes. Meeting these reductions will require stronger and faster national implementation and enforcement mechanisms. Investment of about EUR 1 trillion per year will be required through 2050 for the EU27 energy transition. This amounts to EUR 23 trillion and EUR 26 trillion in cumulative terms for the PES and DES, respectively.

In the transport sector, policies need to encourage lower-cost mobility, establish stronger links between modes and last-mile services, encourage modal shifts and emphasise energy efficiency. Policies and measures to reduce the costs of electric vehicles (EV) for consumers pave the way for a sustainable and competitive sector. Railway quality infrastructure across and within Member States, effective services and lower consumer prices should increase usage of this mode and reduce flights within and between EU Member States. Transport needs to now be treated as a priority decarbonisation frontier, as one of the largest emitters (23% of EU CO_2 emissions in 2022) and lagging in modal shift and electrification. By 2050, domestic transport consumption is expected to fall by 60% from 11 exajoules (EJ) in 2021 to 4.6 EJ in the PES and 4.3 EJ in the DES. Electrification is the main driver for road transport decarbonisation and an annual investment of EUR 11.2 billion will be needed in transport infrastructure.

Innovation and strategic positioning in the green and high-tech value chains can reduce emissions intensity and contribute to cutting emissions, while contributing to competitiveness. Industry is currently the second-highest emitter after transport and needs to reach net zero by 2050. By 2030, the overall percentage of renewable energy in industry, including direct and indirect consumption, is set to reach 47%. The share of renewable energy in the industry sector is expected to increase to 58% by 2040 and 65% by 2050, driven by more use of direct renewables and a higher share of renewable electricity. The industrial transition should be accelerated through support for electrification, bioenergy, CCS and green hydrogen, alongside innovation and processes. The supply of renewable fuels for EU industry may depend on strengthening trade in renewable energy between the European Union and other economic blocs. The possible relocation of industries within and outside the European Union should not be ruled out. Up to EUR 14 billion will be required each year in total investment.

Municipalities and provincial governments need to work in close co-operation with Member States to plan ambitious building transformations. Accessible funding for such initiatives will come from national and European funding programmes (including national development banks), as well as hybrid solutions in co-operation with the private sector (*e.g.* construction companies, energy service companies and private banks). Currently, the buildings sector represents one-third of the EU's energy-related greenhouse gas emissions and 40% of the energy consumed in the European Union is used in buildings. Buildings remain a massive untapped opportunity for emissions cuts, requiring a stronger governance model and faster renovation pace. Overall, for the buildings sector to be climate neutral by 2050, energy conservation and efficiency must push down energy consumption by 6 930 petajoules (PJ) relative to 2021. Scaling up of long-term average annual investment to EUR 75 billion will likely be required for renovation work such as improving thermal efficiency. This would represent a 4-fold increase on the investments of 2021.

The EU power sector is set to generate about 70% of electricity from renewables by 2030 and nearly 90% by 2050, in line with EU and national targets. Installed capacity of renewable power will need to reach 122 gigawatts (GW) per year on average over the period 2025-2050, which indicates that renewable rollout needs to scale by factor of just under 2 from recent levels. However, this profound transformation, driven by mostly vast wind and solar expansion, faces critical challenges, notably the need for substantial investments between 2025 and 2050 of EUR 5 600 billion or EUR 220 billion per year on average – a near 50% increase on today's levels. Faster grid expansion, integration and regional planning are essential to unlock this transition and avoid bottlenecks. A more decarbonised system in the DES leads to a more stable long-term price trajectory (~EUR 66/megawatt hour [MWh] by 2050), whereas a more fossil-dependent pathway in the PES results in higher and more volatile prices (~EUR 79/MWh). The difference reflects the cost advantage of renewables as well as grid interconnections over time.

Natural gas power generation capacity remains a strategic asset for the EU27 system, which gives a spotlight to its renewable alternative: biomethane, either as biogas or its upgraded form. Natural gas should be maintained as a backup resource for extreme scenarios to ensure grid reliability while cost competitive technological and system innovations are further deployed. Strategic flexibility, not fossil fuel dependency, should be the guiding principle. Nuclear offers baseload power generation but lacks the operational flexibility required to support variable renewables. The most urgent actions overall, however, include accelerating infrastructure deployment, scaling up storage and demand-side response measures, implementing regulatory reforms to mitigate market risks, and promoting cross-border co-operation to optimise resource use and reduce costs.

A renewables-based power system requires a step change in integration and flexibility to ensure security of supply and cost-effective decarbonisation. Scaling up grids and regional inter-connection, energy storage, demand-side management and smart-grid technologies will need to be prioritised to balance supply and demand efficiently. A shared EU-wide approach to flexibility planning and investment is critical to make this work efficiently and equitably. Regulatory frameworks that embody real-time pricing, demand response and grid-supportive tariffs to incentivise flexibility will be essential in creating the right conditions for effective renewables integration, system flexibility and sector coupling. Strengthening cross-border inter-connections and regional co-operation will be equally important, allowing Member States to optimise resources, reduce system costs and improve resilience. Without a co-ordinated approach, the energy transition will be slower, more costly and less secure.

While hydrogen has a role in the energy transition, its deployment should be prioritised based on sector needs and cost-effectiveness. Focus should be placed on hard-to-abate sectors and international co-ordination to ensure cost-effective scale-up. Although hydrogen and its derivative fuels play a less prominent role in the energy transition than other carriers, they still meet 2% and 4% of final energy consumption by 2030 and 2050, respectively, in the DES. Clear regulations and global collaboration are key to scaling hydrogen in hard-to-abate sectors through investment, aligned standards and robust value chains. Investment in hydrogen production plants will need to reach over EUR 130 billion in the EU between 2025 and 2050, which corresponds to EUR 5 billion per year on average and is a significant scaling on recent levels.

The European Union shows significant potential for bioenergy from crop and forestry residues. This potential far exceeds current consumption levels. Mobilising this potential sustainably requires improved supply chains, innovation and efficient use, not just volume increases. Under the Medium Mobilisation Scenario, over 500 Mt of sustainably sourced biomass – mainly from agriculture and forestry – could be mobilised, enabling the EU to self-supply a significant share of biofuels under strict sustainability and emissions criteria. International trade will remain important to balance supply and demand, especially for key commodities like sustainable aviation fuel, while efficient trade partnerships can support access and downstream development. Improved supply chain efficiency, integration with renewables, and advances in agriculture and innovation could further expand biomass availability and reduce overall system costs. In total, more than EUR 289 billion of cumulative investment may be needed to meet bioenergy requirements for the period between 2025 and 2050, which corresponds to nearly EUR 12 billion per year on average.

Priorities for the 2024-2029 mandate of the European Commission are to promote further electrification across all end-use sectors, enhance and prepare power infrastructure, and scale up energy efficiency and conservation, while establishing a net of trade alliances with other economic blocs pursuing cuts in emissions. This will require urgency and clarity in leadership, ensuring all Member States are aligned, supported and held accountable. Electrification is already the most cost-effective solution for the energy transition. Policies should promote a shift in energy use toward electricity across all sectors. At the same time, there is still significant untapped potential in energy efficiency and conservation. The energy intensity improvement rate must grow from under 2% per year today to over 3% by 2030, as shown in Table S1. All Member States should work to reduce overall energy consumption. In total, more than EUR 2 066 billion of cumulative investment may be needed to meet energy conservation and efficiency needs for the period between 2025 and 2050, which corresponds to nearly EUR 83 billion per year on average.

Under the DES, the EU27 is expected to improve its gross domestic product (GDP) by an additional 2.1% on annual average over the 2023-2050 period compared with the PES. Economic gains would be real and substantial if action is timely and co-ordinated. The EU economy would add approximately EUR 724 billion in 2050 (or around EUR 576 billion per year throughout the 2023-2050 period) under the DES compared with the PES. Investment, indirect and induced effects, and trade (to a lesser extent), are the main macroeconomic factors that have key impacts on the difference in GDP results, depending on the period analysed. Similarly, under the 1.5°C Scenario, cumulative employment is expected to be on average 0.9% higher than under the PES over the 2023-2050 period.

Employment in the EU energy sector would potentially reach nearly 8 million jobs under the DES in 2030 compared with the current figure of around 3.2 million. By 2050, the total number of jobs would fall to 6.8 million in the DES, which would still be 45% higher than the expected figure under the PES (c. 4.7 million). The gain of around 2.7 million jobs in renewables and other transition-related sectors (energy efficiency, power grids and flexibility, vehicle charging infrastructure and hydrogen) would greatly surpass job losses. The job opportunities in the renewable energy sector are projected to increase significantly from 1.3 million in 2021 to more than 1.6 million by 2050 under the PES. Under the DES, wind and solar are expected to dominate the renewable energy job market in the European Union, accounting for more than 1.1 million and around 1.6 million jobs in 2030 and 2050, respectively.

The welfare improvement under the DES over the PES reaches 14.3% by 2050. Social welfare, which provides the greatest improvement, is boosted vastly under the DES owing to significant improvements in public health that stem from reduced air pollution and lower heat stress. The transition is not only an environmental and economic imperative, it is a social one. The distributional dimension is the second-largest driver in improving welfare in the DES in the European Union, followed by environmental benefits, wider energy access and economic gains.

INTRODUCTION

The European Union (EU) is leading the climate change fight, fostering economic competitiveness and pursuing energy security.

In Paris in 2015, signatories to the United Nations Convention on Climate Change agreed to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. In 2021, IRENA presented a pathway to 1.5°C in the first edition of the *World Energy Transitions Outlook*. Over 90% of the solutions shaping a successful decarbonisation outcome in 2050 involve electrification, energy efficiency, renewable energy through direct supply, such as green hydrogen and bioenergy combined with carbon capture and storage.

According to the Outlook, to limit global warming to 1.5°C by 2100, the world must reach net-zero greenhouse gas emissions around 2050. Alternative pathways with delayed action require a heavy reliance on negative emissions and are fraught with risks and uncertainties. Despite the commitments made at the 28th Conference of the Parties (COP28) in Dubai in 2023 and new initiatives from the Group of Twenty (G20), Group of Seven (G7) and COP29 in Baku in 2024, the energy transition remains off track. For COP30 in Belem, Brazil, challenging discussions on scaling up funds to combat climate change await, while recent political changes portend waning support for climate action.

While 2023 saw record growth in renewables deployment in the power sector, progress has been geographically uneven, and lacklustre for other sectors and alternative energy carriers. 2024 was the first year with an average temperature clearly exceeding 1.5°C above the pre-industrial level (European Commission, 2025). Fossil fuels continue to dominate the energy mix in major economies – the world's largest carbon dioxide (CO_2) emitters – and each year the chances of meeting the targets of the Paris Agreement become increasingly remote. The world requires strong leadership and concerted efforts to implement the Paris Agreement.

The European Union has been leading the efforts to accelerate emissions reduction and the energy transition. In 2014, the 27 European Union countries (EU27) represented 7.74% of global CO_2 emissions (2 709 million tonnes of carbon dioxide equivalent [$MtCO_2eq$]); renewable energy was 16% of final energy consumption (European Commission, 2016). After several years (2021), the EU27 represented 7% of global CO_2eq emissions (2 568 $MtCO_2eq$), while renewables were about 21% of final energy consumption. Furthermore, the European Union is strongly committed to further decarbonisation. Progress on several fronts has been announced raising targets for energy efficiency, renewable power and renewable fuels, as well addressing sustainable solutions in end uses and reducing overall emissions.

The European Union has also been promoting renewable energy as part of the solution to foster energy security. The European Commission (EC) made additional plans to complement the Green New Deal, such as REPowerEU and REfuelEU, which suggest raising ambitions for renewable power and renewable fuel production within the European Union, in substitution for fossil fuel imports. Other initiatives, such as the expansion of the Emissions Trading System to additional sectors, and the establishment of the Carbon Border Adjustment Mechanism (CBAM), aim to create the right environment and incentive structures for accelerating the energy transition.

The principles of combatting climate change, enforcing energy security and enhancing competitiveness were reiterated by EC President Ursula von der Leyen at the time of her re-election and reinforced in the Mission Letter[1] to Teresa Ribera Rodriguez, executive vice-president for a clean, just and competitive transition (European Commission, 2024a); "My view is that our era's greatest challenges – from security to climate change to competitiveness – can only be solved through joint action … Our threats are too great to tackle individually. Our opportunities are too big to grasp alone" (von der Leyen, 2024).

Consistent with those principles, the EC adopted the following pillars for the five years to 2029:

- Make business easier and deepen the European Single Market
- Build a Clean Industrial Deal to decarbonise and bring down energy prices
- Put research and innovation at the heart of the European economy
- Boost productivity through the diffusion of digital technology and invest heavily in sustainable competitiveness
- Tackle the skills and labour gap (Draghi, 2024; European Commision, 2025; European Commission, 2024b).

This is the context of this report: A new set of government priorities at the EU level, emphasising the Union's leading role in fighting climate change while fostering EU economic competitiveness and affordable energy security.

[1] *Mission Letters are received by each commissioner from the President of the European Commission at the beginning of each new mandate. The letters set the specific priorities and responsibilities of the commissioners in line with the European Commission's broader objectives.*

Aim and scope of the REmap analysis for the EU27

This is the second time that IRENA has co-operated with the European Commission to assess the energy transition in the European Union. In 2018, IRENA, in close collaboration with the Commission, laid out a renewable energy roadmap for the European Union to show how the proposed renewable energy share target could be realised. The study was welcomed and contributed to support negotiations and the raising of ambitions (IRENA, 2018a). In 2022, IRENA and the European Commission agreed to collaborate on the present study to further assess pathways for EU decarbonisation through 2050. The analysis aims to help the European Commission define its energy transition strategy and policy making and to underpin communications with stakeholders and Member States. The analysis also provides a combined assessment of the measures and policies currently in place in the European Union for 2030, 2040 and 2050.

This analysis relies on two key scenarios:

Planned Energy Scenario

The **Planned Energy Scenario (PES)** is the primary reference case for this study and represents a transition pathway consistent with the European Commission and Member State plans and policies as of December 2024. This scenario strives for climate neutrality and elaborates on the anticipated trajectory.

Decarbonising Energy Scenario

The **Decarbonising Energy Scenario (DES)** represents alternative pathways or additional measures towards reaching the goals, targets and aspirations set by the European Commission, to combat climate change enforce energy security and enhance competitiveness. This scenario is designed to be compatible with a 1.5°C trajectory.

Both scenarios aim to fulfil three principles – combatting climate change; enforcing energy security by reducing fossil fuel imports by 78% and 92% by 2050 with respect to 2021 in the PES and DES, respectively; and enhancing competitiveness. These reductions strengthen resilience against external supply shocks, ensuring a more stable energy system. Additionally, average wholesale electricity prices follow distinct trends under each scenario, with the DES leading to a more stable long-term price trajectory (~EUR 66/megawatt hour [MWh] by 2050) compared to the PES (~EUR 79 /MWh), reflecting the cost advantage of a decarbonised and more integrated system. This is not necessarily yet reflected in domestic legal frameworks or formally transformed into force by the European Commission.

The analysis builds on a foundation of previous power sector studies, integrating lessons and data from multiple scales and time horizons. Recent global-level work in the *World Energy Transitions Outlook* 2024 (IRENA, 2024) provides a pathway for the EU27 power sector to achieve a 1.5°C-compatible future by 2050. Regional studies, such as the Central and South-Eastern European Energy Connectivity 2020 and an EU study completed in 2018, highlight immediate ambitions for 2030 and the operational measures necessary for the transition (IRENA, 2018a, 2020a).

This new analysis includes energy transition pathways, both the energy supply (power generation and fuels, including hydrogen and its derivatives, biofuels) and end-use sectors (buildings, industry and transport), for the period between 2022 and 2050. The REmap methodology also includes a high-level analysis of the potential impacts of accelerated deployment of renewables in the EU power systems of 2050, by means of a power sector dispatch model. The analysis and results were also presented and discussed with Member States, via workshops, as well as with EC experts, who provided extensive input and feedback.[2]

Key questions that policy makers may wish to discuss while formulating new directives and regulations follow.

- Is the 2050 net-zero target technically feasible?
- Are the current plans and policies implemented domestically sufficient for the net-zero target by 2050?
- How to get to 90% emission reduction by 2040?
- What is the key focus on policy making in the next years – what is the best strategy to reduce emissions?
- Which technologies and energy carriers are going to dominate in the coming decades?
- What are the sector gaps in policies, regulation and market designs for implementing the targets?
- What are the investments and costs, as well impact on energy prices to consumers?
- Is the pace of the implementation of energy transition compatible with energy security and competitiveness in the short term?
- What is the role of energy trade and imports to the EU targets?
- What are the socio-economic implications, including for industrialisation and jobs?

This report is structured as follows:

Chapter 1 describes the overall results of the REmap analysis for the European Union and key insights and messages.

Chapter 2 presents the main outcomes, findings and messages of the transport sector analysis.

Chapter 3 presents the main outcomes, findings and messages of the industry sector analysis.

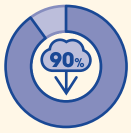
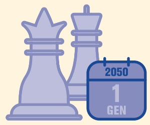
Chapter 4 presents the main outcomes, findings and messages of the buildings sector analysis.

Chapter 5 presents the main outcomes, findings and messages of the power sector and hydrogen derivatives analysis.

Chapter 6 presents insights of the socio-economic impacts of the energy transition in the region.

[2] *The results of the scenario analysis were presented to representatives from the European Commission and Member States in the course of an online consultation workshop on 16 and 17 October 2024.*

Table I1 Overall decarbonisation and energy transition targets, policies, plans and strategies from the European Commission

2030 TARGETS	2040 CLIMATE TARGET	2050
 **European Union (EU) policy, strategy and legislation for 2030 environmental, energy and climate targets.**	 **Reducing net emissions by 90% by 2040.**	 **Long-term low greenhouse gas (GHG) emission development strategies.**

2030 climate targets
• Reducing the EU's GHG emissions by 55% by 2030, compared to 1990 levels.
 	
Energy efficiency targets
• The European Union has agreed on an ambitious energy efficiency target of reducing final energy consumption by at least 11.7% compared to projections of the expected energy use for 2030 in the 2020 EU Reference Scenario.
• Key figures by 2030:
  • At least 11.7% – energy efficient target
  • 763 million tonnes of oil equivalent (Mtoe) – final energy consumption
  • 992.5 Mtoe – primary energy consumption
	• The recommended 2040 climate target is based on the Commission's detailed impact assessment and the advice of the European Scientific Advisory Board on Climate Change.	• The European Union aims to be climate neutral by 2050 – an economy with net-zero GHG emissions. This objective is at the heart of the European Green Deal and is a legally binding target thanks to the European Climate Law. The law also sets the intermediate target of reducing net GHG emissions by at least 55% by 2030, compared to 1990 levels.

Renewable energy targets
The European Union wants to accelerate the take-up of renewables to contribute and reach the target of reducing net GHG emissions by at least 55% by 2030.
• 23% – share of renewables in EU energy consumption 2022.
• 32% – 2030 target set in 2018 which was subsequently revised upwards.
• The revised Renewable Energy Directive EU/2023/2413 raises the EU's binding renewable target for 2030 to a minimum of 42.5%, up from the previous 32% target, with the aspiration to reach 45% (20 November 2023).
• Alternative Fuels Infrastructure Regulation.
• In the context of the "Fit for 55" package, the co-legislators agreed on a new Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure repealing Directive 2014/94/EU. The regulation has been applicable since 13 April 2024.
 	
Global targets for renewables and energy efficiency
• The European Union suggests developing global targets on two of the most effective levers of the clean energy transition.
• The European Commission has adopted a set of proposals to make the EU's climate, energy, transport and taxation policies fit for reducing net GHG emissions by at least 55% by 2030, compared to 1990 levels. More information on Delivering the European Green Deal.
	• The Communication launches the process of setting the 2040 climate target for the European Union. It opens a political debate on the choices of European citizens and governments on the way forward. This will inform the 2024-2029 mandate of the European Commission.
	• The Commission will make the legislative proposal to include the 2040 target in the European Climate Law and will ensure that the appropriate post-2030 policy framework is in place to deliver the 2040 target in a fair and cost-efficient manner.
		• The European Green Deal will transform the European Union into a modern, resource-efficient and competitive economy, ensuring:
		  • No net emissions of GHGs by 2050.
		  • Economic growth decoupled from resource use.
		  • No person and no place is left behind.

The circular economy action plan • The European Union measures from production and consumption to waste management, and the market for secondary raw materials. **Zero pollution action plan** • The European Union suggests developing global targets on two of the most effective levers of the clean energy transition, most for industries.		

Environment Action Programme Vision to 2030 • The 8th Environment Action Programme will guide European environmental policy until 2030. • (Sustainable Development Goals). **EU biodiversity strategy** • The EU biodiversity strategy aims to halt the loss of biodiversity and ecosystem services in the European Union.		• The long-term strategies should be consistent with Member States' integrated National Energy and Climate Plans (NECPs) for the period 2021-2030.
Public engagement • The European Union promotes public consultations and awareness campaigns to increase acceptance of the energy transition, mitigate resistance from industries and highlight socio-economic benefits. This aligns with the European Green Deal and REPowerEU.	**Fast-tracking permitting and public acceptance** • The 2023 Action Plan on Grid Modernisation and Permitting stresses the need for early stakeholder engagement to accelerate renewable deployment and energy infrastructure projects with public acceptance. • "There is a need to reinforce the engagement framework towards the public into a regular and meaningful collective effort that harnesses trust and participation in grid development".	**Just transition** • Policies such as the Just Transition Mechanism and Social Climate Fund support equitable economic adjustments, ensuring resilience against climate and economic disruptions, long-term strategies need to strive for a just transition.

Green Deal Industrial Plan:

The goal of the plan is to enhance Europe's net-zero industry's competitiveness while accelerating the sector reaching climate neutrality by creating more supportive environment to scale up production of net-zero technologies in meeting Europe's climate targets. The Green Deal Industrial Plan covers four key pillars such as:

1) Predictable and simplified regulatory environment; 2) Faster access to funding; 3) Enhancing skills;
4) Open trade for resilient supply chain

Clean Industrial Deal:

Provide business plan supporting Europe's industry competitiveness and resilience. The Deal aims to accelerate the decarbonisaton of the Europe's manufacturing sector while maintaining its security in the future linking mainly the energy-intensive industries and clean tech. There are seven pillars this Clean Industrial Deal composed of which are:

1) Ensuring social and territorial justice and quality jobs; 2) Unleash investments into sustainable development;
3) Make the energy transition affordable for industry; 4) Strengthen European integration and cohesion;
5) Stimulate demand for non-toxic and circular products; 6) Boost zero-pollution, non-toxic circularity and reduce resource use; and 7) Promote a fair and green trade policy

The European Union Emissions Trading System (EU ETS):

The ETS requires polluters to pay for their GHG emissions. Launched in 2005, the EU ETS is based on a "cap and trade" principle. The cap refers to the limit set on the total amount of GHG that can be emitted by installations and operators covered under the scope of the system. This cap is reduced annually in line with the EU's climate target. The EU ETS revenue primarily flows to national budgets and Member States must use it to support investments in renewable energy, energy efficiency improvements and low-carbon technologies that help reduce emissions and, with this, companies' carbon costs. The cap has been tightened to bring emissions down by 62% by 2030, compared to 2005 levels.
This covers emissions from maritime transport, which have been included in the EU ETS from 2024. A new emissions trading system, called ETS2, has been created to cover emissions from buildings, road transport and additional sectors. The new system will become operational in 2027.

The Carbon Border Adjustment Mechanism (CBAM):

The EU's CBAM is the EU's tool to put a fair price on the carbon emitted during the production of carbon-intensive goods that are entering the European Union. By confirming that a price has been paid for the embedded carbon emissions generated in the production of certain goods imported into the European Union, the CBAM will ensure the carbon price of imports is equivalent to the carbon price of domestic production, and that the EU's climate objectives are not undermined. The CBAM will apply in its definitive regime from 2026, while the current transitional phase lasts between 2023 and 2025. This gradual introduction of the CBAM is aligned with the phaseout of the allocation of free allowances under the EU ETS to support the decarbonisation of EU industry. The CBAM will initially apply to imports of certain goods and selected precursors whose production is carbon intensive and at the most significant risk of carbon leakage: cement, iron and steel, aluminium, fertilisers, electricity and hydrogen.

Box I1 The Competitiveness Compass: An overview

Earlier this year, the European Commission presented a major initiative to provide a clear strategic framework for regaining and securing industrial competitiveness, and achieving sustainable prosperity: the EU Competitiveness Compass (European Commision, 2025). The European Union is confident that it can leverage its available capital, savings, unique social infrastructure, and talented, educated workforce to solve a key challenge: the persistent gap in productivity growth that has hindered the region from keeping up with other major economies for some time.

The Competitiveness Compass synthesised a report by the former European Central Bank President, Mario Draghi, and transformed it into a roadmap covering the areas of innovation, decarbonisation and security, which are seen to be transformational imperatives to boost competitiveness (Draghi, 2024). The European Union has acknowledged that it needs to close its innovation gap as one of the main actions to answer its productivity challenge. Thus, ramping up productivity to maintain sustainable growth rates is imperative. Under its dedicated EU Start-up and Scale-up Strategy, the European Union is eager to promote tech-based industrial leaderships in the high-growth sector, while creating an appropriate ecosystem to support innovation by start-ups, addressing obstacles that prevent new companies from emerging and scaling up. Artificial intelligence (AI) is planned to be at the centre of innovation, with “AI gigafactories” and “Apply AI” as the core initiatives to adopt AI in advanced materials, biotech, robotics and space technologies, among others. Simplifications of corporate law, insolvency, labour and tax laws are also proposed under the 28th regime. Its primary purpose is to attract and retain innovative start-ups in the region, making it easier for companies to operate across the European Union and helping them compete with other major global economies.

These initiatives are anticipated to address the fundamental barriers to innovation within the European Union, which are entangled in a vicious cycle of low investment and low innovation, particularly within the digital technology industrial structure. Moreover, the lack of dynamism impedes the emergence of new sectors, and there is a scarcity of academic institutions with pipelines from innovation to commercialisation, among other issues (Draghi, 2024). Further, the European Parliament has introduced the EU Clean Industrial Deal, which addresses the need for ambitious European industrial standards. This initiative is built on seven inter-connected pillars: ensuring social and territorial justice and quality employment, stimulating investment towards sustainable development, making the energy transition affordable for industry, strengthening European integration, promoting a demand for non-toxic and circular products, advancing zero-pollution and non-toxic circularity while reducing resource use, and fostering fair and green trade policies (The Greens/EFA, 2025).

EU decarbonisation targets are notably ambitious, especially in the short term. This will result in additional short-term costs due to the substantial investment required for its industry, compared with other major economic competitors such as the United States and China. On the other hand, it offers an opportunity to lower EU energy prices and take the lead in clean technologies and become more energy secure. The European Union’s aim to achieve minimum 42.5% of energy consumption from renewables by 2030 means it needs to triple its solar photovoltaic installed capacity while doubling its wind capacity. Chinese technology may offer the lowest-cost route to some of these short-term targets (Draghi, 2024).

The urgent question is how to pursue EU decarbonisation targets while maintaining industrial competitiveness. The key for energy sector decarbonisation is to lower the cost of energy for end users. The Competitiveness Compass outlines interventions to promote clean and affordable energy through tailor-made action plans for energy-intensive industry sectors such as steel, metals and chemicals through the elaborated integration of the Affordable Energy Action Plan, Clean Industrial Deal and Industrial Decarbonisation Accelerator Act.

To boost the security of raw materials, clean energy, sustainable transport fuels and clean technology from across the world, the European Union, through its Competitiveness Compass, is developing a new range of clean trade and investment partnerships. This initiative is supported by a review of public procurement rules, allowing the introduction of European preference in public procurement for critical sectors and technologies. These efforts must also be carried out in parallel with the effort to optimise the potential of the region’s domestic resources through mining, recycling and innovation in alternative materials.

1

THE ENERGY TRANSITION IN THE EUROPEAN UNION

This chapter describes the overall results of the REmap analysis for the EU and key insights and messages. This section aims to provide clarification for policy makers on the following questions:

1. Based on the existing directives and plans, how the EU27 energy mix and emissions would evolve?
2. Which sectors would contribute more to the economy-wide decarbonisation and which are the existing gaps?
3. What is the role of trade in the coming decades?
4. How much investment is required per year for the energy transition?
5. What is the role of electrification with renewables and direct use of renewables, particularly bioenergy?

KEY FINDINGS

★ **The transport and power sectors are the biggest consumers of fossil fuel in the European Union (EU). Over 50% of the carbon dioxide (CO_2) emissions reductions expected from now to 2050 would be due to the decarbonisation of these two sectors.** Policy makers should thus prioritise these sectors, with a focus on boosting their energy efficiency and use of renewables-based electricity in the near future, which will also boost competitiveness and energy security.

★ **Electrification is the main avenue towards decarbonisation, more so than expected in previous studies. Electricity delivers between 56% and 64% of final energy consumption by 2050** according to both the Planned Energy Scenario (PES) and Decarbonising Energy Scenario (DES), respectively, up from 22% today. Electrification is most prominent in electric mobility and heating solutions – in both buildings and low-temperature industrial processes. Most EU Member States will see electrification rates above 60% in 2050.

★ **Renewable energy's share of final energy consumption is anticipated to reach 40% and 44% by 2030, rise to 55% and 68% by 2040 and 67% and 84% by 2050,** in both the PES and DES respectively. Modern use of bioenergy and clean hydrogen complement electrification to deliver the emissions reduction targets. The renewable energy share in gross final energy consumption reaches 39% in PES and 43% in DES by 2030, with the DES surpassing the EU's binding target of at least 42.5% by 2030 (RED III). The shares rise to 56% and 69% by 2040, and 70% and 85% by 2050, in PES and DES respectively.[3]

★ **Renewable energy capacity increases by a factor of 2.5 (to 1.2 terawatts [TW]) by 2030 in both the PES and DES, and by a factor of 4 (to 2 TW) in the PES and a factor of 5 (to 2.5 TW) in the DES by 2050.** An additional 122 gigawatts (GW) per year of renewable capacity are required between 2025 and 2030, reshaping power markets and deliver a structurally less volatile power price over the long term.

★ **Solar and wind capacity additions will need to increase in the DES at a pace of 73 GW and 42 GW per year, respectively, until 2050,** when they will represent a combined 84% of all installed capacity in the EU27. In 2023, new solar photovoltaic, onshore wind and offshore wind installations amounted to 56 GW, 13 GW and 3 GW each, respectively. A cumulative investment of EUR 2.7 trillion (and an annual average of about EUR 110 billion) will be needed between 2025 and 2050 for all renewable electricity capacity. Notably, EU countries invested almost EUR 110 billion in renewable power generation in 2023; while this is close to what is needed in the long term, scaling up deployment in capacity terms to meet future targets remains a challenge.

★ **Variable renewable electricity will rise to nearly 80% of generation by 2050, requiring urgent and co-ordinated action to ensure system flexibility and resilience, particularly in the face of prolonged low-renewable periods.** Without immediate investments in grid expansion, modernisation and sector coupling, power systems risk increased volatility and curtailment. A mix of solutions – including stronger inter-connections, large-scale battery deployment and expanded pumped hydro storage – must be rapidly deployed. Thermal-based hydrogen, bioenergy and natural gas facilities can provide critical backup during seasonal variations in wind and solar capacity, ensuring security of supply during extended periods of low wind and solar availability. The scale of transformation requires not just incremental improvements but a paradigm shift in how energy systems are planned and operated.

★ **The top five energy consumers today – Germany, France, Italy, Poland and Spain – will remain so in 2050 according to the analysis, consuming as much as 65% of all electricity in the region.** Tracking implementation in these countries is key for EU decarbonisation targets to be met.

★ **By 2050 bioenergy will be responsible for 12% of final energy consumption in the European Union,** meeting key energy demand in aviation and shipping, heating in buildings and industry, as well as supplying green gases to the power sector. Import-export dynamics will play a crucial role in balancing supply and demand, with imports being needed to supplement domestic production.

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[3] *Please refer to the considerations for calculating the share of renewable energy in final energy consumption and in gross final energy consumption, as outlined in the page note of Section 1.2, Chapter 1.*

- **Hydrogen and its derivatives, such as ammonia and methanol, could reach 5% of final energy consumption by 2050 in the DES.** This would correspond to 37 million tonnes (Mt) of hydrogen equivalent in 2050, including 9.2 Mt of hydrogen in the form of ammonia, 8.4 Mt in methanol and 8.5 Mt in e-fuels. Electrolysis-based production would represent 80% of that total. Blue hydrogen and biomass-based hydrogen production together represents 18% and fossil-based the remaining 2%. Given the expected geographical imbalances in production and demand globally, international trade in hydrogen and its derivatives will play a key role, with imports supplementing domestic production in the European Union. Imports are expected to represent a share of around 22% by 2030 in both scenarios and of 58% and 44% by 2050 in the PES and DES respectively. Most will be derivatives such as ammonia, methanol and e-fuels, since these can be transported more efficiently than pure hydrogen.

- **Cumulative investment and acquisition costs of technologies would reach EUR 23 trillion in the PES and EUR 26 trillion in the DES.** Average annual values across 2025-2050 would be similar in both scenarios (at EUR 877 billion in the PES and EUR 992 billion in the DES). Infrastructure investments – including in renewable capacity, grids and building retrofits – account for one-third of total spending, reaching EUR 8 trillion in the PES and EUR 10 trillion in the DES by 2050. Acquisition costs, of, for example, electric vehicles (EVs) and energy-efficient appliances, amount to EUR 15 trillion in the PES and EUR 16 trillion in the DES. The largest investments would be in renewable capacity, grids and flexibility amounting to a combined EUR 4.9 trillion and EUR 5.6 trillion in the PES and DES respectively between 2025 and 2050. EV sales represent the highest consumer expenditure(EUR 10.3 trillion in both scenarios), followed by efficient appliances (EUR 638 in the PES and EUR 1.2 trillion in the DES) and buildings retrofits (EUR 969 billion under the PES and EUR 2 trillion under the DES).

KEY MESSAGES

- **Power sector and transport decarbonisation are key priorities for the next five to ten years and successful enabling policies to scale up investments and decarbonisation of these sectors should be prioritised**. Incentives and measures to scale up EV sales are important to meet EU decarbonisation targets, as is the accelerated growth of renewable gigawatts (and their system integration, with a focus on flexibility). Also, access to EV charging stations needs to expand at the right pace to boost consumer confidence.

- Beyond **electrification, scaling bioenergy production is the second most important measure to deliver decarbonisation across end-use**. Hydrogen also plays a role, but lower than expected by 2030.

- **More co-ordination at the EU level as part of a more integrated energy planning and implementation might accelerate the energy transition without compromising Member States' right to choose between different energy sources and the general structure of their energy supply** (European Commission, 2012). Efforts might include encouraging Member States to enhance policies to increase market integration, sector coupling solutions, grid connectivity, storage, pumped hydro and other flexibility measures as well as the electrification of end-use sectors.

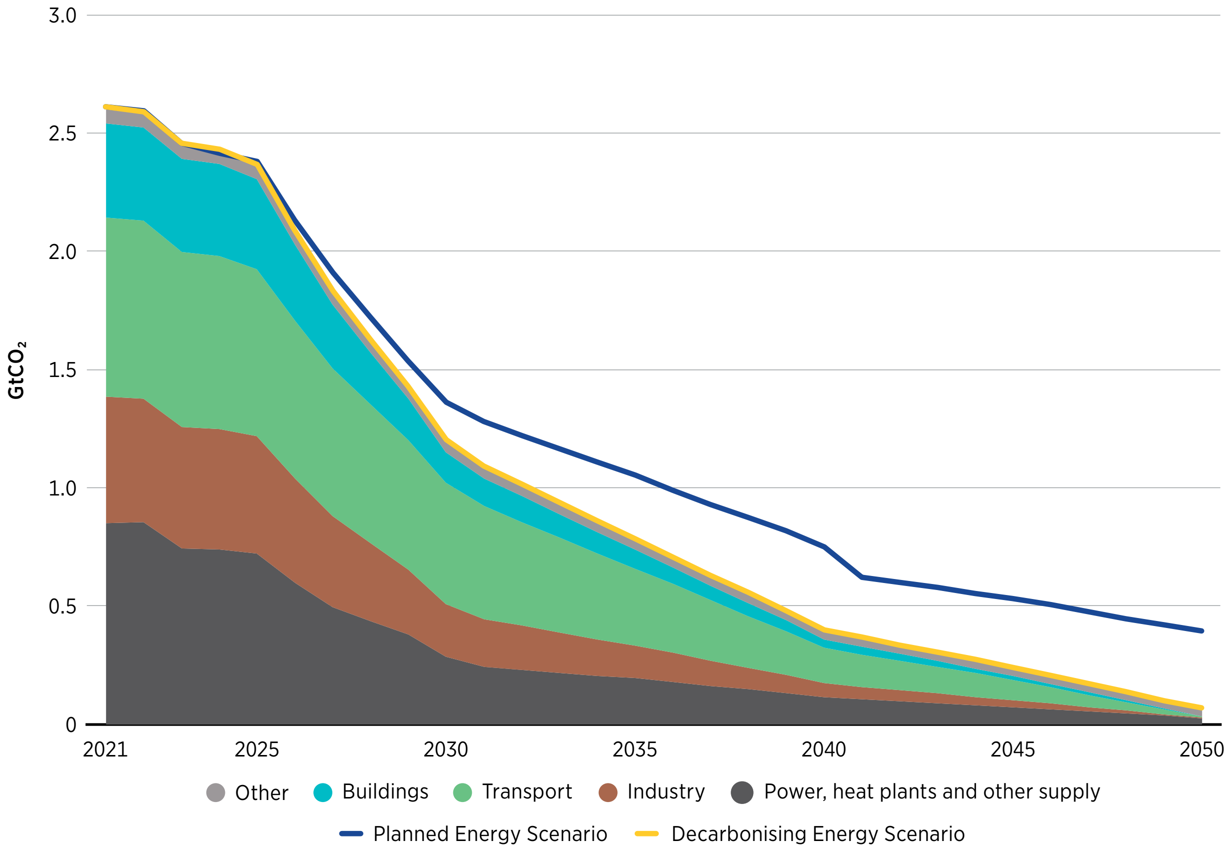
- **Electrification and renewable power generation alone are not a complete solution.** Direct use of renewables – including bioenergy, solar thermal and geothermal – must also be incentivised for the remaining gap to be closed.

- **Not just policies for scaling up and de-risking investment on physical assets and infrastructure are important, but the energy transition depends a lot on the deployment of appliances-goods for customers**, as said, such as EVs and efficient appliances on buildings. Dedicated incentive structures need to be featured as enablers and promoters. Rebates, finance schemes to consumers and tax benefits are possible measures, beyond plans.

1.1 GLOBAL CHALLENGES AND THE EU ROLE IN REDUCING EMISSIONS

Under the PES developed by IRENA for the 2024 *World Energy Transitions Outlook* (WETO), global annual emissions are still as high as 36.5 gigatonnes of carbon dioxide ($GtCO_2$) in the year 2050. This analysis assesses CO_2 emission reduction. The rest of the GHG emissions are out if the scope of this study. Aligned with the Intergovernmental Panel on Climate Change's special report on limiting global warming to no more than 1.5°C by 2050, IRENA's 1.5°C Scenario envisions a way to achieve net-zero emissions by 2050. A steep, accelerated downward trajectory from now to 2030 would be followed by a gentler but still downward curve, reaching net-zero by 2050. Because the energy sector is responsible for around 80% of anthropogenic CO_2 emissions, it has a central role to play, requiring urgent action on multiple fronts.

Figure 1.1 EU27 CO_2 emissions in the PES and DES, by sector

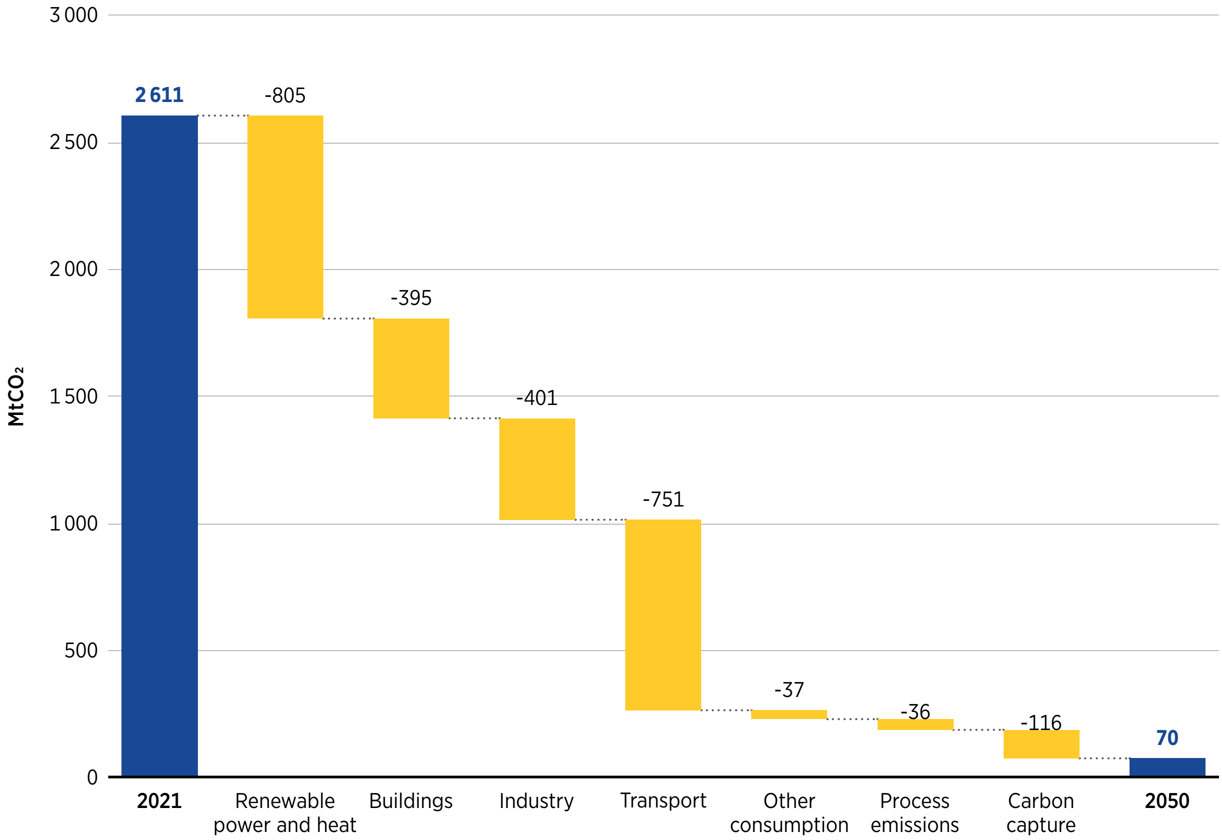


Note: $GtCO_2$ = gigatonnes of carbon dioxide.

This chapter examines how the EU27 is advancing the aspirations of the Paris Agreement, focusing on net-zero emissions by 2050. Two scenarios are considered: the PES, which reflects current energy plans and policies, and the DES, which explores additional measures to accelerate climate action, enhance energy security and boost competitiveness. The Emissions Database for Global Atmospheric Research (EDGAR) indicates that the EU27 was responsible for 7.33% of global emissions in 2021, down from 16.8% in 1990 (European Commission, 2022a). This marked improvement reflects the EU27's ongoing efforts to decarbonise its economies.

As shown in Figure 1.1, EU emissions levels are expected to decline significantly in both the PES and DES. EU pledges and plans, represented in the PES and modelled with an alternative trajectory in the DES, are well aligned with the 1.5°C Paris Agreement. All sectors contribute to this downward trajectory, as shown in Figure 1.2.

Figure 1.2 EU27 CO_2 emissions reduction in 2050 with respect to 2021 in the DES, by sector or method



Note: $MtCO_2$ = megatonne of carbon dioxide.

Box 1.1 The IRENA 1.5°C Scenario: A framework for aligning energy and climate strategies and tracking plans

The *World Energy Transitions Outlook* (WETO) offers a framework for developing energy transition strategies and tracking progress towards net-zero emissions by mid-century. Six key performance indicators (KPIs) help policy makers identify priority actions, assess progress and guide strategic actions towards the 1.5°C climate goal at a global scale, as shown in Table 1.1. First, the use of renewables to generate electricity is monitored through two subindicators: (1) the amount of electricity generated from renewables, and (2) the share of renewables in the total electricity generated. This indicator highlights the importance of increasing renewable energy capacity and its contribution to the overall energy mix. Second, the direct use of renewables is assessed by looking at the share of renewable energy in total final energy consumption and the quantity of modern bioenergy used. It is necessary to integrate renewables across various sectors and increase the use of sustainable bioenergy. Energy intensity improvement rates are a proxy for energy efficiency improvement rates. Energy intensity is calculated as total primary energy supply divided by gross domestic product; energy intensity improvement is the compound rate at which energy intensity declines annually at the global level. Improvements in energy intensity are tracked to measure the efficiency gains in energy use, crucial for reducing overall energy demand and emissions. The electrification of end-use sectors is another key indicator, as it reflects the shift towards electricity as a key energy carrier, essential for decarbonising sectors like transport and heating and energy efficiency improvement. The production and supply of green hydrogen and its derivative fuels are also monitored. As versatile, carbon-free energy sources, these play a central role in the energy transition. Finally, the framework tracks the amount of CO_2 captured and removed by various measures, underscoring the importance of carbon capture and carbon removal technologies in achieving net-zero emissions. Table 1.1 introduces the KPIs that underpin the WETO framework, comparing the 1.5°C Scenario with the Planned Energy Scenario for 2030 and 2050. It provides a snapshot of the progress required across sectors to meet the 1.5°C climate target.

Table 1.1 Key performance indicators for achieving the 1.5°C Scenario vs. the PES, 2030 and 2050: Global perspective

	Historical 2021	Historical 2022	Historical 2023	Planned Energy Scenario [1] 2030	Planned Energy Scenario [1] 2050	1.5°C Scenario [1] 2030	1.5°C Scenario [1] 2050	Essential milestones
KPI.01 RENEWABLES (POWER)[2]								
Renewable energy electricity generation (TWh/yr)	7 873	8 440	N/A	16 504	38 118	27 358	82 148	Almost tripling renewable capacity by 2030.
Renewable energy share in electricity generation (%)	28	29	N/A	46	73	68	91	Nine-fold increase in renewables by 2050.
Renewable energy installed capacity (GW)	3 083	3 391	3 865	6 773	15 835	11 174	33 216	Renewable electricity share in electricity generation to reach c. 70% by 2030 and 90% by 2050.
Renewable energy share in installed capacity (%)	38	40	43	58	80	77	94	
KPI.02 RENEWABLES (DIRECT USES)								
Renewable energy share in TFEC (%)	17[3]	17[3]	N/A	23	33	35	78	Doubling the direct use of renewable energy by 2030 and quadrupling it by 2050.
Modern use of bioenergy[4] (EJ)	23[3]	24[3]	N/A	30	41	46	53	Tripling modern use of bioenergy by 2050.
KPI.03 ENERGY INTENSITY								
Energy intensity improvement rate (%)	0.7[5]	2[5]	N/A	2[6]	2[7]	4[6]	3[7]	Urgent doubling energy efficiency improvements by 2030.
KPI.04 ELECTRIFICATION IN END-USE SECTORS (DIRECT)								
Electrification rate in TFEC (%)	22[3]	23[3]	N/A	23	28	30	52	Direct electrification of end-use sectors would need to increase by 50% by 2030 and more than double by 2050.
KPI.05 CLEAN HYDROGEN AND DERIVATIVES								
Production of clean hydrogen (Mt)	0.6[8]	0.7[8]	0.7[8]	2	21	125	523	A new set of hydrogen facilities to be scaled up by 2030 and beyond.
KPI.06 CCS, BECCS AND OTHERS								
CO_2 captured from CCS, BECCS and other removal measures (Gt)	0.05[9]	0.05[9]	0.05[9]	0.1	0.5	2.2	7.0	CO_2 removal, capture and storage measures also needed – to 2.2 Gt and 7 Gt by 2030 and 2050.

Notes: The scenario results presented herein are subject to upward revision in the 2025 edition of the *World Energy Transitions Outlook*, given the current pace of solar and storage growth in certain countries.
BECCS = bioenergy with carbon capture and storage; CCS = carbon capture and storage; CO_2 = carbon dioxide; EJ = exajoule; GW = gigawatt; Gt= gigatonne; KPI = key performance indicator; Mt = megatonne; PES = Planned Energy Scenario; TFEC = total final energy consumption; TWh/yr = terawatt hour per year.

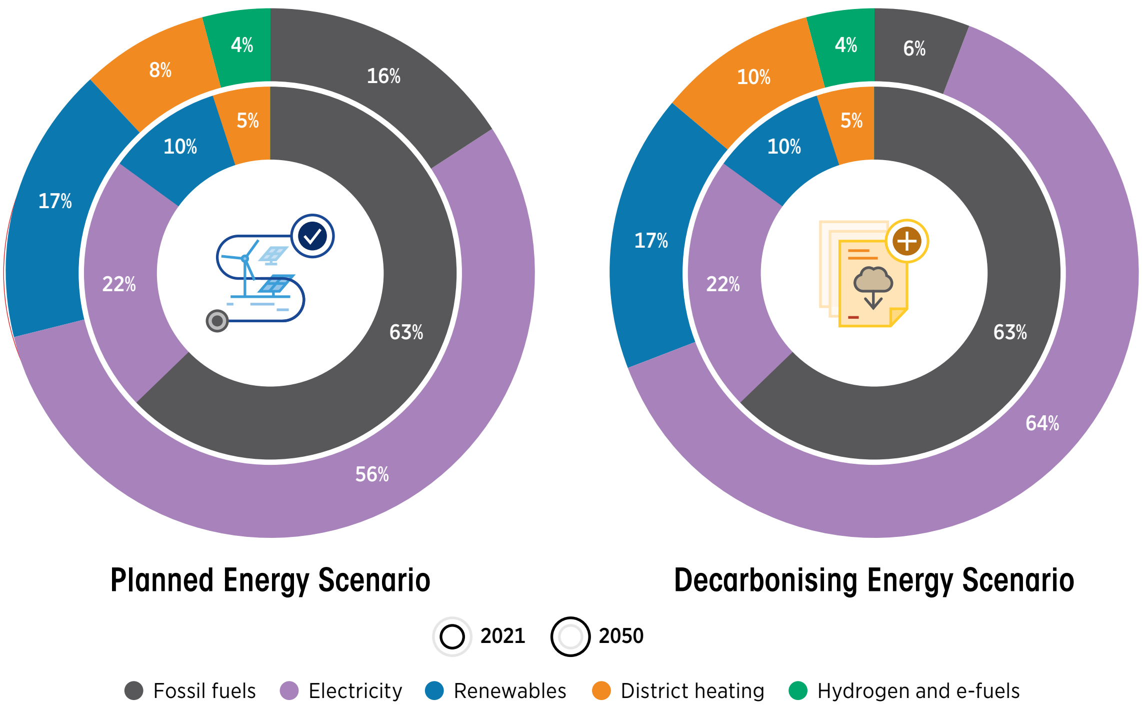
[1] PES and 1.5°C Scenario analyses as of March 2023. [2] (IRENA, 2024a). [3] Based on (IEA, 2024b). [4] Excludes non-energy uses. [5] Energy intensity improvement achieved estimated using (IEA, 2024b) for primary energy supply and (CE, n.d.) for GDP statistics. [6] Average annual improvement rate from 2023 to 2030 uses (IEA, 2024b) for primary energy supply (historical data), and (CE, n.d.) for GDP historical statistics. [7] Average annual improvement rate from 2023 to 2050 uses (IEA, 2024b) for primary energy supply (historical data), and (CE, n.d.) for GDP historical statistics. [8] (IEA, 2023a). [9] (IEA, 2024c).

1.2 ROADMAP FOR THE EU27'S DECARBONISATION

Following the same key performance indicators as IRENA's WETO (Box 1.1), Table 1.1 outlines a roadmap for decarbonising the EU27 bloc, reaching close to net-zero CO_2 emissions by 2050. The direct and indirect renewable energy share in final energy consumption 40% in the PES and 44% in the DES by 2030[4]. In terms of gross final energy consumption this corresponds to renewable share of 39% and 43% in PES and DES respectively by 2030.[5] This indicates that to meet the renewable energy target set in the Renewable Energy Directive (RED III), of a 42.5% share in gross final consumption of energy, additional efforts need to be made in the short term.

The PES and DES envision a transition driven by the deployment of renewable energy, improvements in energy efficiency and deep electrification of end-use sectors. Electricity becomes the main energy carrier by 2050 owing to its cost competitiveness and scalability. The shift would result in electricity accounting for about 64% of total final energy consumption (TFEC) by 2050 in the DES, a substantial increase from 2021 levels (see Figure 1.3). Alongside direct electrification, bioenergy and other direct renewables such as solar thermal (17%) and clean hydrogen and its derivatives (4%) would also play an important role in decarbonising hard-to-abate sectors for which alternatives are limited.

Figure 1.3 Shares of final energy consumption by carrier, 2021 and 2050



[4] Direct and indirect renewable energy share in final energy consumption has been calculated as: the renewable final energy consumption, including direct renewables (bioenergy, solar and geothermal), renewable electricity, renewable hydrogen and derivatives and renewable district heating and cooling, divided by the total final energy consumption.

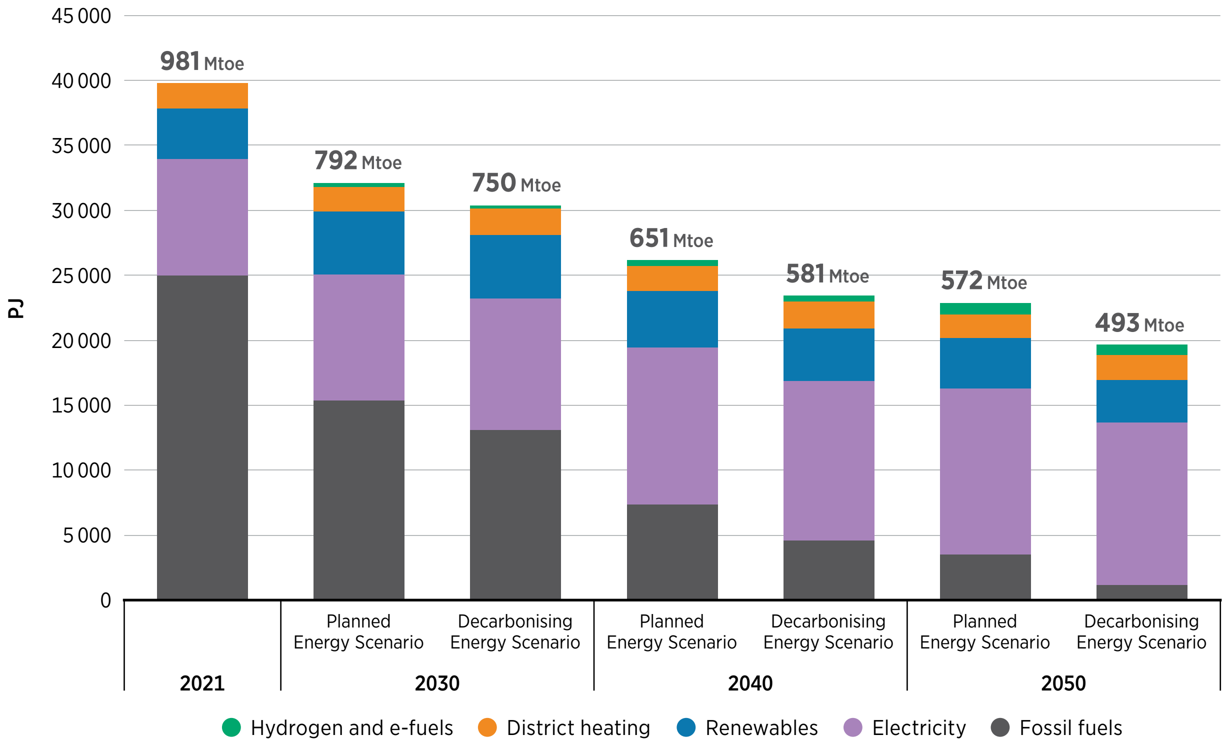
[5] The renewable energy share in gross final energy consumption (GFEC) has been calculated using different methodological approaches, though only one, aligned with Directive (EU) 2023/2413 (RED III), is used in the main text. GFEC includes not only energy delivered to final consumers, but also electricity and heat consumed by the energy sector itself, as well as transmission and distribution (T&D) losses. The methodology includes renewable fuels supplied to international aviation and marine bunkers in the numerator, while including all aviation bunkers (fossil and renewable) and renewable marine bunkers only in the denominator. Based on this approach, the renewable share in 2030 reaches 39% in the PES and 43% in the DES.

For comparison, an alternative method was also assessed: one including both international aviation and marine bunkers fully. In this case, renewable energy use in both aviation and marine bunkers is included in the numerator, and all energy for both aviation and marine is included in the denominator. These methods yield lower shares in 2030: 37% (PES) and 41% (DES).

1.2.1 Final energy consumption

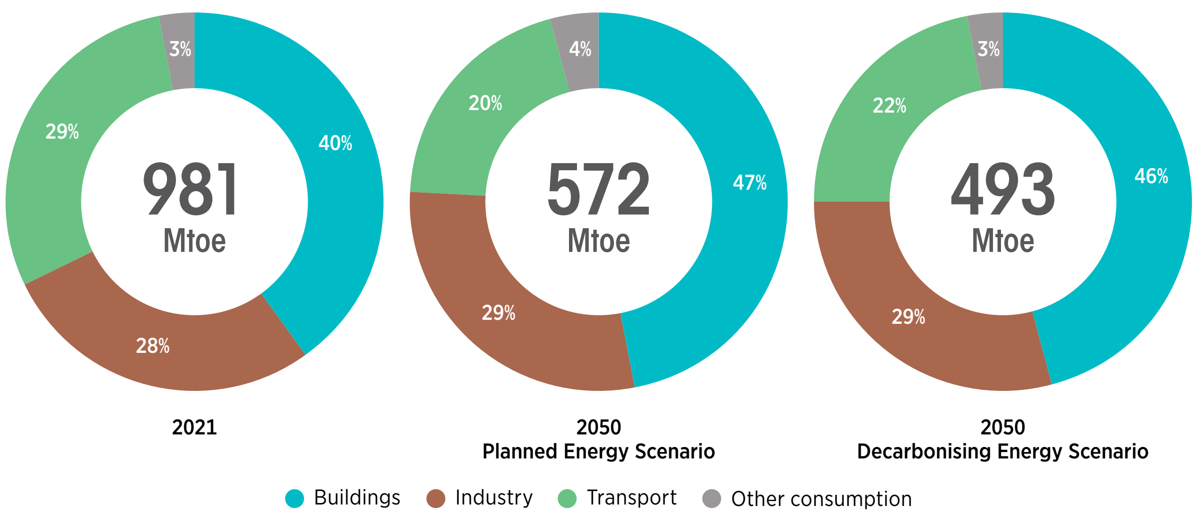
All sectors – including industry, transport and buildings – will see energy consumption decline in absolute terms compared to current levels, while economic activities and energy service requirements continue to rise. Energy efficiency and conservation play a key role. By 2050, the EU27 might cut its energy needs in half, as shown in Figure 1.4. The transport sector's share of consumption will fall by 2050 in the PES and the DES, to 20% and 22%, respectively (from 29% in 2021; Figure 1.5).

Figure 1.4 Final energy consumption by carrier



Note: Mtoe = million tonnes of oil equivalent; PJ = petajoule.

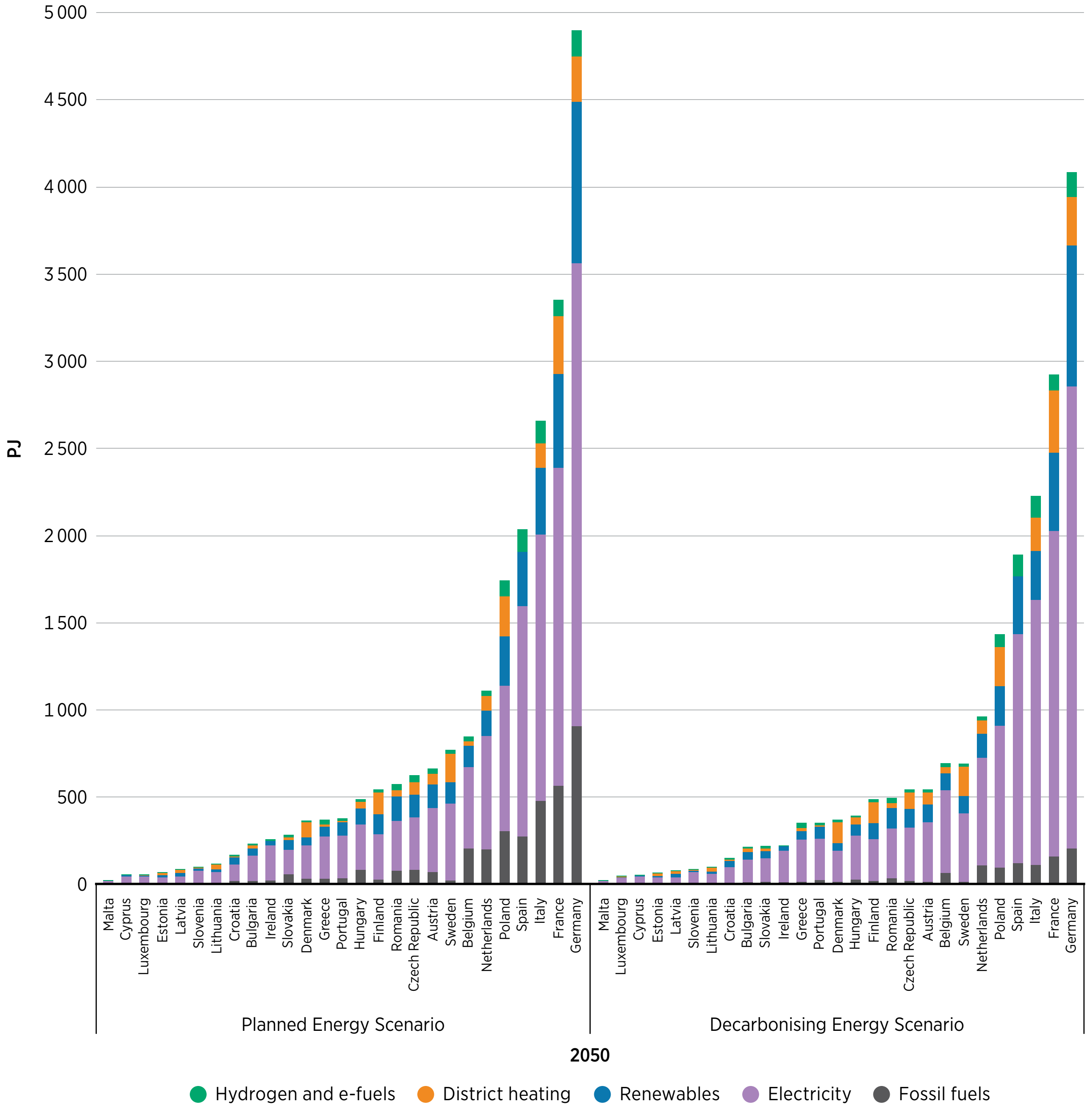
Figure 1.5 Shares of final energy consumption by sector



Note: Mtoe = million tonnes of oil equivalent; PJ = petajoule.

In 2021, the top five consumers were Germany, France, Italy, Spain and Poland; they are expected to still be the top five in 2050 according to the analysis, representing 75% of EU27's final energy consumption (Figure 1.6). These five countries are expected to decrease their energy intensity during the study period as their gross domestic product (GDP) per capita increases, as presented in Figure 1.7.

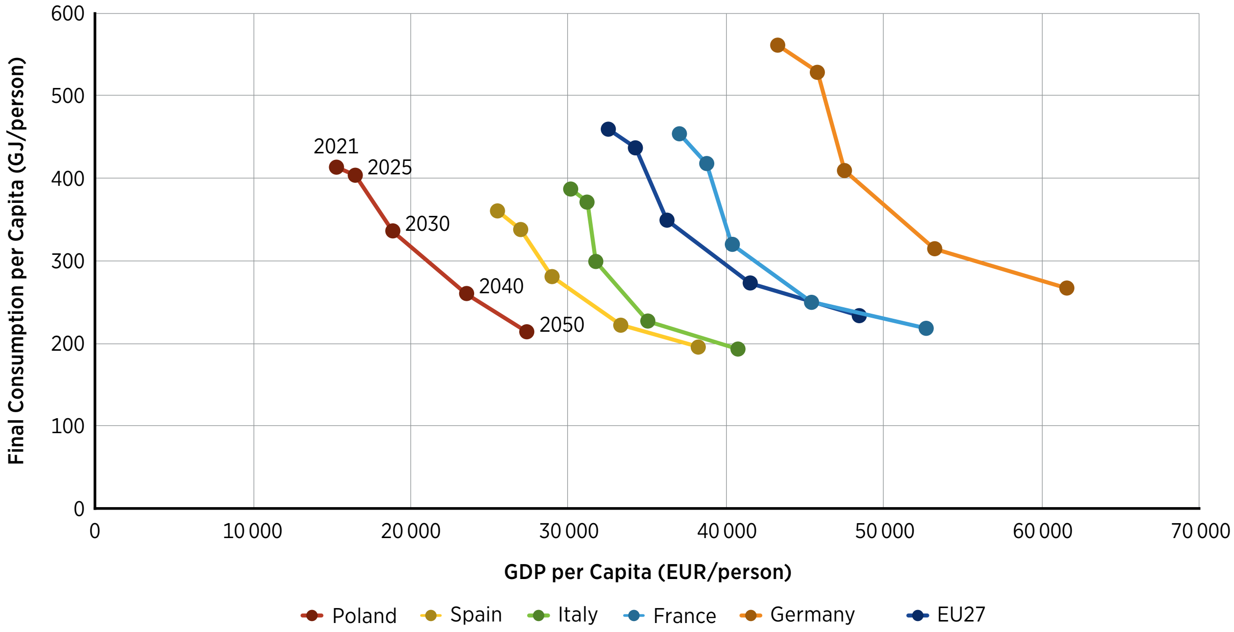
Figure 1.6 Final energy consumption by country, 2050



Note: PJ = petajoule.

In the next five years, leveraging energy efficiency will be crucial to cut energy demand, reduce reliance on fossil fuels and accelerate decarbonisation. Policy makers should implement binding efficiency targets, scale up building retrofits and mandate industrial energy savings while investing in electrification, public transport and digital energy management to optimise consumption and reduce costs. These near-term actions will enhance energy security, lower emissions and strengthen economic resilience, lowering the energy intensity of the wider European economy. In the long term, sustained improvements in energy efficiency will reduce infrastructure costs, support economic competitiveness and ensure a more resilient and sustainable energy system aligned with 2050 decarbonisation goals.

Figure 1.7 EU27 and top five consumers' GDP per capita vs. final energy consumption per capita in the DES

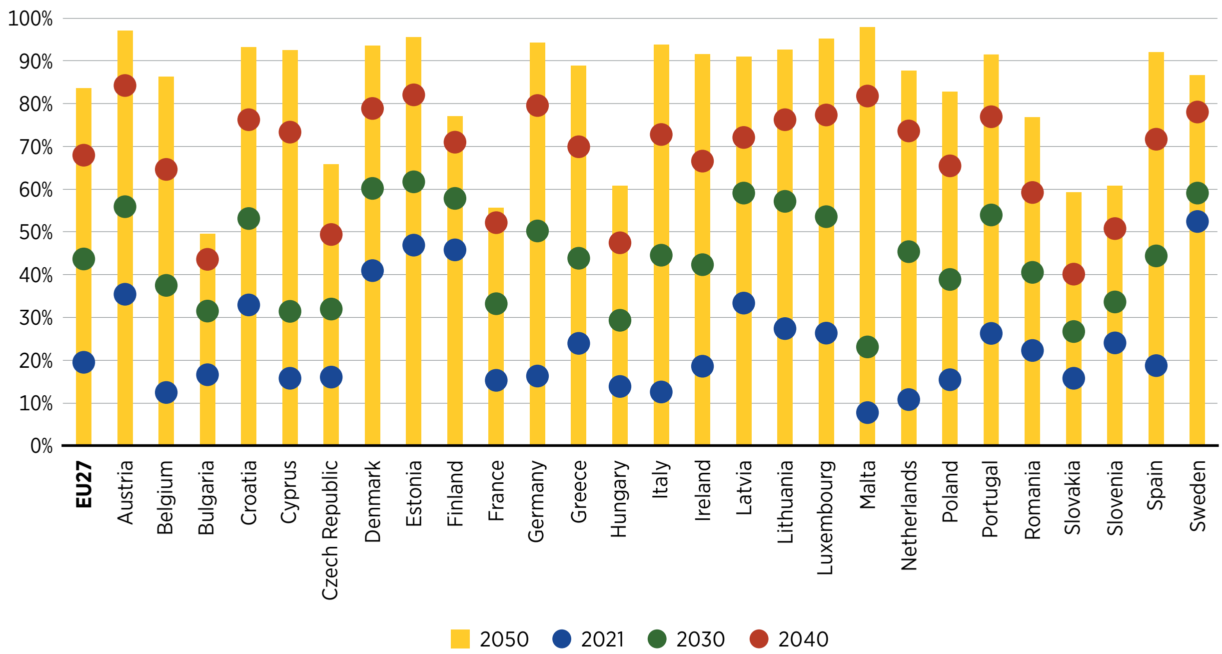


Notes: GJ = gigajoule; GDP = gross domestic product; USD = United States dollar.

Renewable shares of final energy consumption for the EU27 bloc will rise from 22% in 2021 to 39% and 43% in 2030, 54% and 67% in 2040, and 65% and 81% in 2050 in the PES and DES, respectively. All countries will see their share of renewables increasing over time: by 20-60% as of 2030, and by 55-95% as of 2050 (see Figure 1.8).

Nuclear power plays a key role in shaping these figures. Countries with a high share of nuclear power, such as France, Slovakia, Bulgaria and Hungary, tend to have lower shares of renewables, since inflexible nuclear generation limits space for variable renewables. By contrast, countries phasing out nuclear, such as Germany and Belgium, are seeing a rapid increase in renewables as they replace nuclear capacity with wind, solar and storage.

Figure 1.8 Renewable energy shares of gross final energy consumption in the DES, by country



1.2.2 Increasing electrification across end-use sectors

Electrification is expected to increase from 22% (2021) to 33% by 2030 and 64% by 2050 in the DES. All sectors contribute to this increase, with transport taking the lead (see Chapter 2). To support the electrification needed to decarbonise the EU27, the Commissioner for Energy and Housing was tasked in his Mission Letter to propose an Electrification Action Plan powered by homegrown, clean electricity (European Commission, 2024c). All countries will see electrification reach more than 50% of final energy consumption in 2050, up to 70% in several inland countries and up to 90% in smaller island countries (see Figures 1.9 and 1.10).

Figure 1.9 EU27 electrification rate relative to final energy consumption in transport, buildings and industry and in total in the DES

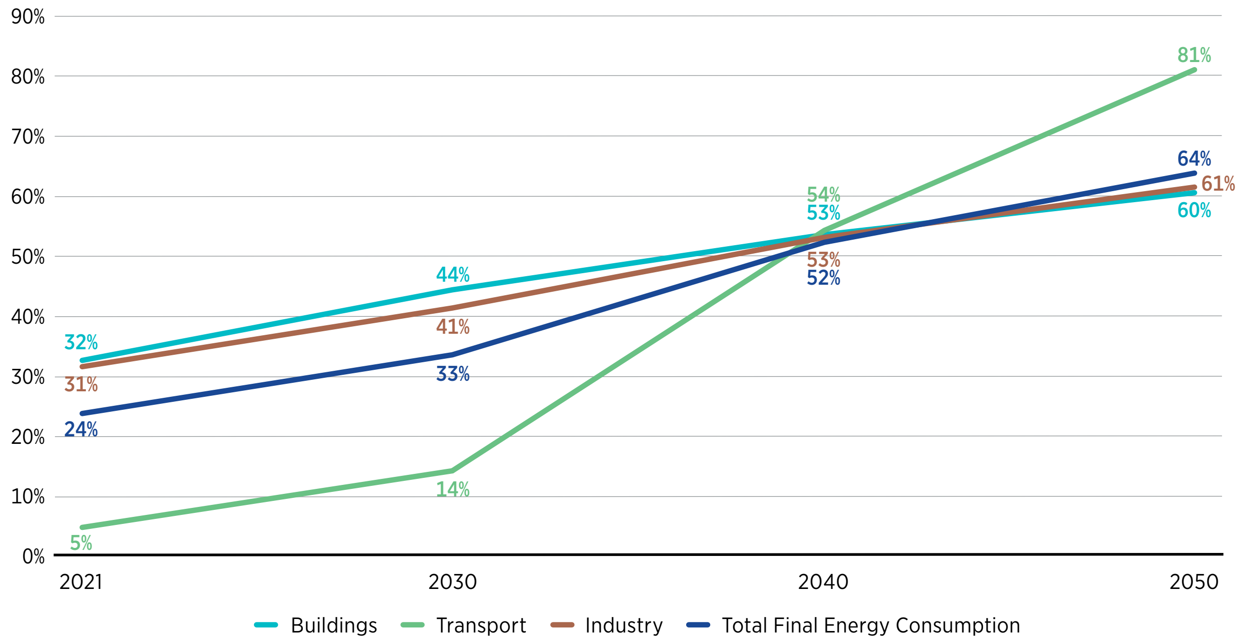
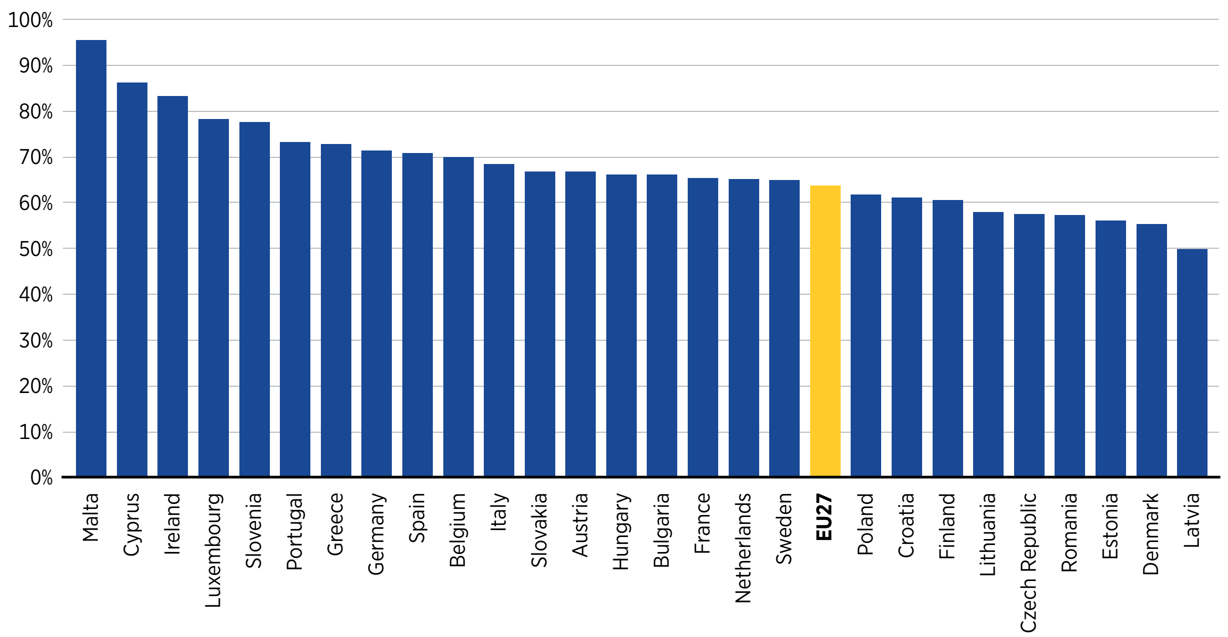


Figure 1.10 EU27 electrification rates over final energy consumption in the DES, by country, 2050



Achieving targeted electrification rates will require widespread adoption of advanced technologies across the buildings, industry and transport sectors. Such technologies' uptake would be supported by emissions reduction policies, energy prices and market readiness across the supply chain. Research and innovation are also expected to play a key role in their development and utilisation, as defined in the Mission Letter of the Commissioner for Startups, Research and Innovation (European Commission, 2024d). In buildings, technologies like heat pumps will play a crucial role in reducing reliance on fossil fuels; it is envisioned that their use will grow ten-fold by 2050 in the DES. The transport sector will need to see the deployment of EVs accelerated, supported by robust charging infrastructure, advancements in battery technology and the electrification of rail in particular, and of all public transport. The stock of all types of EVs would need to grow from 3.5 million units in 2021 to 335 million units in 2050 in the DES.

Besides the direct electrification of end-use sectors, both the EU PES and DES foresee a substantial expansion of electrolysers to produce green hydrogen as part of the indirect electrification process. Hydrogen and its derivative fuels – ammonia, methanol and e-fuels – would account for around 5% of TFEC in 2050. Early investment in the green hydrogen supply chain (electrolysis, fuel cells, transport pipelines, storage caverns, *etc.*) is vital to the uptake of hydrogen applications in end-use sectors and to carbon reduction targets. This is especially the case for hard-to-decarbonise sectors like aviation, marine and heavy-duty transport, in which hydrogen may be part of a portfolio of energy services solutions, as well as some primary industrial processes. In the EU27, the electricity needed for this indirect electrification via green hydrogen production would amount to approximately 10% of EU power generation in 2050, which if fully met by renewable capacity would amount to about 250 GW of additional renewable capacity. This implies that cumulative installed electrolyser capacity would need to grow significantly over the period to over 120 GW by 2050.

In the next five years, the development and implementation of the Electrification Action Plan as mandated by the European Commission will be crucial to set concrete targets and roadmaps. Accelerating the deployment of charging infrastructure could support the mass adoption of EVs. The launch of incentive programmes for households and businesses could foster the transition to electrified heating and industrial processes. To support the rapid increase of electricity demand, strengthening grid resilience through digitalisation, storage solutions or demand-response mechanisms can also play a key role in the short term.

1.2.3 Power sector supply – a complete transformation

Under the DES, renewable power generation capacity will need to expand in all countries to stay under the 1.5°C threshold (Table 1.2). While the 1.5°C threshold is global, it translates into regional efforts through sectoral carbon budgets and energy transition pathways. In the power sector, this means rapidly increasing renewable electricity generation to replace fossil fuels in meeting existing and future electricity demand growth.

EU Member States' renewable capacity would need to almost triple by 2030, reaching 1.2 TW from 0.5 TW in 2021, and scale up by a factor of four by 2040 to nearly 2 TW and by a factor of five by 2050 to 2.5 TW. All countries will see renewable energy capacity expand, further details of this can be seen for selected countries in Figure 1.12. Scaling up renewable electricity generation would require adding 122 gigawatts (GW) of renewable capacity per year on average from 2025 to 2050.

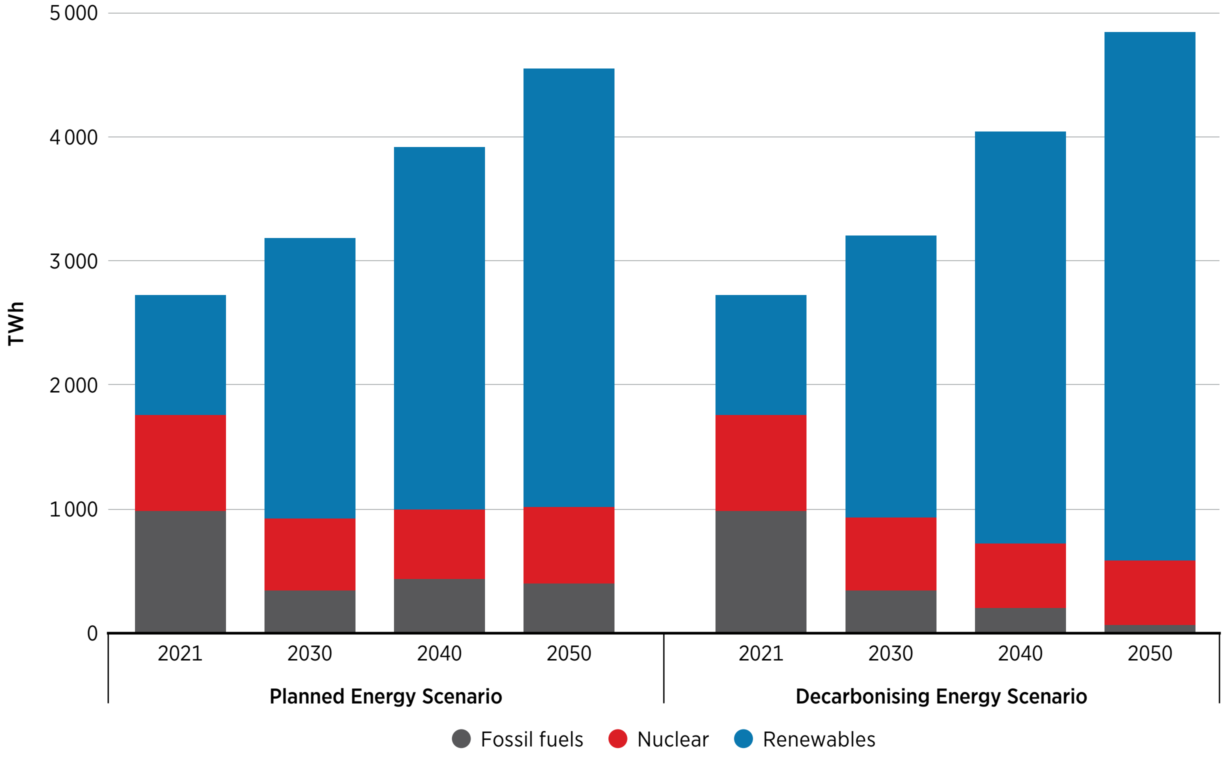
Electricity generation would have to expand from 2.8 petawatt hours (PWh) in 2021 to approximately 3 PWh by 2030 and nearly 5 PWh by 2050 (Figure 1.11). Renewable energy sources would provide the bulk of the power mix, accounting for 71% and 88% of the total electricity supply by 2030 and 2050, respectively – a significant rise from the 38% observed in 2021. The share of fossil fuels in the generation mix would significantly shrink from 36% in 2021, to 11% by the end of this decade and further to 1% by 2050. Nuclear power plants are expected to provide 18% of total electricity needs by 2030 and around 12% by 2050. This is to serve a growing electricity demand from end-uses and energy input for production of hydrogen and its derivative fuels, as shown in the electricity balance presented in Table 1.3.

Table 1.2 EU27 installed capacity by technology

GW		Planned Energy Scenario			Decarbonising Energy Scenario		
	2021	2030	2040	2050	2030	2040	2050
TOTAL	**945**	**1 571**	**2 006**	**2 297**	**1 571**	**2 169**	**2 702**
Fossil	**348**	**229**	**192**	**206**	**229**	**152**	**149**
Coal	120	66	33	33	66	0	0
Natural gas	202	147	145	159	147	137	137
Oil	26	16	14	14	16	15	12
Nuclear	**105**	**95**	**98**	**98**	**95**	**98**	**98**
Renewable	**491**	**1 246**	**1 717**	**1 993**	**1 247**	**1 919**	**2 456**
Biomass solid	34	38	35	33	38	35	33
CSP	2	3	3	3	3	3	3
Geothermal	1	1	1	1	1	1	1
Hydro	105	108	111	116	108	111	116
Ocean tide wave	0	0	4	8	1	21	41
Solar PV	161	651	937	1 109	651	1 098	1 443
Wind offshore	15	97	201	216	97	210	303
Wind onshore	173	349	424	508	349	439	517

Notes: CSP = concentrated solar power; GW = gigawatt; PV = photovoltaic.

Figure 1.11 EU27 electricity generation



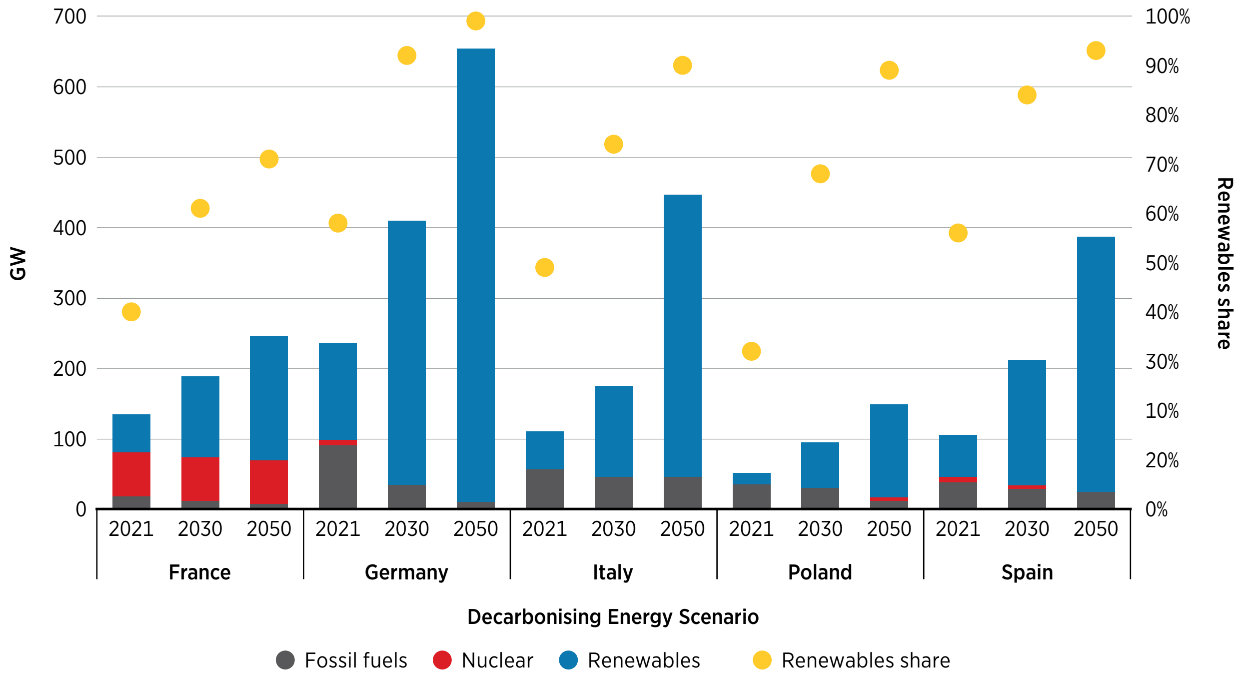
Note: TWh = terawatt hour.

Table 1.3 Electricity balance

TWh		Planned Energy Scenario			Decarbonising Energy Scenario		
	2021	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Net imports	**45**	**-98**	**78**	**39**	**50**	**164**	**91**
Electricity generation and other transformation	**2 708**	**3 117**	**3 680**	**3 987**	**3 083**	**3 749**	**4 231**
Hydrogen and e-fuels plants	-	-43	-215	-560	-38	-200	-525
Final energy consumption	**2 477**	**2 713**	**3 366**	**3 540**	**2 813**	**3 397**	**3 486**
Industry	956	929	1 018	1 082	909	946	973
Buildings	1 410	1 419	1 442	1 421	1 507	1 558	1 518
Transport	56	321	870	1 006	356	862	970
Other consumption	54	44	36	32	41	31	26

Note: TWh = terawatt hour.

Figure 1.12 Installed capacity in selected countries by technology in the DES



Notes: DES = Decarbonising Energy Scenario; GW = gigawatt.

Comparing the PES and DES highlights key differences in the transition's pace. In the PES, fossil fuels, particularly natural gas, play a continued role in system flexibility. In the DES, fossil fuel use is nearly eliminated, but gas remains critical for capacity adequacy during low-renewables periods. Nuclear power, while maintaining stable capacity, faces declining capacity factors in the DES, requiring greater operational flexibility to accommodate fluctuating renewables.

Successfully managing this transition will require modernised grids, energy storage and enhanced market mechanisms to integrate large shares of renewables while ensuring system reliability. Cross-border electricity trade and co-ordinated infrastructure planning will be key to balancing decarbonisation with security and affordability. To ensure system adequacy and cost-effectively manage the transition, flexibility needs must be quantified using metrics such as ramping capability, reserve adequacy, grid congestion indicators and system inertia. Quantifying the economic value of flexibility services – such as the avoided costs of curtailment and system imbalances – will be crucial for informing market designs and investment frameworks.

Over the next five years, policy makers must reform markets to properly value flexibility, including storage, demand response and grid-supportive technologies. Strengthening cross-border co-ordination and grid infrastructure will improve renewable balancing, while standardised flexibility metrics can align planning with 2030 targets. Support for sector coupling – such as green hydrogen, electrified heating and vehicle-to-grid integration – will unlock further flexibility. Resilience planning must also reflect the role of storage and demand-side solutions. A co-ordinated, data-driven approach is essential to ensure a secure, affordable and efficient transition.

1.2.4 Bioenergy and other direct uses of renewables

Electrification and renewable power generation are not the only efforts required for decarbonisation. Direct use of renewables – including bioenergy, solar thermal and geothermal – offers options. Modern use of bioenergy is expected to play a growing role, accounting for 15% and 12% of TFEC by 2030 and 2050, respectively, from 9% in 2021.

Total consumption of all forms of bioenergy would increase from 5.8 exajoules (EJ) in 2021 to 6.6 EJ in 2050. Liquid biofuels, such as aviation biofuel, have an important role to play in the decarbonisation of the transport sector, particularly international marine and aviation bunkers. Given the prominent role of electricity in road transport, the importance of liquid biofuels in the decarbonisation of road transport declines over time. Biomethane, either as biogas or its upgraded form, sees its contribution to the energy mix increase over the period to 2050 as biomethane plays important roles in the decarbonisation of transformation centres (mainly heat and power generation) as well as in international marine bunkers and end-use sectors. Solid biomass fuels see their role remaining largely the same in the decarbonisation of heat and power generation, but decline in the supply of energy in end-use sectors. The total primary energy supply of biomass needs to increase from just over 6.0 EJ in 2021 to 8.2 EJ in 2050, dominantly sourced from biomass of shorter carbon cycles and a slight increase in forestry biomass supply. The domestic supply is limited in line with the European Commission's study "Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels". A significant portion of supply overall should come through imports of liquid biofuels. Liquid biofuel imports would increase almost eight-fold in the period (see Table 1.4).

Table 1.4. EU27 bioenergy consumption by source

				PLANNED ENERGY SCENARIO			DECARBONISING ENERGY SCENARIO		
			2021	2030	2040	2050	2030	2040	2050
SOLID BIOMASS (PJ)	Primary biomass production		5 034	5 909	5 613	5 286	5 749	5 616	5 132
	Net imports		164	20	20	20	-	0	-
	Consumption	Power and heat	2 259	2 511	2 285	2 138	2 411	2 484	2 285
		Buildings	1 842	1 951	1 840	1 667	1 918	1 782	1 576
		Industry	1 025	1 409	1 461	1 459	1 365	1 310	1 238
		Other consumption	71	57	47	41	54	40	34
LIQUID BIOFUELS (PJ)	Primary biomass production (feedstock)		832	735	927	1 133	730	900	1 147
	Transformation losses (feedstock)		173	240	397	561	249	385	573
	Net imports (liquid biofuels)		115	268	901	941	344	934	902
	Consumption (liquid biofuels)	International bunkers	-	153	1 111	1 315	153	1 127	1 301
		Domestic transport	701	576	289	174	639	297	154
		Industry	23	14	13	13	14	12	11
		Other consumption	20	16	13	12	15	11	10

			PLANNED ENERGY SCENARIO			DECARBONISING ENERGY SCENARIO		
		2021	2030	2040	2050	2030	2040	2050
BIOGAS AND BIOMETHANE (PJ)	**Primary biomass production (feedstock)**	**139**	**2 961**	**3 274**	**3 367**	**2 993**	**2 903**	**2 019**
	Transformation losses (feedstock)	**70**	**1 527**	**1 685**	**1 732**	**1 543**	**1 520**	**1 075**
	Net imports	**1**	**-**	**-**	**0**	**-**	**0**	**-**
Consumption	Power and heat	15	495	707	758	542	766	484
	International bunkers	-	18	134	291	18	123	256
	Domestic transport	-	24	12	4	16	9	4
	Industry	20	338	277	205	377	269	174
	Buildings	-	530	436	357	468	195	8
	Other consumption	35	28	23	20	27	20	17

Note: PJ = petajoule.

In the next five years, the development of sustainable bioenergy supply chains and import strategies to meet the increasing demand of bioenergy, particularly liquid biofuels for international bunkers, will be key. A conservative approach was applied to loss reductions in this analysis but reducing losses of biomass along supply chains is crucial, as is energy system integration. Bioenergy is expected to play a key role in the decarbonisation of hard-to-abate sectors like aviation and shipping, as well as some industrial processes. The use of biogas and biomethane will play a more predominant role in the power and heat sectors, and relevant infrastructure might need to be expanded to support their integration into the energy system. These considerations are in line with recent perspectives from the European Biogas Association, which emphasises the role of biogases in achieving the EU's energy and climate objectives (European Biogas Association, 2024, 2025). Therefore, making funding available for the development of advance biofuels as well as enhancing cross-border bioenergy agreements can be key for the decarbonisation of these sectors.

1.2.5 The role of hydrogen, ammonia, methanol and other e-fuels

Hydrogen, ammonia, methanol and other e-fuels offer the means to decarbonise some hard-to-abate sectors. Overall, the use of these carriers would increase from negligible values today to 10.6 and 36.8 Mt of hydrogen equivalent in 2030 and 2050, respectively (see Table 1.5). These total quantities are notably lower than those assessed in the European Commission Impact Assessment Report for the 2040 Climate Target Communication. In particular, they would support the decarbonisation of international and domestic aviation and navigation, together with biofuels. The use of these hydrogen-derived fuels in transport, including international bunkers, would grow from negligible volumes today, to 23.5 Mt of hydrogen equivalent in 2050, in the DES.

In other end-use sectors, their main contribution would be in the decarbonisation of industrial processes in sectors where other decarbonisation pathways are not viable, like iron and steel making and the production of chemicals. Total industry consumption would reach 1.7 Mt of hydrogen equivalent by 2050. Also, hydrogen is a key component (at 5 Mt by 2050) of flexible technologies mitigating the challenges posed by very large shares of intermittent renewable electricity generation.

In 2030, the share of hydrogen and its derivatives produced in the EU27 from clean technologies, including water electrolysis, biomass-based and natural gas with carbon capture and storage would be 29%, and in 2050 this share would grow to 98%, with electrolysis-based production representing 81% of the total. Net imports of hydrogen, ammonia, methanol and other e-fuels would play a growing role over the course of the next decades, reaching 2 Mt by 2030, 9 Mt by 2040 and 16 Mt in the DES by 2050. The specific production needs for green hydrogen in the European Union are further elaborated in Chapter 5.

Table 1.5 EU27 consumption of hydrogen, ammonia, methanol and other e-fuels in the DES

MILLION TONNES OF HYDROGEN EQUIVALENT			DECARBONISING ENERGY SCENARIO	
			2030	2050
	End use	Industry	0.8	1.7
		Buildings	0.0	0.0
		Transport	0.9	5.2
	Transformation	Power grid flexibility	0.0	5.0
		Heat and power	0.0	0.0
		Oil refineries	2.6	0.2
	Bunkers		**0.5**	**18.3**
	Non-energy		**5.7**	**5.9**
	Total		**10.6**	**36.3**

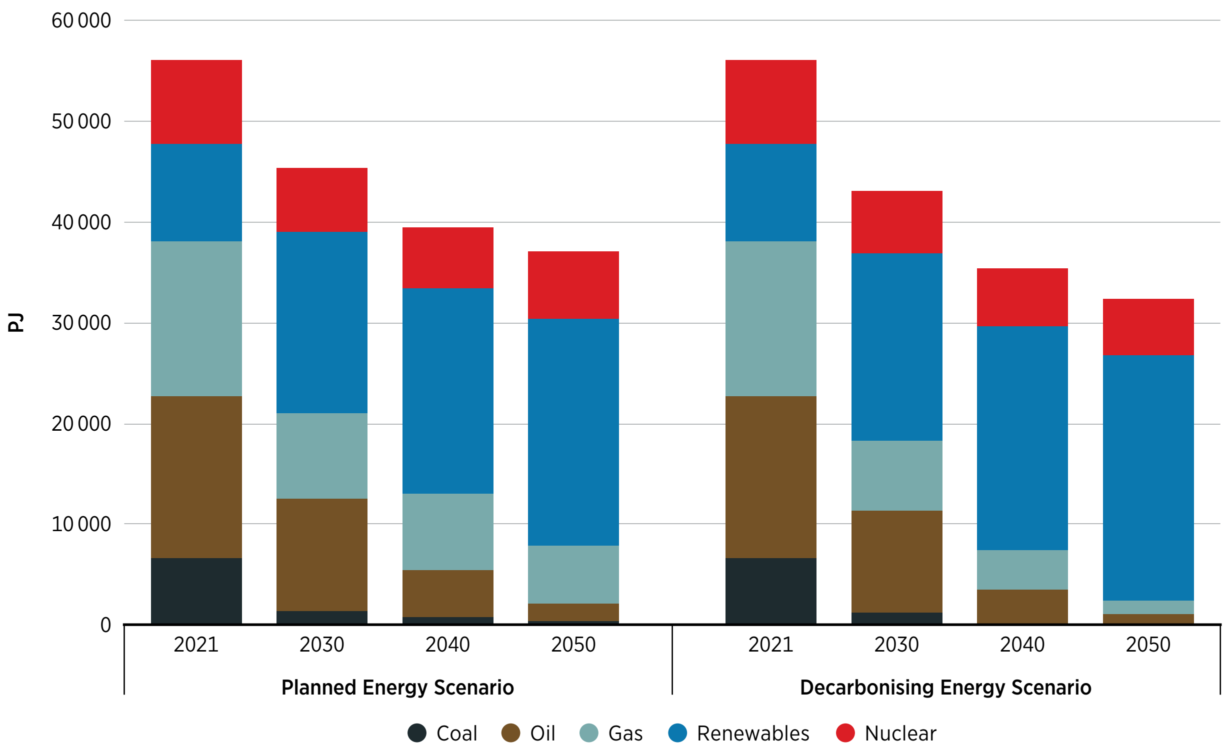
To scale up hydrogen, ammonia, methanol and other e-fuels, policy makers can focus on several key actions over the next five years towards effective and measured development. First steps include setting clear regulations, creating incentives and ensuring investment flows into effective and carefully deployed clean hydrogen production and infrastructure. Research and development funding is important to drive down costs and improve efficiency, while robust certification schemes will be essential to guarantee sustainability. At the same time, international co-operation is crucial. Strengthening partnerships can help secure supply chains for critical materials and establish a stable framework for hydrogen imports. As hydrogen becomes more embedded in industrial decarbonisation and energy system flexibility, it must be properly integrated into broader energy and industrial strategies. Grid infrastructure will need upgrades to support large-scale electrolysis where this is deployed, ensuring the system can handle larger shares of renewables.

1.2.6 Total primary energy supply – fossil fuels' share must diminish

Renewable energy's share of the EU27 primary energy supply would grow from 17% in 2021 to 75% in 2050 (see Figure .13). The energy mix would change drastically in the process. In 2021, the EU27 energy mix was dominated by fossil fuels, contributing 68% of total primary supply, while renewables and nuclear accounted for 15% and 17%, respectively.

Fossil fuel use would have to decline by more than 90% by 2050 (Figure 1.13). Fossil fuels would still have roles to play, mainly in power and to an extent in industry, providing 7% of the primary energy supply in 2050. The EU27 supply of oil is expected to drop by more than 90% by 2050. Most of it would be used in industry for petrochemicals (non-energy uses), and in aviation and shipping. The EU27 coal supply would decline even more drastically, from around 3.3 EJ to just a small fraction of that in 2050. The remaining coal demand would be largely restricted to industry, mostly for steel production. Natural gas would be the largest remaining source of fossil fuel in 2050, making up 55% of total fossil fuel supply and 4% of total primary supply (down from 30% in 2021). In 2050, natural gas would primarily be used in industrial processes and power plants, mainly for flexibility.

Figure 1.13 EU27 total primary energy supply by carrier



Note: PJ = petajoule.

The next five years will be crucial in setting the course for a successful energy transition. Accelerating renewable deployment requires reducing red tape, streamlining permitting and ensuring grid expansion keeps pace with demand. Investment in storage, inter-connections and demand-side flexibility will be key. At the same time, fossil fuel phaseout policies must be ambitious yet pragmatic, combining carbon pricing with targeted support for affected industries and workers. In industry, scaling electrification will be essential, while the power sector must balance renewables, nuclear and transitional technologies to maintain reliability. Energy efficiency across buildings, transport and industry will ease pressure on supply, while international co-operation on infrastructure, critical raw materials and innovation will be vital to securing a resilient and cost-effective transition.

1.3 INVESTING IN THE ENERGY TRANSITION – THE KEY FOCUS

To support all the efforts required to achieve climate objectives, the development of a clean energy investment strategy for Europe will be instrumental. The Commissioner for Energy and Housing has been tasked with doing so in a Mission Letter, with the aim of supporting the development of clean energy infrastructure (European Commission, 2024c). Average annual investment over 2025-2050 is similar in both scenarios, at EUR 905 billion in the PES and EUR 1 030 billion in the DES, corresponding to 6% and 7% of Europe's GDP in 2021 respectively. This results in a cumulative EUR 23 trillion in the PES and EUR 26 trillion in the DES, as shown in Table 1.6.

Cumulative investments in the transformation, including energy conversion processes such as power generation, refining, hydrogen production and district heating, would amount to EUR 6.5 trillion in the PES (and EUR 7.4 trillion in the DES) over 2025-2050. This include EUR 2.6 trillion in the PES (and EUR 2.9 trillion in the DES) in power plants; EUR 330 billion in the PES (and EUR 350 billion in the DES) in flexible technologies; and EUR 2.2 trillion (and EUR 2.5 trillion) in grids. The increase in installed renewable power capacity requires a parallel commitment to significant investment in the electricity network and methods of integrating variable supply. For several years, investment in electricity grid networks has lagged investments in renewable power capacity.

In addition to investment in power plants, cumulative investment in transformation centres like bioenergy plants, heating and e-fuel plants would amount to around EUR 1.1 trillion in the PES (and EUR 1.6 trillion in the DES) over 2025-2050. In end-use sectors, cumulative investments in transition-related technologies would amount to EUR 2.5 trillion in the PES (and EUR 2.6 trillion in the DES) over the same period. This includes investments in building renovation (EUR 1 trillion in the PES and EUR 1.9 trillion in the DES); smart meters in buildings (EUR 37 billion in both scenarios) and EV chargers (around EUR 300 billion in both scenarios).

Table 1.6 Acquisition costs and infrastructure investments relevant to the energy transition in the PES and DES

			AVERAGE ANNUAL INVESTMENT FOR 2025 - 2050		CUMULATIVE INVESTMENT FOR 2025-2050	
			PLANNED ENERGY SCENARIO	DECARBONISING ENERGY SCENARIO	PLANNED ENERGY SCENARIO	DECARBONISING ENERGY SCENARIO
BILLION EUROS	Expenditure	Conventional demand-side technologies	100	100	2 550	2 600
		Direct uses of renewables, hydrogen and derivatives, district heating	40	50	1 050	1 200
		Electrification of end-uses	420	465	4 900	5 800
		Energy conservation and efficiency	20	10	6 100	6 200
		Total	**580**	**629**	**14 600**	**15 700**
	Infrastructure	Biofuel, hydrogen, e-fuels, DH supply	45	60	1 100	1 600
		Carbon removal	7	6	200	200
		Conventional demand-side technologies	0.3	0.2	7	5
		Conventional supply-side technologies	25	15	600	350
		Direct uses of renewables, hydrogen and derivatives, district heating	1	1	30	20
		Electrification of end-uses	12	13	310	330
		Energy conservation and efficiency	45	85	1 100	2 100
		Power grids and flexibility	100	115	2 500	2 900
		Renewable electricity generation capacity	90	110	2 300	2 700
		Total	**325**	**405**	**8 200**	**10 050**

In the next five years, adequate and timely investment in electricity grids and system flexibility will be key, as solutions that prevent bottlenecks in renewable energy deployment or electrification. Expanding green financing tools, such as tax incentives or subsidies, can make a difference in facilitating the wider adoption of clean technology. It is also important to ensure a just transition by directing investment towards human resources development in areas affected by the energy transition.

2

TRANSPORT

This chapter presents the main outcomes, findings and messages of the transport sector analysis for EU27. Some of the key questions this section will tcover are:

1. What is the current status of the decarbonisation of transport in the region?
2. Are the existing directives, plans and measures sufficient to deliver net zero by 2050?
3. Are there additional measures that could be implemented to further decarbonise the transport sector?

KEY FINDINGS

- ★ **Transport emissions decline significantly from about 760 $MtCO_2$ at baseline year 2021 to 16 $MtCO_2$ and 5.4 $MtCO_2$ by 2050 in the Planned Energy Scenario (PES) and Decarbonising Energy Scenario (DES) respectively**. Road transport emissions represented 96% of the total transport emissions in the base year. Its decarbonisation, mostly driven by the electrification of the fleet, leads to reaching close to zero emissions by 2050 in both scenarios. By 2050, remaining emissions come mostly from the aviation and shipping sectors.

- ★ **Transport sector electricity use has to increase about 17 times by 2050 under both scenarios compared with 2021**, reaching 1 000 terawatt hours (TWh) in the Planned Energy Scenario (PES) and 970 TWh in the Decarbonising Energy Scenario (DES). Electricity demand in the DES is lower than in the PES due to increased vehicle occupancy, driven by car sharing policies and behavioural change, and by truck payload capacity, as well as by a modal shift to rail. As a result of transport sector electrification, fossil fuel demand—and consequently, dependence on imports—is expected to decline. This transition would strengthen the region's energy security and competitiveness.

- ★ **Average annual electric vehicle (EV) sales are about 19 million in the period 2021-2030, up from 2.5 million today** (EEA, 2024), while over 2030-2040, sales should increase to around 40 million. EVs represent 25% and 30% of the stock in the Planned and Decarbonising Energy Scenarios, respectively, by 2030; about 82% by 2040; and approximately 98% by 2050 in both scenarios.

- ★ **By 2050, around 9.4 million public chargers and 108 million private chargers, including home and depot chargers, will need to be installed.** That is an addition of about 320 000 public chargers per year on average, from 153 000 today (ACEA, 2024). An average annual investment of EUR 7.2 billion for private chargers and EUR 4.2 billion for public ones will be needed from now until 2050.

- ★ **Passenger rail activity will reach 740 billion and 900 billion passenger-kilometres (pkm) in the PES and DES, respectively, by 2050, representing an 80% increase in the PES and more than double the activity in the DES compared with the pre-COVID levels of 2019.** Freight rail activity is also expected to increase, reaching 725 billion (PES) and 860 billion tonne kilometres (tkm) (DES) by 2050; this is 70% and 100% more than the pre-COVID levels of 2019.

- ★ **Biofuel use in road transport is expected to decline towards 0 as EVs gradually dominate the fleet. Blending ratio of biofuels in road transport sector increase until 2030 to contribute to the emissions reduction in the short term in the DES.** Biofuel use is expected to increase in aviation and shipping, where domestic consumption will grow from about 27 million litres in 2021 to 4 970 million litres and 4 640 million litres in the PES and DES, respectively, by 2050.

- ★ **The domestic demand for hydrogen and its derivatives reaches 5.35 Mt and 4.9 Mt in the Planned and Decarbonising Energy Scenarios, respectively, by 2050, from none in 2021.** The demand in the DES is lower than in the PES due to less use of hydrogen trucks for freight transport, resulting from a modal shift towards railways. Based on the results of this study, the role of hydrogen and its derivatives in the transport sector will be limited to niche applications while electrification will be the main decarbonisation pathway.

KEY MESSAGES

- **Ambitious targets for decarbonising the transport sector and reducing its carbon dioxide (CO_2) emissions have already been set**. Reducing fossil fuel dependence and shifting towards the electrification of the sector can also provide benefits to the EU if the electricity is locally produced. The development of new renewable energy capacity and transport technologies could mobilise new industrial activity if developed appropriately. The current regulatory framework sets ambitious targets already in the short term, requiring immediate action to ensure their compliance. Based on the outcomes of this analysis, it can be concluded that strong efforts and action are needed now to meet the targets defined, indicating challenging times ahead for the transport sector.
- **Financial incentives for the promotion and competitive manufacturing of EVs within Europe will be key particularly in the short term until they reach price parity with internal combustion engine (ICE) vehicles** to ensure that their production in Europe is competitive, their sales share increases and that the objectives in terms of emissions reduction are met. Additionally, EU citizens and businesses could benefit from potential cost savings from the reduced operational and fuel costs of electric vehicles. EV charging infrastructure should be developed quickly to give confidence to consumers. Incentives for the installation of private and public EV chargers, the development of a robust and EU-based supply chain for charging infrastructure, the definition of smart and bidirectional charging strategies and planning for demand integration and sector coupling services, could bring numerous benefits to the power system and to consumers.
- **The quality of rail transport will need to be enhanced to accommodate the modal shift from passenger cars, heavy duty trucks and aviation.** Mechanisms to encourage the use of rail transport could include subsidised rail tickets, tax incentives for businesses, the modernisation of stations and loading and unloading facilities, and efforts to raise public awareness of the safety, efficiency and environmental benefits of rail transport.
- **The use of hydrogen and its derivatives, and of biofuels such as biodiesel, bioethanol or bio-jet, will be key to decarbonising the transport modes that cannot be electrified.** Country-level feedstock analysis could be carried out to determine if local resources are sufficient to cover demand or if imports are needed.
- **Hydrogen and its derivatives will only play a role in the decarbonisation of transport services that cannot be electrified**, which is foreseen as the main decarbonisation pathway in the transport sector. Country-based potential analysis and definition of production, import and export strategies are recommended to ensure security of supply and affordable prices.
- **Intra-EU trade could ensure local natural, technological and human resources are exploited fully**. The transition towards zero-emission technologies represents a great development opportunity that Member States could take advantage of. Ease of regulatory requirements would facilitate further exchange between EU countries.
- **The definition of a specific set of indicators that all countries need to report on, for instance in the NECPs, would facilitate the monitoring of the transport industry evolution on their way to meeting the targets defined in the current regulatory framework**. The definition of these specific targets could also facilitate countries understanding the feasibility of meeting them and establishing specific mechanisms if needed so that they can be met.
- **Co-ordinated action among the different transport subsectors' stakeholders and across sectors is key to ensuring appropriate planning and implementation of actions.**

2.1 THE ROLE OF TRANSPORT IN MEETING EU EMISSIONS REDUCTION TARGETS

The mobility of people and goods plays a vital role in today's society and economy. The transport sector relies heavily on fossil fuels, which represent about 92% of the sector's final energy consumption, and alone accounts for 26% of all greenhouse gas (GHG) emissions in Europe (Eurostat, 2024). Passenger as well as freight transport are expected to increase towards 2050, reaching 6.6 trillion pkm and 3.2 trillion tkm, or 10% and 40% higher than the pre-COVID levels of 2019.

The European Union leads global energy transition discussions and aims to reduce its economy-wide GHG emissions by at least 55% by 2030 over 1990 levels and become climate neutral by 2050 (European Commission, 2021). This target was defined in the European Green Deal and is legally binding, thanks to the European Climate Law. Achieving this target will require decarbonising the transport sector. Table 2.1 presents key transport sector regulations, directives, plans and strategies that were revised for the development of the transport sector analysis. If the targets defined in these documents are met, transport sector emissions will be very close to net zero by 2050.

Table 2.1 Transport regulations and relevant documents considered in the PES and DES

REGULATION / PLAN / STRATEGY	REFERENCE
• Sustainable and smart mobility strategy that aims for a 90% cut in transport sector emissions by 2050 delivered by a smart, competitive, safe, accessible and affordable transport system	(European Commission, 2020a)
• *Regulation (EU) 2023/851* on strengthening the carbon dioxide emission performance standards of new passenger cars and new light commercial vehicles consistent with the Union's increased climate ambition	(European Commission, 2023b)
• *Regulation (EU) 2023/1804* on the deployment of alternative fuels infrastructure	(European Commission, 2023c)
• *Regulation (EU) 2023/1805* on the use of renewable and low-carbon fuels in maritime transport	(European Commission, 2023d)
• *Directive (EU) 2023/2413* regarding the promotion of renewables-based energy (Renewable Energy Directive [RED III])	(European Commission, 2023e)
• *Regulation (EU) 2023/2405* on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation)	(European Commission, 2023f)
• *Regulation (EU) 2024/1610* on strengthening the carbon dioxide emission performance standards for new heavy-duty vehicles and integrating reporting obligations	(European Commission, 2024e)
• *Regulation (EU) 2024/1679* on Union guidelines for the development of a trans-European transport network	(European Commission, 2024f)
• Proposal for a Regulation on the use of railway infrastructure capacity in the single European railway area	(European Commission, 2023g)
• Proposal for a directive on establishing a support framework for intermodal transport of goods and on the calculation of external costs savings and generation of aggregated data	(European Commission, 2023h)
• National Energy and Climate Plans	(European Commission, 2024g)

Notes: EU = European Union; CO_2 = carbon dioxide; RED III = Renewable Energy Directive III.

Additionally, the EU Emissions Trading System (EU ETS) has been in place since 2005, making the European Union the world's first carbon trading market. The EU ETS, based on a "cap and trade" principle (European Commission, 2003), seeks to reduce overall emissions in the region while generating revenues to finance the green transition. The system has been covering the aviation sector since 2012 and emissions from large ships (of 5 000 gross tonnage and above) since 2024.

The ETS Directive has been revised several times since 2003. In the 2023 revision, a new emission trading system (ETS2) was created, that will become fully operational in 2027. This new system will cover and address CO_2 emissions from fuel combustion in road transport as well as emissions from the buildings sector and additional sectors (European Commission, 2023i). The carbon price set by the ETS2 seeks to provide a market incentive for investments in low-emissions mobility.

For the European Commission's 2024-2029 mandate, the Commissioner for Sustainable Transport and Tourism, Apostolos Tzitzikostas, has been tasked in his Mission Letter to focus on supporting industry and Member States in implementing and strengthening a single market for transport, advancing a modal shift towards sustainable transport and accelerating the roll-out of trans-European infrastructure (European Commission, 2024h). The enhancement of European manufacturing capacity for net-zero transport technologies such as batteries or fuel cells is also encompassed under the Net-Zero Industry Act. In parallel, Commissioner Dan Jørgensen, responsible for Energy and Housing, has been tasked to "ensure that Europe's transition towards net zero is powered by an energy system with homegrown, clean electricity," with a focus on boosting renewable energy, energy storage, and the grid infrastructure needed to support electrification across sectors, including transport.

Table 2.2 outlines how the PES and DES were defined in the transport sector analysis. The pathway described in the PES is already quite ambitious, and robust efforts are expected from all Member States. With the current fleet electrification targets presented by some Member States in their National Energy and Climate Plans (NECPs), meeting the emission reduction targets for road transport might be challenging by 2030.

Table 2.2 Scenarios definition in the transport sector

Planned Energy Scenario	Decarbonising Energy Scenario
Encompasses legally binding targets for the transport sector already defined by the European Commission in its regulatory framework.	Extends beyond the legally binding targets set in the current regulatory framework to consider additional measures, such as a modal shift from road and aviation to rail, and increased vehicle occupancy truck payload rates.
Outlines the pathway the transport sector would follow if the legally binding targets currently defined are met.	Slightly more ambitious in the short term for light passenger vehicle electrification.

The analysis covers roads, railways, domestic aviation and shipping, and international aviation and shipping as international bunkers. Road transport releases the most emissions (80%) of all transport modes. Its decarbonisation is therefore key to reducing emissions from the sector. Fleet electrification is the main pathway towards clean technologies. EVs are becoming more competitive: battery prices having decreased 89% since 2010, and soon EV's upfront costs could start to be competitive with ICE vehicles without subsidies (BNEF, 2024).

Europe could exploit the growing significance of clean technology manufacturing in decarbonising transport. The Net-Zero Industry Act seeks precisely to scale up the manufacturing capacity of clean technologies that release extremely low, zero or negative GHG emissions when they operate (European Commission, 2023j). The act seeks to make the EU industry more competitive, create quality jobs and support the European Union's efforts to become energy independent. Grid technologies and fuel cells are among the key technologies expected to be supported.

The transition towards clean transport technologies could also boost the bloc's energy security with the use of EVs powered by locally produced renewable electricity, a shift towards active transport modes, public transport and railways.

2.2 PATHWAYS FOR DECARBONISING TRANSPORT

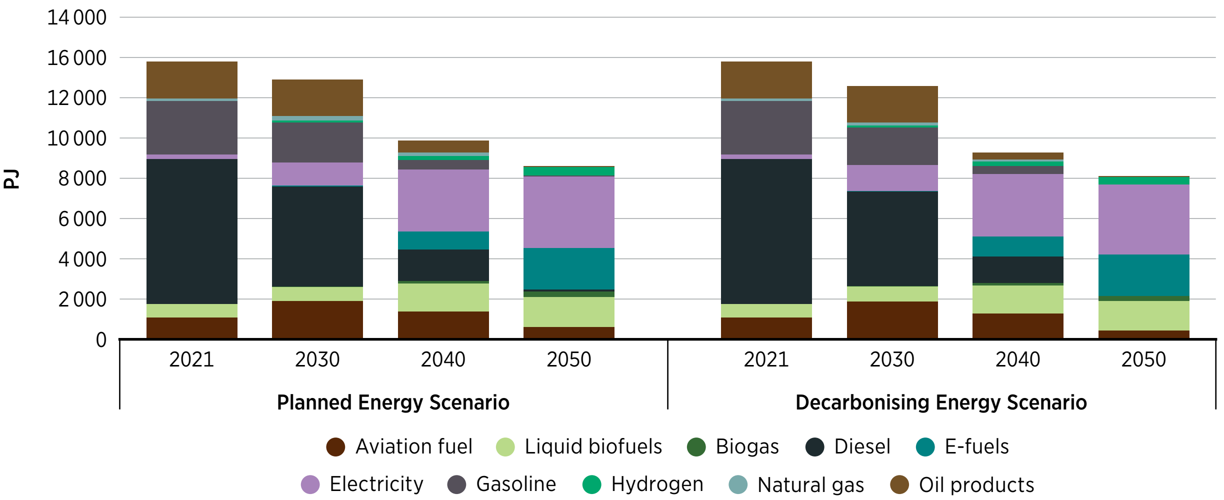
The latest update of the Renewable Energy Directive (RED III) establishes targets for mainstreaming the use of renewable energy in the transport sector (European Commission, 2023e). All Member States shall mandate fuel suppliers to ensure that the amount of renewables supplied to the transport sector leads to an at least 29% share of renewable energy in transport final energy consumption by 2030 or a GHG intensity reduction of at least 14.5% by 2030.[6] Also, advanced biofuels, biogas and renewable fuels of a non-biological origin (RFNBOs) should have at least a 1% share in the energy supplied to the transport sector in 2025 and 5.5% in 2030, of which at least 1% should be from RFNBOs in 2030.

These targets are met in the PES and DES after considering the multipliers defined in the Directive. Member States with maritime ports also have to comply with the target of reaching a 1.2% share of RFNBOs by 2030, which is also considered in both scenarios for the analysis. However, achieving this target requires ambitious actions across transport modes.

2.3 GENERAL OVERVIEW OF THE TRANSPORT SECTOR

The transport sector is expected to undergo a complete transformation, as illustrated in Figure 2.1. The sector's final energy consumption was dominated by fossil fuel derivatives in 2021. By 2050, the total demand is expected to decrease by approximately 40% relative to 2021, mainly due to efficiency gains from fleet electrification, the main decarbonisation pathway considered in this analysis.

Figure 2.1 Transport final energy consumption including international aviation and by carrier

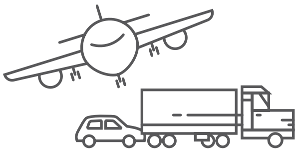


Notes: PJ = petajoule. Oil products refer to those used in domestic and international shipping.

[6] *Article 27 of the RED III establishes the calculation rules for the transport sector and with regard to RFNBOs, including the use of multipliers for the calculation of the minimum renewable energy share.*

The main key performance indicators for the transport sector, presented in Table 2.3, further exemplify its ongoing transformation.

Table 2.3 Key performance indicators for the domestic transport sector



	HISTORICAL	PLANNED ENERGY SCENARIO			DECARBONISING ENERGY SCENARIO		
	2021	2030	2040	2050	2030	2040	2050
KPI.02 RENEWABLES							
Biofuels share in transport FEC (%)	6.2%	6.4%	4.9%	3.8%	7.2%	5.4%	3.7%
Direct and indirect renewable energy share in transport FEC (%)	7%	16%	44%	72%	18%	51%	85%
KPI.03 ENERGY INTENSITY							
Transport - FEC (EJ)	11.4	9.5	6.1	4.6	9.1	5.8	4.3
KPI.04 ELECTRIFICATION IN END-USE SECTORS (DIRECT)							
Share of Electricity in transport FEC (%)	2%	12%	51%	78%	14%	54%	81%
Electric and plug-in hybrid light passenger vehicles (million units)	5.5[1]	61	197	240	75	204	243
Public EV chargers (million units)	0.3[2]	3.8	7.7	9.4	4.6	7.9	9.5
KPI.05 CLEAN HYDROGEN AND DERIVATIVES							
Clean hydrogen and derivatives share in transport FEC (%)	0%	1%	4%	14%	1%	4%	14%
EMISSIONS							
CO_2 emissions ($MtCO_2$/year)	760	549	177	16	512	150	5

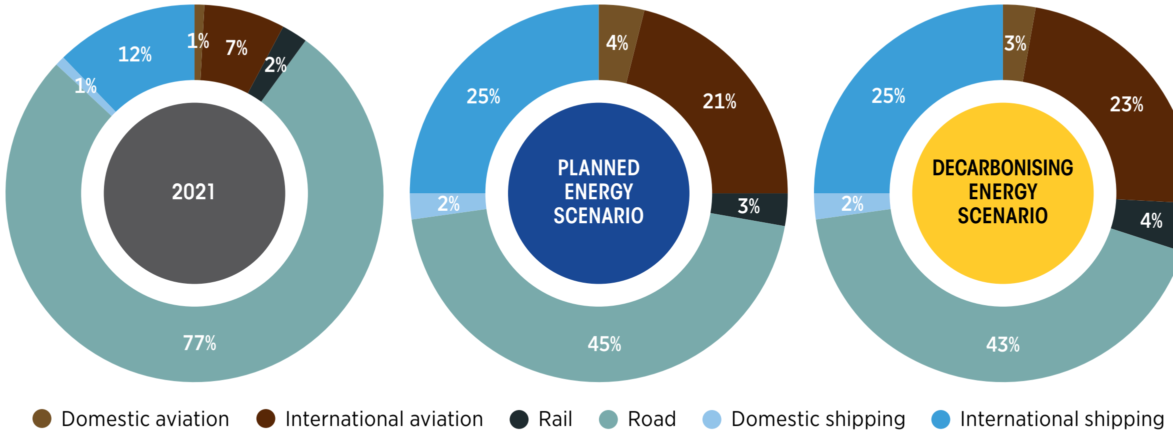
Notes: FEC = final energy Consumption; EJ = exajoule; EV = electric vehicle; CO_2 = carbon dioxide; $MtCO_2$ = million tonnes CO_2; Domestic final energy consumption is considered for the calculation of the indicators; The share of biofuels, direct and indirect renewables, electricity and hydrogen has been calculated as the demand by each of the carriers divided by the total FEC.

[1] Vehicles on European roads 2024 report. **Source:** (ACEA, 2024b).

[2] Charging ahead: accelerating the roll-out of EU electric vehicle charging infrastructure report. **Source:** (ACEA, 2024a).

Figure 2.2 presents the modal shares in transport energy consumption, including international aviation and shipping. As efficiency gains from fleet electrification lead to a decline of energy demand for road transport, international aviation and shipping will have a larger share in final energy consumption. Further information on each transport mode is presented in the sections below.

Figure 2.2 Modal shares in transport energy consumption, including international aviation and shipping

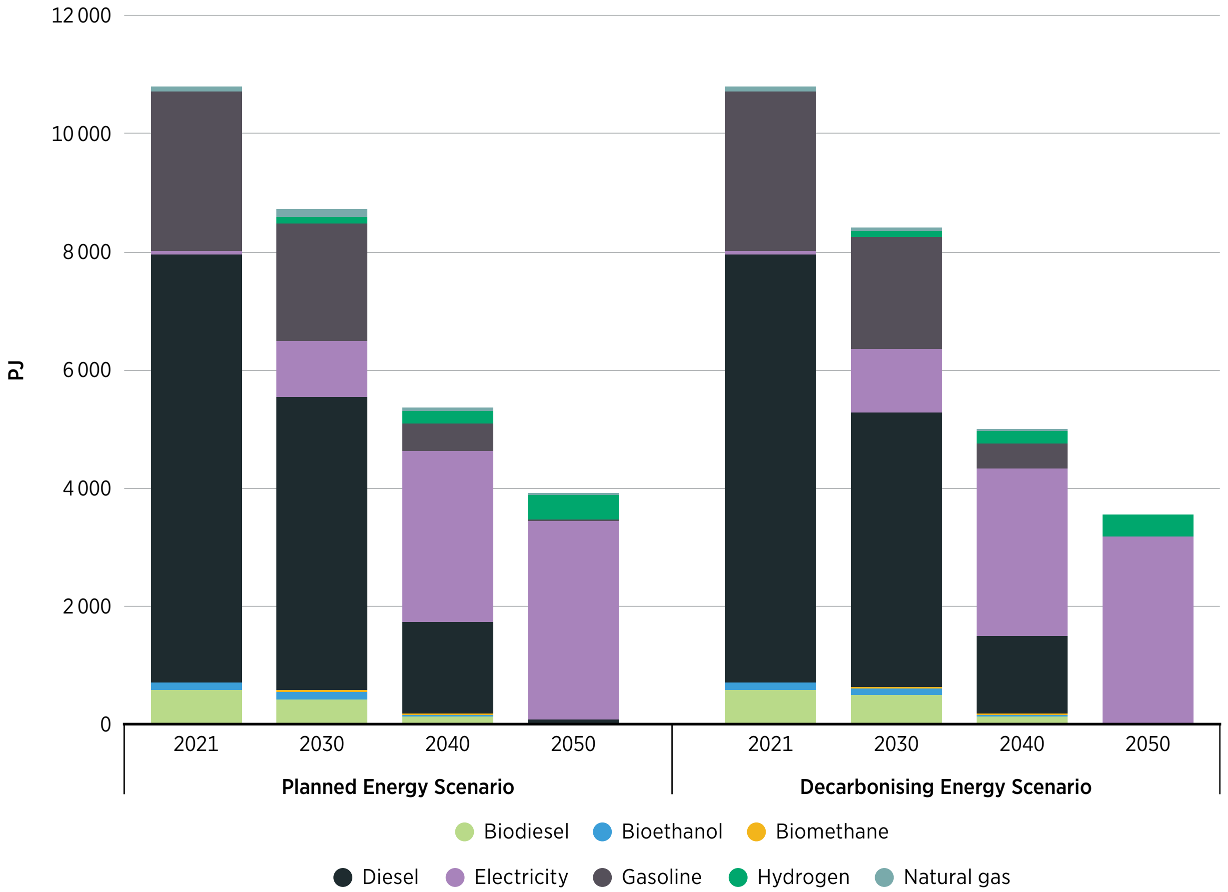


2.4 ROAD TRANSPORT

The European Union has set ambitious targets for the decarbonisation of road transport, as seen in the CO_2 emissions standards set in already approved regulations. For new light passenger vehicles and light duty vehicles, Regulation (EU) 2023/851 applies and establishes a target of a 100% reduction of CO_2 emissions from new light passenger vehicles and light-duty vehicles by 2035, leading to 100% sales of zero-emission vehicles from 2035 (European Commission, 2023b). Regulation (EU) 2024/1610 applies to new buses and heavy-duty vehicles and sets targets to strengthen the grammes of carbon dioxide per kilometre (gCO_2/km) emission standards from 2025, reaching a 90% emissions reduction by 2040 with respect to the average CO_2 emissions of the reporting period of the year 2019 (European Commission, 2024e).

There has been a pushback from some countries and car makers against the strong targets set in these regulations, especially in the short term. In April 2025, the European Commission proposed flexibility to help manufacturers comply with 2025 CO_2 emission targets for new cars and vans (European Commission, 2025c). Yet the targets give a very strong signal to the market on the direction in which the automotive industry should move forward. As can be observed in Figure 2.3, electricity's share in road transport consumption increases from 0.4% in 2021 to 86% in the PES and 89% in the DES, becoming the main decarbonisation pathway. Road transport energy consumption decreases 64% and 67% in the PES and DES, respectively, despite the slight increase in activity due to the energy efficiency gains from the use of EVs.

Figure 2.3 Road transport final energy consumption by carrier



Note: PJ = petajoule.

2.4.1 Road transport electrification

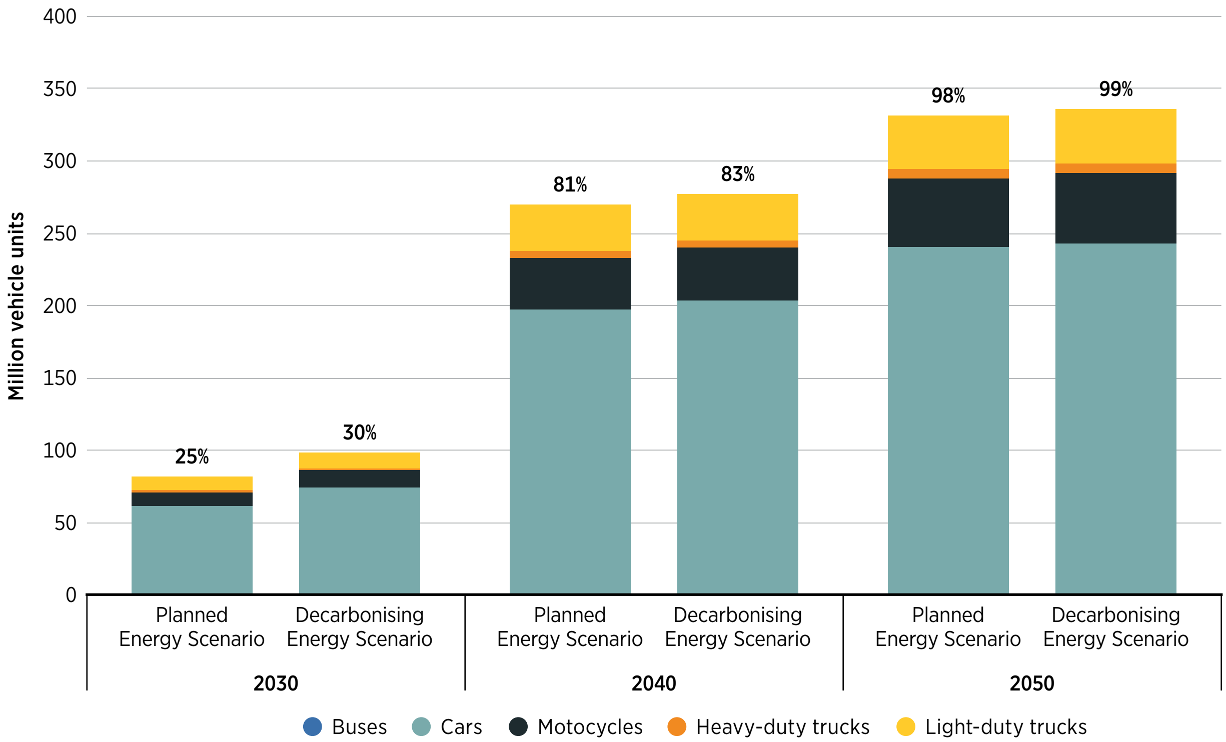
Electricity consumption in road transport is expected to be 24 and 27 times higher by 2030 relative to 2021 in the PES and DES, respectively, and 85 and 80 times higher in the PES and DES by 2050. The lower electricity demand in the DES is due to increased car occupancy and truck payload, and a modal shift from cars and heavy-duty trucks to railways.

EVs are expected to be the main decarbonisation pathway for all vehicle types. ICE cars, motorcycles and light-duty trucks (up to 3.5 tonnes) are fully substituted by EVs. For buses and heavy-duty trucks, fuel cell EVs are assumed to be used in niche applications.

Clean vehicles are introduced into the fleet to meet the CO_2 emission standards set in (European Commission) Regulations 2023/851 and 2024/1610, considering the targets defined in the Member States' NECPs. Analysis of the results of vehicle stock turnover modelling suggests that some ICE vehicles will have to be forced to retire before the end of their lifetime to meet the ambitious targets set in the regulations.

With the current targets in some Member States' NECPs, the 2030 CO_2 emission standards defined for cars will be challenging to meet. This is why more electric cars are on the road in the DES than in the PES by 2030, as can be observed in Figure 2.4, which also depicts EV stock by technology for the years 2030, 2040 and 2050. In the long term, efforts under the PES and DES to achieve road transport decarbonisation by 2050 are quite similar.

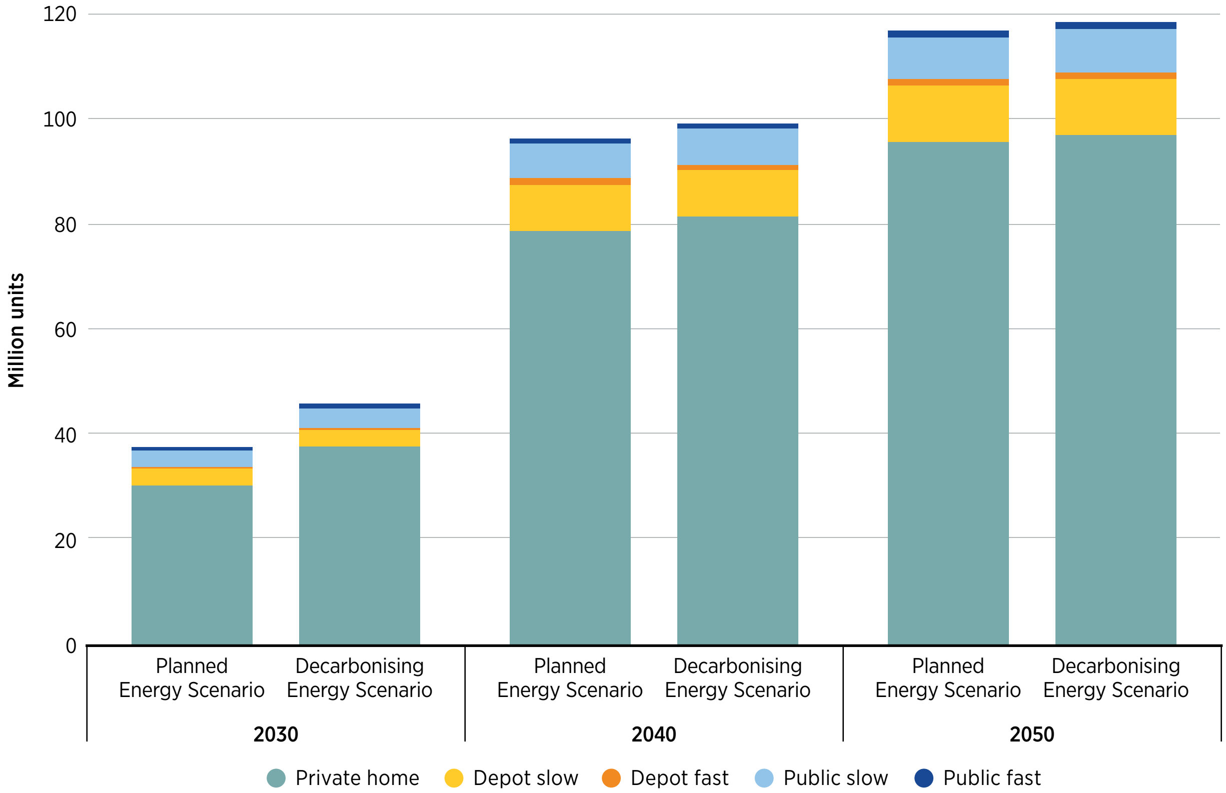
Figure 2.4 Electric vehicle stock and shares in stock, by vehicle type



A successful EV fleet roll-out requires a well-developed network of charging stations. In Europe, the Alternative Fuels Infrastructure Regulation (AFIR) establishes mandatory national targets that drive the deployment of sufficient public alternative fuel infrastructure for road vehicles, trains, vessels and stationary aircraft in the region (European Commission, 2023c). Specific targets for recharging infrastructure dedicated to light- and heavy-duty vehicles along the TEN-T core road network are defined. For private charging points, the Energy Performance of Buildings Directive (EPBD) has set ambitious requirements (European Commission, 2024r).

Additionally, the European Commission set a target of 3.5 million publicly accessible recharging points (European Commission, 2022b). According to the analysis, 3.8 million such points will be available by 2030 in the PES and 4.6 million in the DES. The choice of charger will depend on the EV technology and its specific uses. Figure 2.5 presents the number of chargers, by type, needed in the PES and DES until 2050.

Figure 2.5 Electric vehicle charging points by type



Private cars are expected to be mostly charged at home, which explains the high number of home chargers in Figure 2.5, but also at work or at slow public charging stations for regular use. Fast chargers will also be needed on highways to accommodate charging needs on long-distance trips.

Light-duty vehicles and urban buses are expected to operate on fixed routes in cities and to be charged at depot charging stations when they are not running. Heavy-duty trucks travelling long distances are expected to be loaded at depot charging stations when loading or unloading payload, but also at fast-charging stations that will need to be developed on highways.

Private electric cars and commercial EVs differ in their charging patterns. Private electric cars represent a larger number of vehicles with a low electricity demand and are expected to have geographically distributed charging needs. These vehicles are expected to be parked most of the time, presenting an opportunity to provide flexibility services to the distribution grid via smart and bidirectional charging functionalities. Commercial EVs are fewer in number with a higher electricity demand and are expected to have more geographically concentrated charging needs, as they are expected to spend less time parked. However, they are expected to have more geographically concentrated charging needs, and their use is more predictable than that of private electric cars, which would also allow them to provide flexibility services to the grid.

EVs' charging needs and patterns are to be analysed at a local level to ensure affordable and equitable access to electric mobility for all citizens, and a just transition towards this technology. It is foreseen that the grid will need reinforcement and additional transformation capacity in substations to effectively accommodate the rise in demand and ensure quality of supply (Euroelectric, 2021).

2.4.2 Energy efficiency improvements for road transport

Apart from the energy efficiency gains from EV adoption, the specific fuel consumption of ICE vehicles, EVs and fuel cell EVs is expected to decrease during the study period due to efficiency improvements in the technology. The same level of improvement has been considered in the PES and DES.

In the DES, greater efficiency is foreseen considering higher vehicle occupancy and payload towards 2050, due to an increase in car sharing, and higher truck payloads. As a result, the yearly distance travelled by these vehicle types declines while the activity level remains the same as in the PES.

A modal shift is considered in all EU countries in the DES. The use of passenger cars falls and shifts towards passenger rail, and payload transported in heavy-duty trucks shifts to freight rail. This is a result of efforts to increase the rail network, promote public transport, reduce overall transport demand and increase efficient movement of people and goods.

2.4.3 Alternative fuels in road transport

Biofuel blending can also play a role in decreasing emissions, particularly in the short term. The biofuel demand in the transport sector reached approximately 700 PJ in 2021, representing a strong increase due to different policy incentives from the 81 PJ demand back in 2002 (IRENA, 2018a). Under the DES, bioethanol blending with gasoline and biodiesel blending with diesel increases in all EU countries until 2030, after which biofuel blending stops increasing as greater efforts are made towards fleet electrification.

The RED III establishes targets for the use of advanced biofuels and biogas, and for RFNBOs. Their share should be at least 1% by 2025 and 5.5% by 2030, of which at least 1% should be from RFNBOs. By 2030, 30% of the biofuels blended with gasoline and diesel should be advanced biofuels, to ensure that the related targets are met.

There is feedstock potential in Europe for the production of second-generation bioethanol, although this potential falls short of covering the biodiesel demand, and it would have to be imported from outside Europe (European Commission, *et al.*, 2024).

Hydrogen has a limited role in road transport under the PES and DES. In terms of efficiency, EVs are better due to lower transformation losses. The network of hydrogen stations would have to be rapidly expanded to encourage the use of hydrogen technology, but electric charging stations are expanding more rapidly due to major policy support (Ajanovic, 2023). Also, continued technological innovation is expected to lead to EV prices consistently falling in the coming years (Goldman Sachs, 2024). Battery electric trucks are also expected to be the most cost-effective decarbonisation pathway in Europe (Basma and Rodríguez, 2023). Buses and heavy-duty trucks reach shares of the transport stock of 15% and 20%, respectively, by 2050 in the PES and DES.

2.5 RAIL TRANSPORT

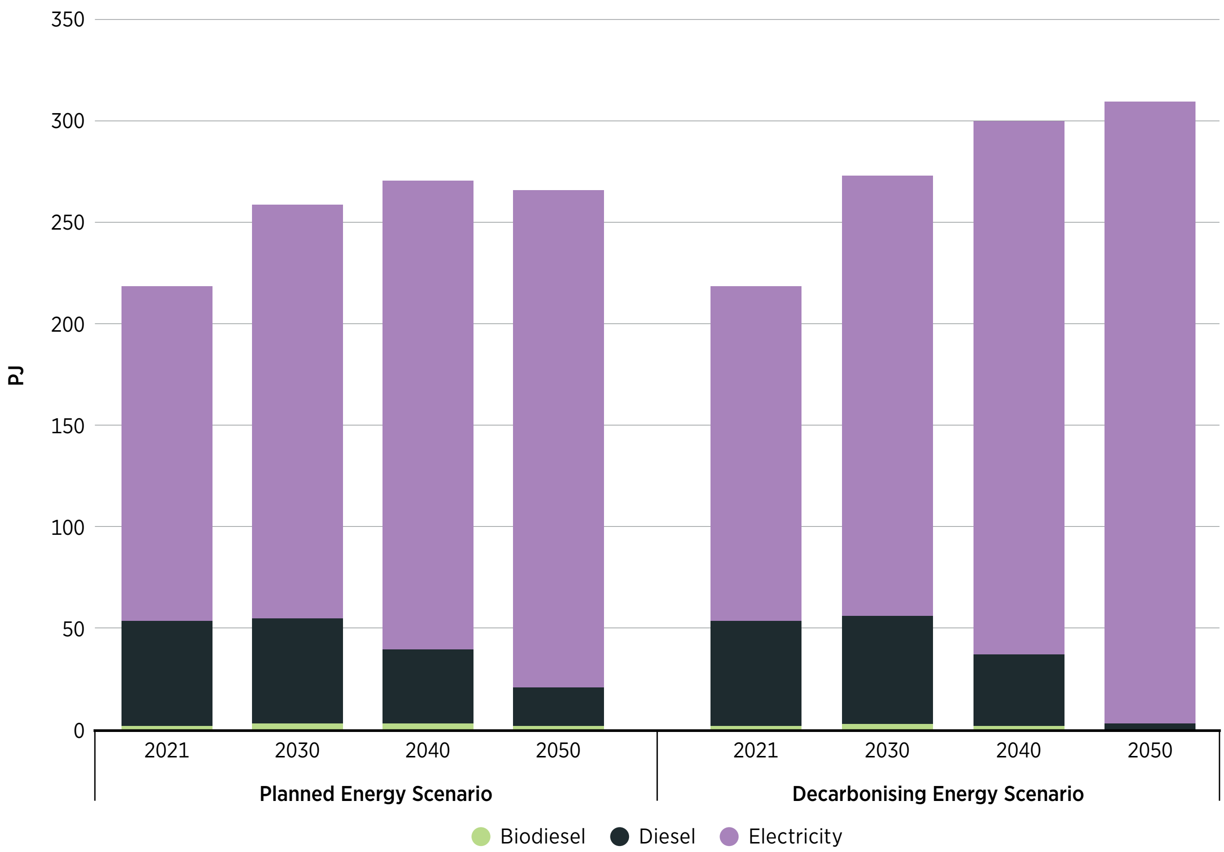
Rail transport in Europe is being incentivised to become more convenient and sustainable to increase its use for passengers and freight. A proposal for a regulation on the use of railway infrastructure capacity in the single European railway area (European Commission, 2023g) focuses on optimising the use of railway tracks, improving cross-border co-ordination, increasing punctuality and reliability, and ultimately attracting more freight companies to rail. A proposal on combining transport modes for more sustainable freight transport (European Commission, 2023k) focuses on making freight transport more sustainable by making inter-modal freight more competitive. These are examples of initiatives that seek to contribute towards the objective of increased rail transport activity.

Passenger rail transport activity is expected to increase, reaching 740 billion and 900 billion pkm in the PES and DES, respectively, by 2050. Freight rail transport activity is also expected to increase, reaching 725 billion and 860 billion tkm in the PES and DES, respectively, by 2050. Activity in the DES by 2050 is higher due to the modal shift from cars and heavy-duty trucks. The increase in passenger rail activity under the DES could be facilitated by the approval of proposals on easing multi-modal digital mobility services for more accessible and convenient rail travel across Europe (European Parliament, 2024).

Electrification is also expected to be the main decarbonisation pathway in rail transport, as depicted in Figure 2.6. Diesel share decreases from 24% in 2021 to 7% and 1% by 2050 in the PES and DES, respectively. Additionally, energy efficiency gains are considered and lead to lower energy needs.

From IRENA's current perspective, electrification will be the main decarbonisation pathway for the rail sector, and hydrogen is not expected to play a role in this transport mode.

Figure 2.6 Rail final energy consumption by carrier



Note: PJ = petajoule.

2.6 DOMESTIC AVIATION

Europe's aviation sector is expected to undergo a complete transformation to become more sustainable, as the targets set out in the ReFuelEU Aviation Regulation began to apply in 2024 (European Commission, 2023q). The Regulation defines minimum shares of sustainable aviation fuels (SAFs) to be used in aviation energy consumption supplied at Union airports, with these shares increasing incrementally every five years from 2025 to 2050. It also sets minimum shares for synthetic aviation fuels, starting from 2030 and rising every five years until 2050. From 2050, a minimum of 70% of aviation fuel must be SAFs, of which at least 35% must be synthetic aviation fuels.

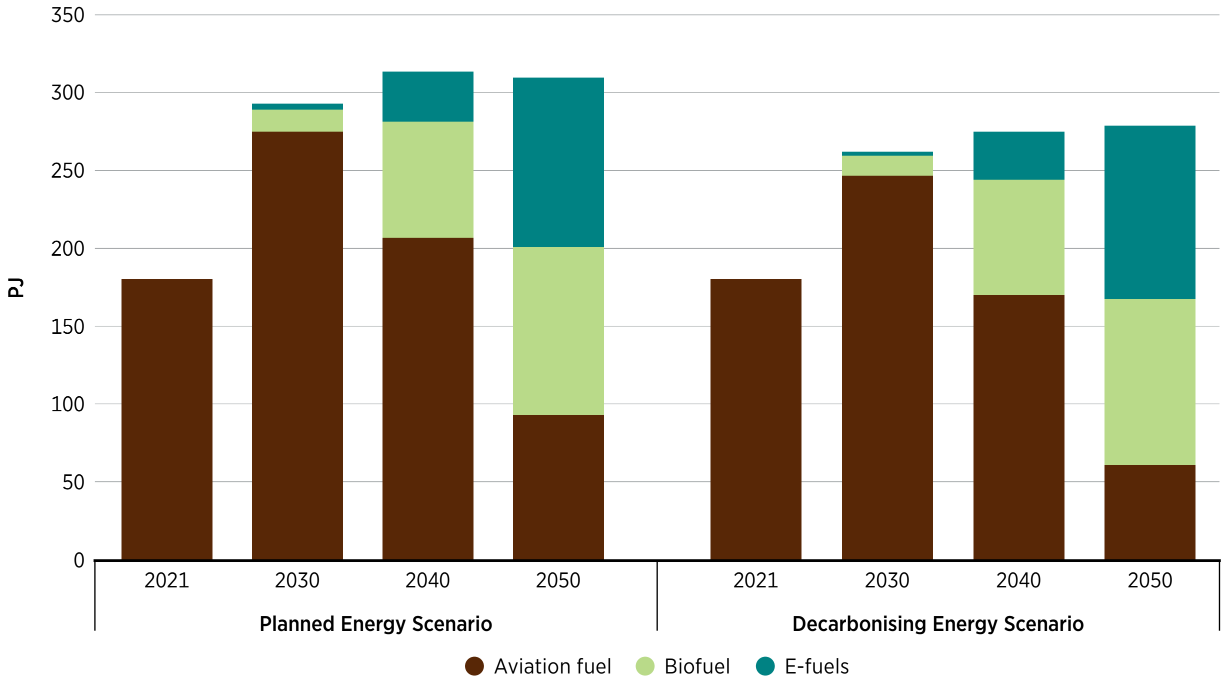
Domestic aviation activity is expected to increase slightly during the study period, reaching approximately 140 billion pkm by 2050 in the PES. In the DES, a modal shift from aviation to railways is considered, and activity by 2050 is 10% lower than in the PES.

Domestic aviation consumption is presented in Figure 2.7. A considerable increase from 2021 to 2030 can be observed, due to the particularly lower demand in the base year due to COVID-19 restrictions. In 2022, domestic aviation final energy consumption reached 250 PJ, increasing towards the pre-COVID levels of 280 PJ in 2019. From 2030, the final energy consumption increases approximately 6% by 2050 in both PES and DES. A 1% annual energy efficiency improvement in specific fuel consumption in both scenarios is considered, which contributes to the slight increase in energy consumption despite the increase in activity.

The SAF shares defined in the ReFuelEU Aviation Regulation are applied in the PES. Bio-jet and e-fuel shares in the SAFs reach 35% by 2050 under the PES. In the DES, the bio-jet share increases to 40% by 2050. There is potential within the European Union to cover the bio-jet demand from domestic flights (European Commission, *et al.*, 2024).

The present analysis focuses on the use of bio-jet and e-fuels in decarbonising the aviation sector. It does not consider the use of hydrogen or electric aircraft.

Figure 2.7 Domestic aviation final energy consumption by carrier



Note: PJ = petajoule.

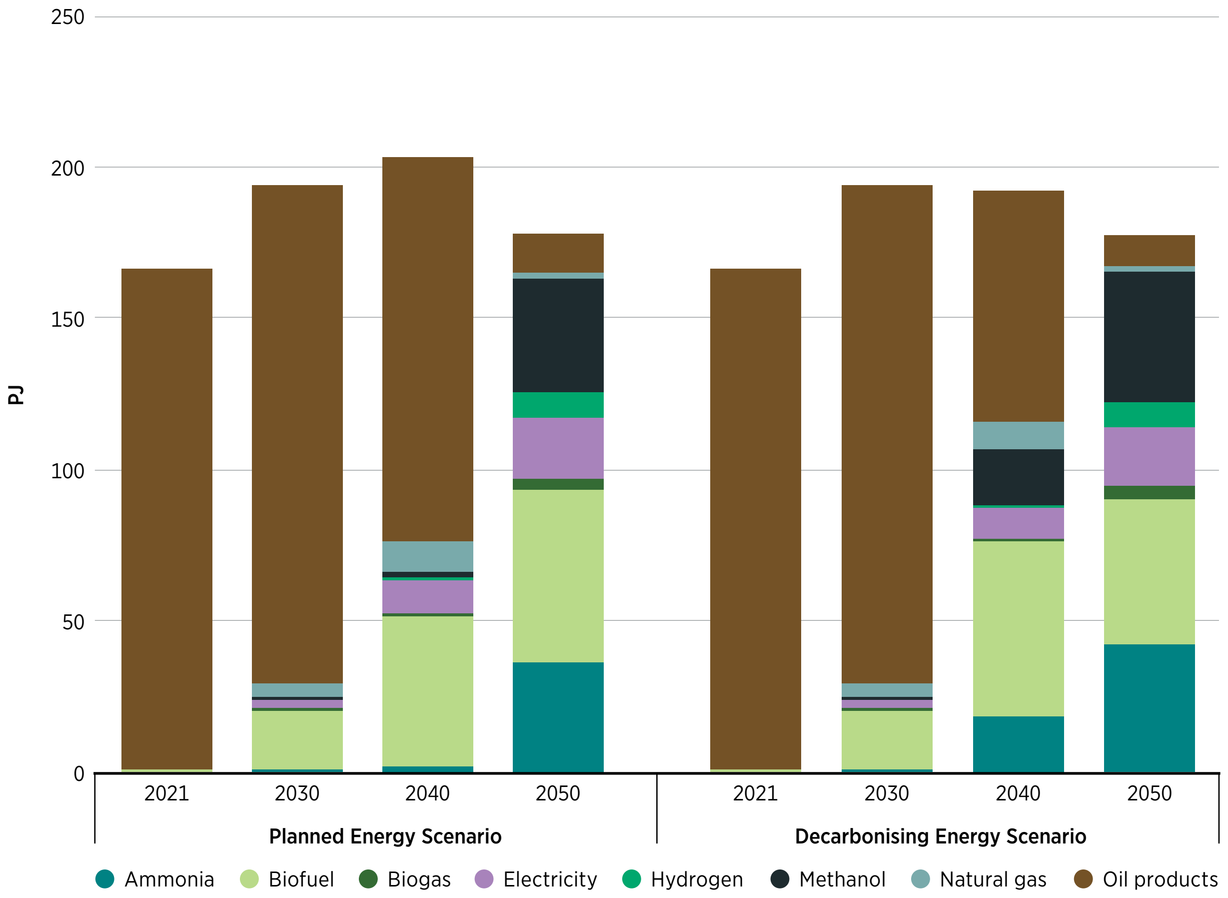
2.7 DOMESTIC SHIPPING

Ambitious targets for the decarbonisation of maritime transport in Europe have already been set in the ReFuel Maritime Regulation (European Commission, 2023d). Emissions limits, set as CO_2 equivalent per megajoule with respect to a reference value, are defined from 2025 until 2050. The Regulation also requires the main European ports to use onshore power supply from 2030.

Figure 2.8 depicts the final energy consumption by carrier for domestic shipping. The final energy consumption increases towards 2040 from 2021, and from 2040, it starts decreasing towards 2050 due to efficiency gains from considering more efficient technologies, such as electric boats for short distances (European Commission, 2024i).

The final energy consumption in 2021 was dominated by fossil fuels. By 2050, fossil fuels are expected to represent a share of 8% and 7% in the PES and DES, respectively. The fuel mix is envisaged to be dominated by e-fuels, including methanol and ammonia, and biofuels.

Figure 2.8 Domestic shipping final energy consumption by carrier

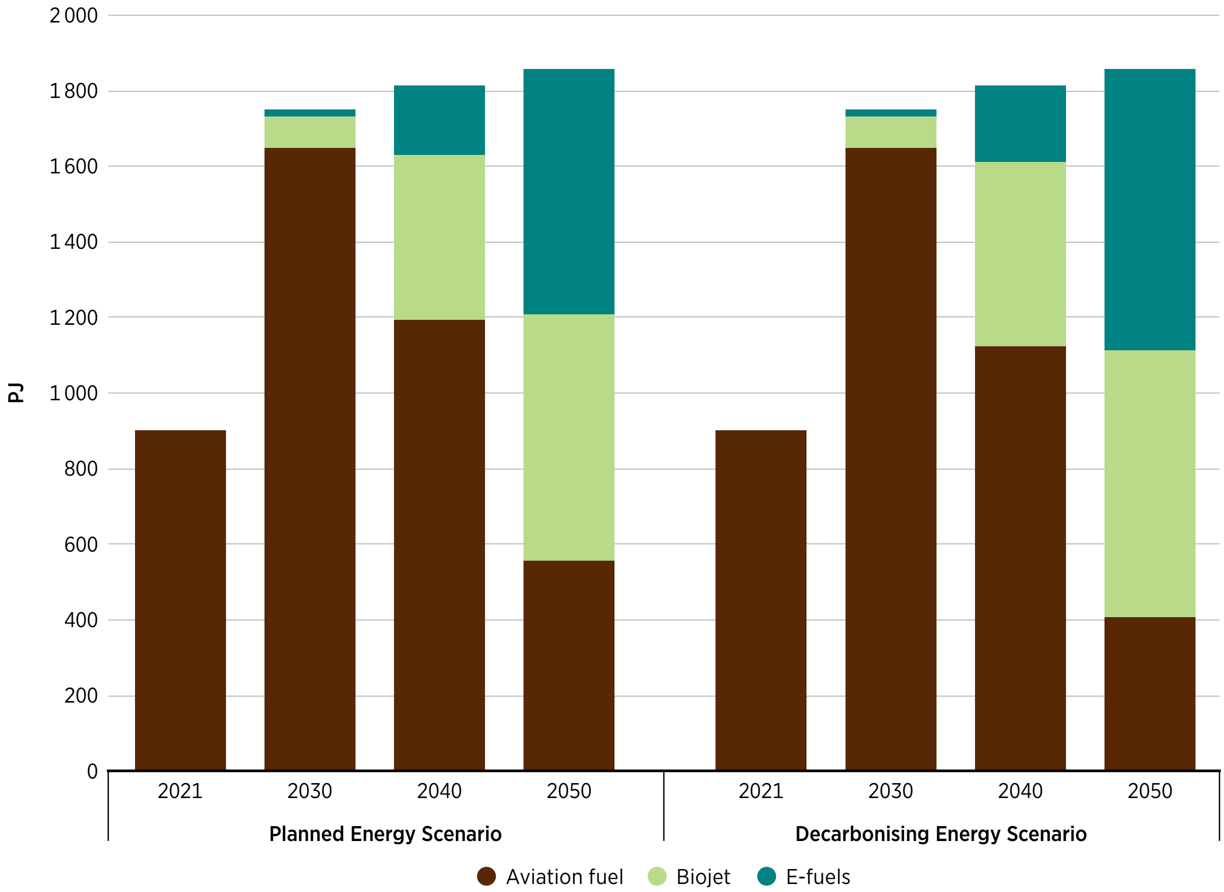


Note: PJ = petajoule.

2.8 INTERNATIONAL AVIATION AND SHIPPING

The above-mentioned ReFuelEU Aviation targets also apply for all international flights, intra- and extra-EU, and were considered in the PES and DES as illustrated in Figure 2.9. The high SAF targets in energy demand aim to support the decarbonisation of the aviation sector and contribute to achieving the Long-Term Aspirational Goal (LTAG) of reaching net-zero CO_2 emissions in international aviation by 2050 set by the International Civil Aviation Organisation (ICAO *et al.*, 2023). More stringent targets in Europe might incentivise aircraft operators to avoid transit via EU airport hubs, which could lead to competition distortions. Mechanisms to avoid this situation might need to be established if needed. The EU SAF targets were designed in a way to accelerate the transition to SAF, while at the same time, limiting as much as possible any effects of carbon leakage or competitive disadvantage for airlines flying to and from the EU. The European Commission is currently conducting a study to analyse such possible effects. The ICAO Global Framework for SAF, Lower Carbon Aviation Fuels (LCAF) and cleaner energies for aviation should also contribute to a global level playing field.

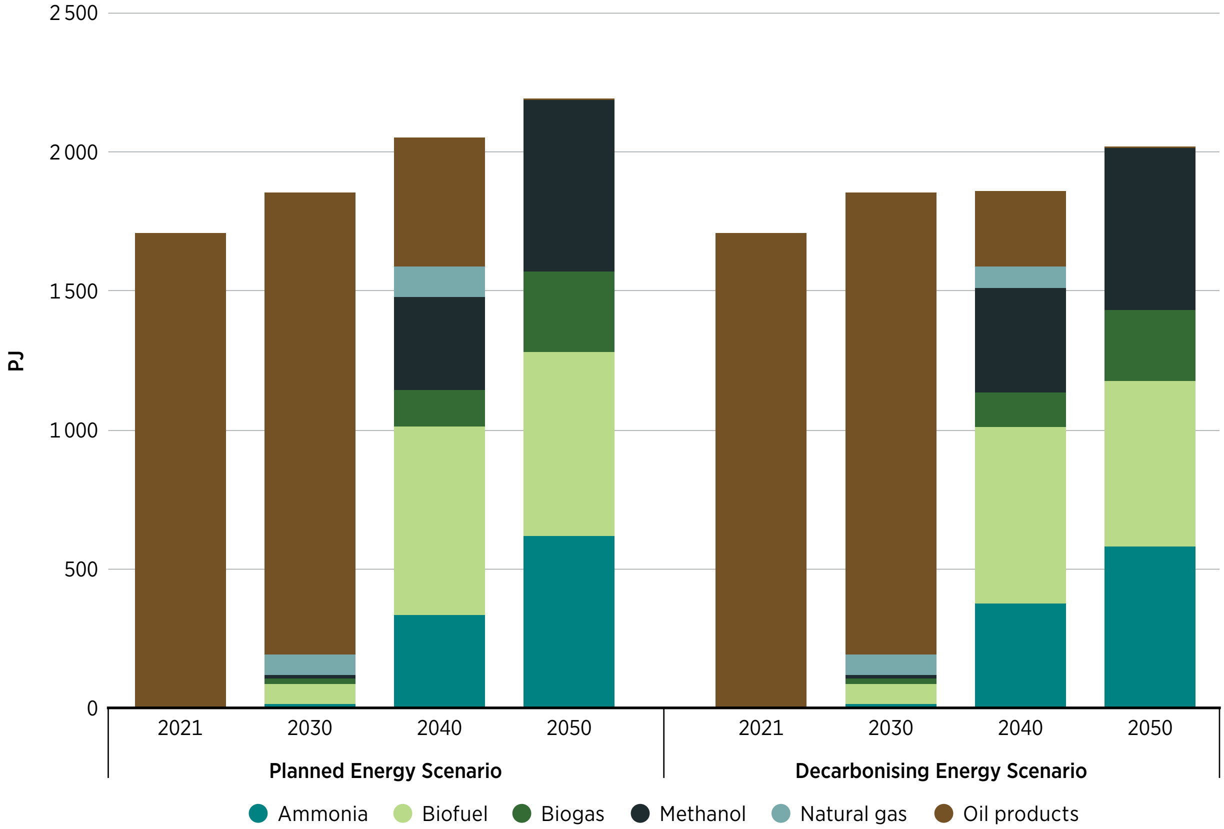
Figure 2.9 International aviation energy consumption by carrier



Note: PJ = petajoule.

The ReFuelEU Maritime regulation applies to shifts above 5 000 gross tonnage that travel to and from EU ports and to 50% of the energy used on voyages arriving at or departing from a port under EU jurisdiction to a port outside the bloc. Figure 2.10 presents international shipping energy demand, which is defined based on the projected energy demand from the 2040 climate target communication impact assessment report (European Commission, 2024i).

Figure 2.10 International shipping energy consumption by carrier



Note: PJ = petajoule.

Bio-jet and biofuels needed for international aviation and shipping will have to be imported from non-EU countries since the European Union has limited available potential for their local production (European Commission, *et al.*, 2024).

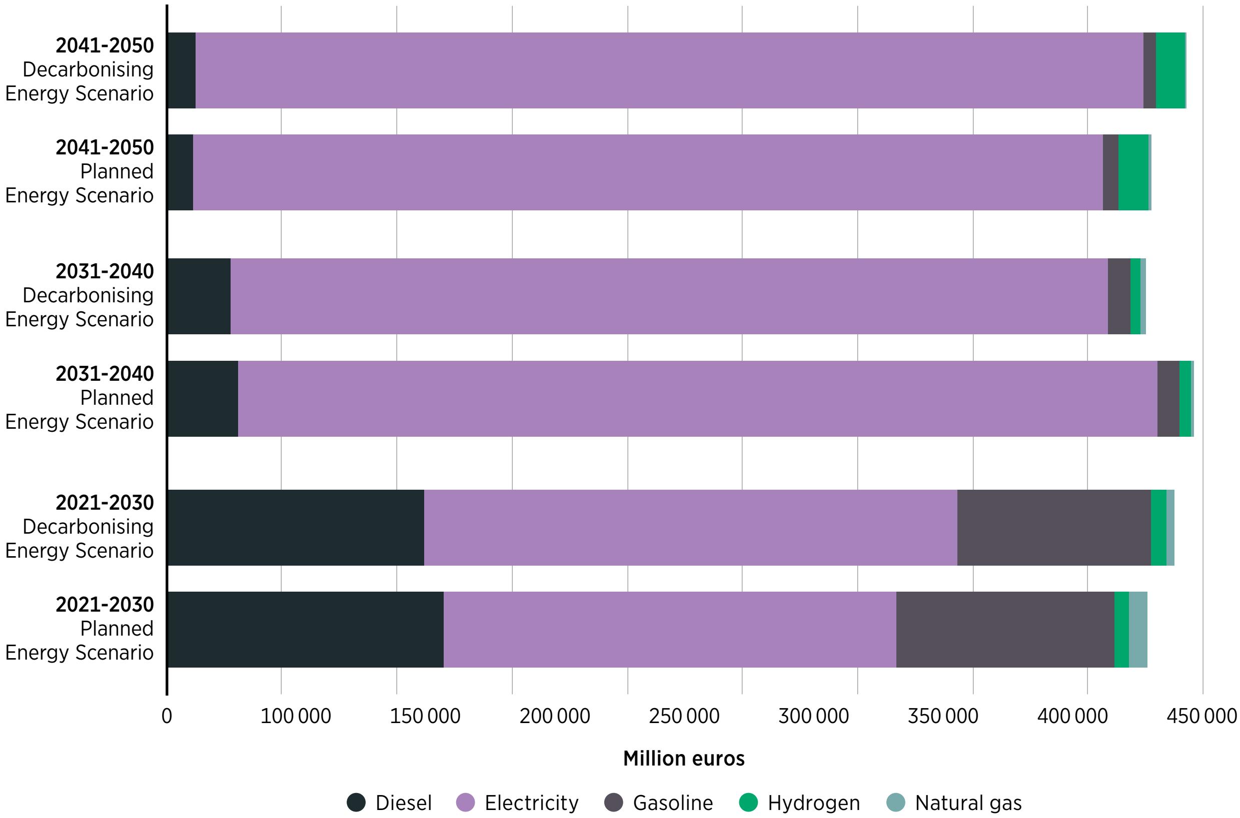
2.9 INVESTMENT IN TRANSPORT

Decarbonising transport involves costs for end users as well as associated investments.

The cost for end users consists of the amount spent on the vehicles. Figure 2.11 shows the average annual costs of vehicles by carrier across three time periods. For the period 2021-2030, the costs of EVs are higher in the DES than in the PES. This is because of the higher efforts considered in the DES in the short term to adopt EVs and further reduce emissions to ensure they are within the limits set by the current regulation. For 2030-2040, investment under the PES is slightly higher than in the DES, where the lower investment is compensated for by more robust efforts in the previous decade. In the last period, 2040-2050, consumers are expected to bear similar costs in both scenarios.

Despite considerably wider adoption of EV technologies, the average annual spending in 2030-2040 and 2040-2050 does not increase relative to spending in the first decade. This is due to the EV price reductions that are expected in the coming years. In the short term, financial incentives could be provided to boost EV sales (*e.g.* government subsidies, low-interest loans from private banks or other economic benefits such as reduced annual registration and circulation fees, or reduced parking prices in city centres). Additionally, strategic public and private support to the automotive industry to transition to EV production and to stimulate innovation and manufacturing capacity could be beneficial for all since it would contribute to greening the EU industry, retaining jobs and reducing reliance on technology imports from outside the European Union.

Figure 2.11 Average annual end-user costs for vehicles by carrier

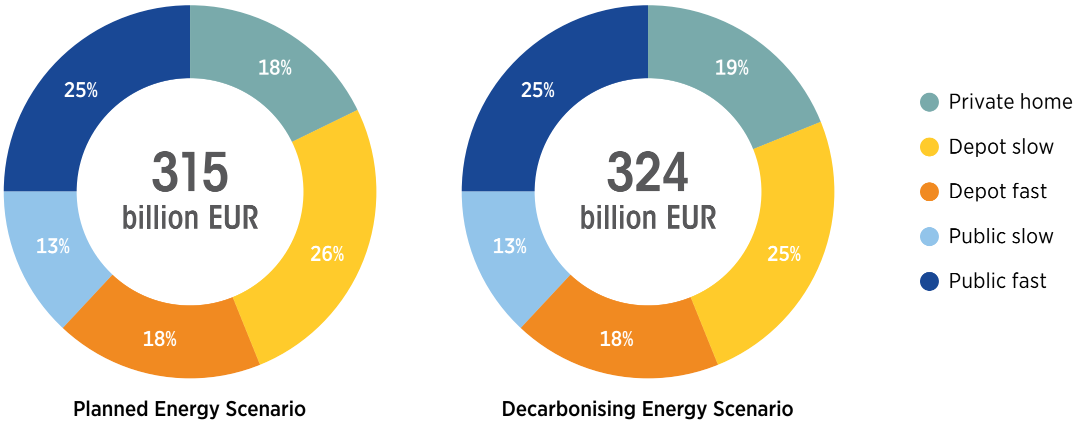


Additionally, investment in EV charging infrastructure will be required for the rapid roll-out of EVs on roads. Cumulative investment in 2021-2050 is expected to be around EUR 315 billion in the PES and around EUR 324 billion in the DES. An average annual investment of around EUR 11 billion is expected for the installation of private and public chargers, equivalent to 0.06% of Europe's GDP in 2023. Robust fleet electrification is assumed in both scenarios and, therefore, similar EV charging needs will have to be met. Cost reductions in electric vehicles and charging infrastructure are expected to be reached in the coming years in both scenarios through economies of scale and technological advancements.

Figure 2.12 presents investment by charger type. Private chargers, including home and depot chargers, represent approximately 60% of the investment during the study period, and public chargers the remaining 40%.

The European Commission has established the Connecting Europe Facility (CEF) Transport programme for the development of high-performing, sustainable and inter-connected Trans-European transport networks (European Commission, 2024j). Under the first phase of its Alternative Fuels Infrastructure Facility, which ran between 2021 and 2024, over EUR 1.3 billion were made available for proposals covering the roll-out of alternative fuel infrastructure. The second phase, running between 2024 and 2025, will make EUR 1 billion available to support megawatt recharging stations for heavy-duty vehicles, electricity and hydrogen supply at airports, and electricity supply and ammonia and methanol bunkering facilities at ports. The Innovation Fund could also be a source of support for the manufacturing, production and the use of net zero and innovative technologies in the transport sector. These initiatives could foster the development of charging infrastructure to meet the targets set in the current regulatory framework.

Figure 2.12 Cumulative investment in electric vehicle charging points, 2021-2050



The investment costs associated with the supply of alternative fuels in the transport sector, such as biodiesel, bioethanol, bio-jet, hydrogen and other RFNBOs, are considered on the energy supply side.

Table 2.4 Key actions and priorities in transport

OUTCOMES	CURRENT REGULATIONS, DIRECTIVES OR PROPOSALS	ADDITIONAL MEASURES AND ACTIONS SUGGESTED
Fleet electrification, reaching shares in stock of 95% and 100% for cars and motorcycles by 2050 in the Planned Energy Scenario (PES) and Decarbonising Energy Scenario (DES), respectively, and of 75% and 85% for buses and 70% and 80% for heavy-duty vehicles in the PES and DES respectively.	Regulation (EU) 2023/851 and Regulation (EU) 2024/1610 on strengthening the grammes of carbon dioxide per kilometre (gCO_2/km) emissions standards for new cars, vans, buses and heavy-duty vehicles. Alternative Fuels Infrastructure Regulation (AFIR). Industrial Action Plan for the European automotive sector. Clean Industrial Deal.	• Providing financial incentives for the purchase of electric vehicles (EVs) in the short term until they reach price parity with internal combustion engine vehicles. Such incentives could include government subsidies, innovative leasing options, low-interest loans, reduced annual registration and circulation fees, or reduced parking prices
		• Providing financial incentives for the installation of an EV charging network as well as defining streamlined regulatory frameworks and permitting processes to accelerate its adoption
		• Standardising batteries and charging processes
		• Defining zero- or low-emission zones in cities
		• Installing fast chargers on highways
		• Fostering industrial partnerships and collaborations within the EU for the development and scale up of transport decarbonisation technologies
		• Designing a transition strategy for workers currently employed in the traditional automotive industry that might require training and upskilling opportunities and therefore ensuring a just transition

Energy efficiency annual improvements in specific fuel consumption for internal combustion engine and EVs, railways, aviation and shipping	Renewable Energy Directive III	• Improving driving techniques in road transport vehicles to optimise vehicle performance, thereby reducing overall energy consumption and indirectly supporting higher renewable energy shares by lowering the total energy demand.
Occupancy increase in cars and payload increase in trucks in the DES	Renewable Energy Directive III	• Promoting car-sharing schemes and efficiency programmes for freight transportation • Setting parking restrictions and car-free streets in cities
A modal shift from cars to passenger rail and from heavy-duty trucks to freight rail will increase activity (passenger-kilometres and tonne kilometres) by 20% by 2050 in the DES compared to the PES. By 2050, 10% of aviation passenger activity will also shift to railways in the DES compared to the PES by 2050.	The Economic Commission's proposals on combining transport modes for more sustainable freight and on making freight transport more efficient and sustainable by improving rail infrastructure management	• Increasing rail transport services to accommodate the new demand • Expanding the rail network if needed • Introduction of incentives (*e.g.* subsidies or increased parking prices in cities) for passengers to further use railways • Promoting inter-modal mobility to facilitate transit using a combination of transport modes
Biofuel blending increases as identified in National Energy and Climate Plans in the PES and by 30% by 2030 in the DES, if biodiesel and bioethanol blends are lower than 10% and 6%, respectively.	Renewable Energy Directive III	• Promoting biofuel production if local potential is available • Enhancing partnerships with biofuels exporting countries
Introduction of hydrogen-based buses and heavy-duty vehicles, which compose 15% and 20% of the vehicle stock, respectively, in both scenarios.	Regulation (EU) 2024/1610 on strengthening the gCO_2/km emission standards for new buses and heavy-duty vehicles	• Providing financial incentives for the acquisition of hydrogen-based heavy-duty vehicles for niche applications
Electrification of the rail network.	The Economic Commission's proposal on making freight transport more efficient and sustainable by improving rail infrastructure management	• Making funding available for the electrification and modernisation of the rail network
Sustainable aviation fuel (SAF) blending shares will reach 70% by 2050 in the PES and 78% in the DES.	Regulation (EU) 2023/2405 or REFuelEU Aviation on defining SAF targets in the aviation final energy consumption	• Developing an analysis of local feedstock potential and studies of the feasibility of local production, and, if needed, import strategies to ensure security of supply
Alternative fuels achieve shares of 92% and 93% in final energy consumption by 2050 under the PES and DES, respectively.	Regulation (EU) 2023/1805 or FuelEU Maritime on defining GHG intensity limits on the energy used on board	

Notes: PES = Planned Energy Scenario; DES = Decarbonising Energy Scenario; EU = European Union; gCO_2 = grams of carbon dioxide; ICE = internal combustion engines; EV = electric vehicle; pkm = passenger-kilometre; tkm = tonne kilometre; EC = European Commission; NECP = National Energy and Climate Plans; SAF = sustainable aviation fuels; FEC = final energy consumption; GHG = greenhouse gas.

3

INDUSTRY

This chapter presents the main outcomes, findings and messages of the industry sector analysis for EU27. Some of the key questions this section will cover are:

1. What is the status of the ongoing decarbonisation of industry in the region?
2. Are the existing directives, plans and measures sufficient to deliver net-zero by 2050?
3. What are the points of attention for policy makers?

KEY FINDINGS

- ★ **Industrial emissions decline by more than half – from about 537 $MtCO_2$ at baseline year 2021– by 2030 in both scenarios. Emissions continue to be highest from cement, chemicals, and iron and steel, constituting 64% of overall industrial emissions, despite significant reductions across the decade.** Overall industrial emissions can reduce significantly, to about 9.8 $MtCO_2$ in the Planned Energy Scenario (PES) by 2050. In the Decarbonising Energy Scenario cement, and iron and steel reach negative emissions by 2050, as the European Union (EU) deploys all the decarbonisation options available.

- ★ **Energy efficiency and a shift in carrier drive a decline in EU industrial energy consumption from 12.4 EJ in 2021 to 7.7 EJ and 6.6 EJ by 2050 in the PES and DES, respectively.** Energy intensity declines by -57% and -63% in the PES and DES, reaching 425 GJ/million EUR and 364 GJ /million EUR, respectively.

- ★ The share of direct renewable energy use grows from 9% at baseline to 22% in both scenarios by 2050. Direct renewable energy consumption ranges from 1.7 EJ in the PES to 1.4 EJ in the DES. **When accounting for indirect use of renewable electricity, renewable energy accounts for 65%-75% of the sector's energy consumption.**

- ★ **Electricity consumption in industry in the PES grows from 956 TWh at baseline to 1 082 TWh by 2050, while energy efficiency and efficient material consumption keep electricity consumption rather flat at 973 TWh, in the DES.** Nevertheless, electricity's overall share of energy consumption grows from 31% at baseline to 59% and 61%, respectively in the PES and DES by 2050.

- ★ **Industrial green hydrogen consumption increases by a factor of 1.9 and 2.0 between 2030 and 2050 under the PES and DES, reaching 2.2 Mt and 1.7 Mt, respectively.** This rate is below what is expected in EU plans in all the scenario years, due to the foreseen high recycling rates of steel, imports of green iron and green direct reduced iron (DRI), and a reduction in chemical and fertiliser production.

- ★ **EU industrial emissions can be reduced significantly through all available decarbonisation avenues.** To achieve this, the sector must capture as much as -114 $MtCO_2$ and -99 $MtCO_2$ from industrial energy and processes by 2050 in the PES and DES, respectively.

- ★ **The investment requirements for industrial decarbonisation will reach EUR 14 billion and EUR 12 billion annually in the PES and DES, respectively, across all industry subsectors.** The overall investment required in industry equipment reaches up to EUR 343 billion by 2050. This is about half of the total EU27 national recovery and resilience plan funds under the NextGeneration EU invested by the Recovery and Resilience Facility for green measures, including investment supporting industrial decarbonisation.

KEY MESSAGES

- ★ **Subsector-specific decarbonisation roadmaps, particularly for high-intensity industrial processes, could help track progress in achieving the Net-Zero Industry Act' goals via targets and milestones.** Policy makers should consult with the private sector to ensure the continued competitiveness of industries during decarbonisation. **They would also do well to set up a carbon pricing system that is dynamic and adaptable to emerging technologies.**
- ★ **Public-private partnerships can encourage the research and development of clean and green technologies.** Financial incentives for first movers would encourage investment in green technologies.
- ★ **EU industrial policies and plans, such as the Net-Zero Industry Act as well as the Green Deal Industrial Plan, are key to ensuring regional-level competitiveness and energy security.** Establishing a central body to co-ordinate and monitor the implementation of all decarbonisation plans across Member States, and emphasise the importance of EU industry to speak as one voice in international trade and, to help accelerate the pace.
- ★ **The European Union needs to explore all possible avenues to accelerate its decarbonisation, including reducing emissions via imports in the short term, while building an ecosystem for transformative net-zero and decarbonisation technologies.** The PES outlines the path forward. The additional measures discussed in the DES to boost circular economy and material use may help the European Union achieve further success since they reduce industrial energy demand while still ensuring EU industry remains competitive in the global market. Decarbonisation in industry sector will also play important role establishing one of the pillars in the EU Clean Industrial Deal, creating renewables and other transition-related sector of around 2.7 million jobs by 2030.
- ★ **The definition of a specific set of indicators that all countries need to report on, for instance in the NECPs, would facilitate the monitoring of the industry evolution on their way to meeting the decarbonisation targets defined in the current regulatory framework**. The definition of these specific targets could also facilitate countries understanding the feasibility of meeting them and establishing specific mechanisms if needed so that they can be met.

3.1 INDUSTRY'S ROLE IN MEETING EU EMISSIONS REDUCTION TARGETS

Industry remains of fundamental importance to the EU economy, as well as to efforts to achieve carbon neutrality by mid-century. Industry represented one-third (32%) of the region's energy end-use energy consumption and was responsible for 30% of end-use emissions in 2021. IRENA analysed the decarbonisation pathways for iron and steel, cement, chemicals, pulp and paper, and aluminium, in light of the EU targets of a 55% emissions reduction by 2030 (relative to the 1990s) and net-zero emissions by mid-century. These five industry subsectors are characterised by high energy and carbon intensity. Iron and steel, chemicals and cement in particular represented more than half of the sector's energy consumption at baseline in 2021.

EU industry still relies heavily on fossil fuels, which meet more than half of the sector's energy demand. The sector released more than 500 million tonnes of CO_2 emissions in 2021.

The Energy Efficiency Directive, which was revised in 2023, has significantly raised ambition on energy efficiency over the 2018 version, given that it states that all Member States must consider energy efficiency in all relevant policy and major investment decisions in the energy and non-energy sectors. The European Union also adopted a new circular economy action plan in March 2020, announcing initiatives to promote circular economy processes and sustainable consumption to prevent waste and ensure resources are kept within the EU economy for as long as possible.

Through the Green Deal Industrial Plan, the European Union would like to ensure sustained industrial competitiveness while transitioning towards climate neutrality. The region's commitment to boosting competitiveness has been specified as part of the Green Deal and Digital Transformation. The European Union is investing heavily in research and development (R&D) for decarbonisation technologies such as hydrogen production, carbon capture and storage (CCS) and low-carbon manufacturing processes through multiple funding programmes, of which, one is the Innovation Fund. Efforts to create a supportive environment for the manufacturing of low-carbon technology and products aim to boost industrial productivity, create new high-tech jobs and maintain industrial competitiveness globally. The European Union has also established the EU Emission Trading System and Carbon Border Adjustment Mechanism, both of which will be crucial for the industry sector in reducing emissions and preventing carbon leakage by ensuring a level playing field.

The European Union has also been increasing efforts to enhance the use of renewable resources and reduce its reliance on fossil fuels, especially from non-EU countries. This effort seeks to ensure the energy system is resilient against external shocks such as supply disruptions or geopolitical conflicts.

Industry is integral to the region's broader energy security targets, especially since the region seeks to reduce its reliance on external energy supply while transitioning to a more sustainable, low-carbon economy. The European Union is focusing on diversifying energy sources, transitioning to renewable energy and implementing energy efficiency measures. These initiatives support industries in reducing emissions by adopting low-carbon technologies, optimising processes and incorporating renewable energy.

The EU energy efficiency directive requires using all available non-fossil means and technologies to generate the cumulative end-use energy savings required, including the use of smart technologies and processes. Further, the Renewable Energy Directive (RED III) document directed the use of electrification for low-temperature industrial heat, as well as renewable fuels of non-biological origin for both energy purposes and non-energy purposes as feedstock to reduce emissions in hard-to-decarbonise industrial processes, which are difficult to electrify (*e.g.* steel and chemicals). Iron and steel, cement and chemicals are among the subsectors prioritising energy and process emissions reductions to contribute to energy security and maintain competitiveness.

Yet despite all efforts, the European Commission recognises that achieving its targets requires developing a new industrial strategy (Box 3.1). Better co-ordination, more investment, more innovation and a bolder use of the single market and economic and trade policies are some of the points that the President of the Commission asked Stéphane Séjourné, Executive Vice-President-Designate for Prosperity and Industrial Strategy, to work on in his Mission Letter (European Commission, 2024h).

IRENA's PES was developed in accordance with policies and regulations enacted in the European Union for decarbonising the sector. The REmap approach assesses these regulations' impact on individual subsectors with a focus on energy consumption and emission reduction targets. The EU industry sector will need to promote all available decarbonisation options to date – from implementing the best available technology to an immediate transition to alternative carriers towards bioenergy, renewable energy system integration, waste heat and even hydrogen. The challenge is to ensure the investment in the transition can guarantee the competitiveness of the industry in the global market.

Table 3.1 Overview of the PES and DES, as used to analyse the industry sector

Planned Energy Scenario	Decarbonising Energy Scenario
Legally binding industry emission target for industry sector that is also included in Impact Assessment Report by 2030.	Complies with legally binding targets set in the current regulatory framework and proposes additional measures, such as accelerated hydrogen DRI in steelmaking, ramping up CCS in cement and chemical industries, more recycling in pulp and paper and aluminum.
Incorporating activity-level projection rate following S3 scenario of Impact Assessement Study for each Industry subsector.	Incorporating activity-level projection rate following LIFE scenario of Impact Assessement Study for each industry subsector.
This scenario results in a pathway the industry sector would follow if the legally binding objectives currently defined are met.	This scenario is slightly more ambitious in the short term and advances low-carbon technology options to reach lower industry sector emissions, while incorporating more circular economy and efficient industry product consumption.

Notes: CCS = carbon capture and storage; DRI = direct reduced iron; LIFE = L'Instrument Financier pour l'Environnement.

Analysis of the PES shows that the EU industry sector can reach its climate targets. The required investment is massive to accelerate pace especially within this decade, and robust policy implementation is needed to get the private sector on board. The DES explores additional steps to mandate more efficient resources, material consumption and circular economy. It seeks to reduce the demand for industrial products in the region by improving recycling, extending product lifespans and employing more appropriate circular economy designs. These measures include more the efficient use of metal products (*e.g.* steel and aluminium), especially in terms of extending their lifetime, and scrap recycling. Pulp and paper production efficiency is mainly driven by increased recycling rates, material efficiency and reusable packaging. The cement subsector will benefit from the increased lifetime and improved utilisation rate of buildings, the higher rate for recycled cement in concrete and the use of low-carbon cement alternatives, whereas additional measures, such as the ban on single-use water bottles and the stronger reduction of plastic packaging, are driving more efficient production in the chemicals subsector. Such measures under the DES follow the approach considered in the LIFE[7] scenario, as outlined in the EU Impact Assessment Study. The results indicate potential lower investment requirements to reach EU climate targets compared with the PES. Table 3.2 summarises the regulations considered under the PES and DES based on the Impact Assessment Study.

Table 3.2 Industry regulations and relevant documents s considered in the Planned Energy and Decarbonising Energy Scenarios

REGULATION / PLAN / STRATEGY	REFERENCE
• Regulation (EU) 2024/1735 on strengthening Europe's net-zero technology manufacturing ecosystem	(European Commission, 2024k)
• EU Clean Industrial Deal[1]	(The Greens/EFA, 2025)
• The Green Deal Industrial Plan	(European Commission, 2023l)
• Fit for 55	(European Commission, 2023m)
• Directive (EU) 2023/959; Emission Trading System	(European Commission, 2023i)
• Directive (EU) 2023/2413 as regards the promotion of energy from renewable sources (Renewable Energy Directive, RED III)	(European Commission, 2023e)
• Circular Economy Action Plan	(European Commission, 2020b)
• Energy Efficiency Directive (EU) 2023/1791	(European Commission, 2023a)

[1] Published on 26 February 2025, our qualitative analysis is in line with majority of the plans laid out in the document.

[7] *Scenario in the Impact Assessment Report that analise key societal trends related to more sustainable lifestyles, resulting from changes in the consumer preferences, from circular economy measures related to the use of energy and materials, as well as from changes in mobility and the food system.*

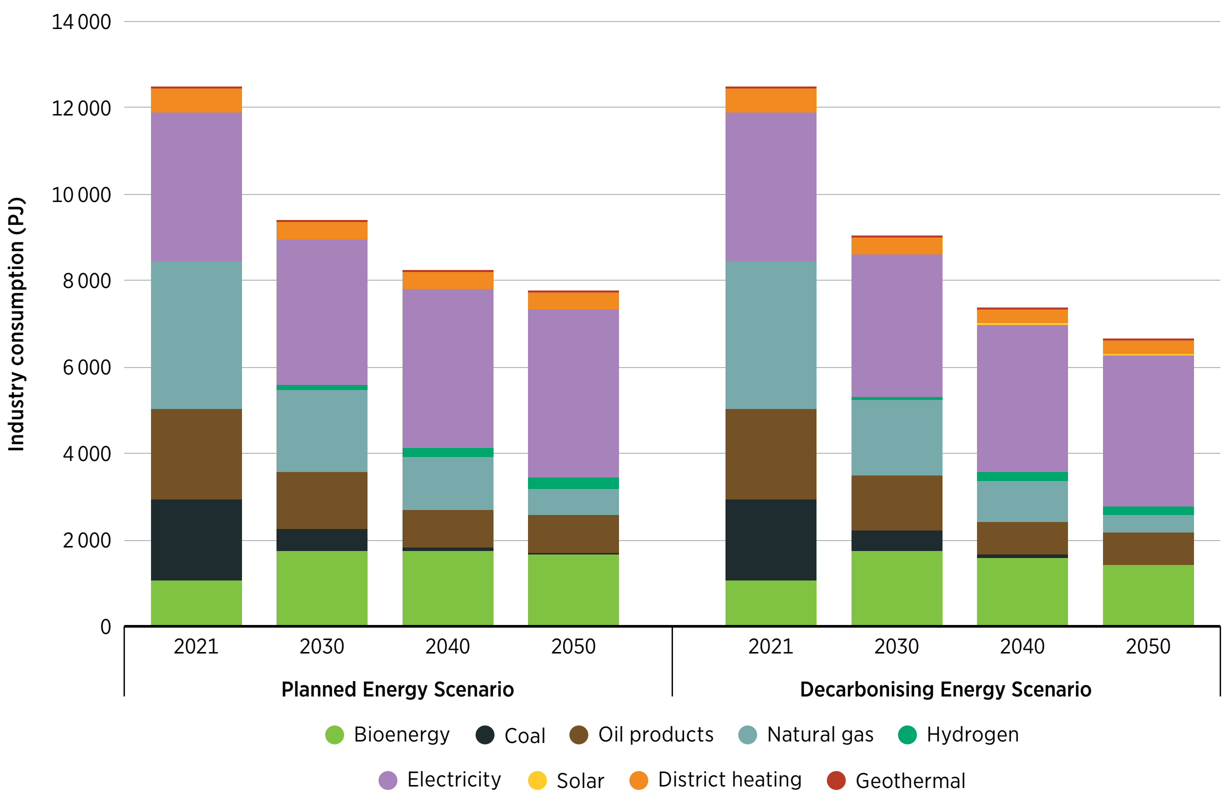
3.2 GENERAL OVERVIEW OF EU INDUSTRY

Fossil fuels continue to dominate EU industrial energy consumption. They constitute nearly one-third of industry's energy demand, most of it in the form of natural gas, despite efforts to increase renewable energy consumption. Bioenergy is, by far, a dominant renewable energy source across the industry of the EU27.

The ambitious EU decarbonisation targets, supported by a transition towards renewables, and increased energy efficiency through the adoption of novel low-carbon industry technologies and alternative fuels, would reduce total industry consumption under the PES at a rate of -1.6% annually; energy demand will be 38% lower in 2050 compared with 12.4 EJ in 2021. Additional decarbonisation measures under the DES, including increased circular economy and more efficient industry material consumption, would allow EU industry demand to reduce by almost half in the same year, due to a reduced demand reduction rate at -2.1% annually.

In the PES, the fossil fuel share declines to 19% by 2050, while in the DES it declines even further, reaching 17%. Renewable electricity dominates industrial energy consumption. It reaches more than 50% – nearly double the 2021 share – under both scenarios by 2050, due to a high electrification rate in low-temperature industrial processes, a larger share of steel production using an electric arc furnace and the transition towards electrochemical processes. By 2050, the electricity demand from industry processes reaches 1 082 TWh and 973 TWh under the PES and DES, respectively. Hydrogen consumption accelerates from 2030 and beyond, reaching about 3% under both scenarios by mid-century. Hydrogen consumption in the sector grows from only about 5 419 tonnes in 2021 to 2.2 Mt and 1.7 Mt under the PES and DES, respectively, by 2050. By 2030, renewables' share, including direct and indirect consumption, under the PES must reach 47%. Renewables' share increases to 58% by 2040 and 65% by 2050, driven by greater use of direct renewables and an increased share of renewables-based electricity.

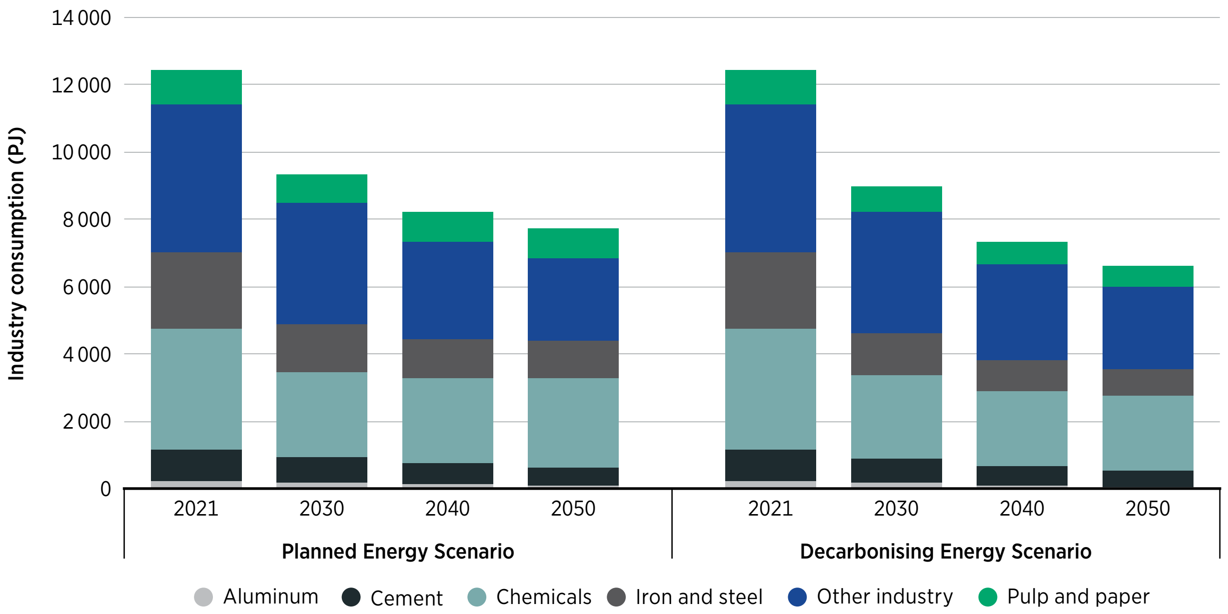
Figure 3.1 Industry final consumption by carrier



Notes: PJ = petajoule. Industry consumption includes energy and non-energy uses.

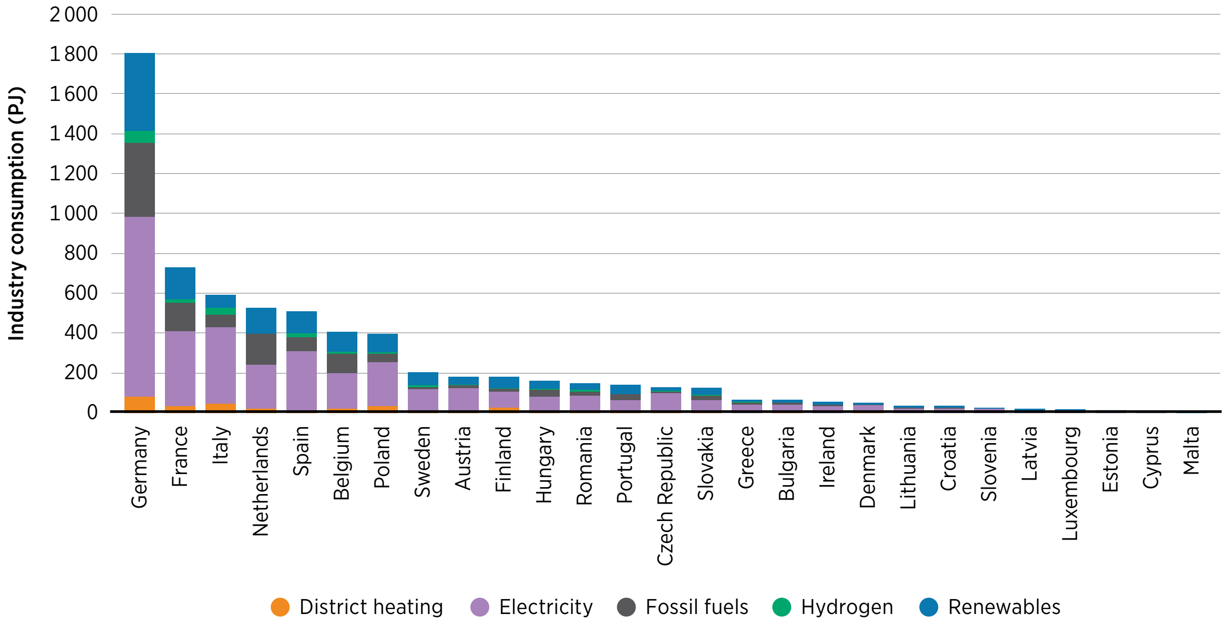
Chemicals, iron and steel, and cement represented more than 54% of EU industrial consumption in 2021, consuming 6.8 EJ. Other industries, including other non-metallic minerals and other non-ferrous metals industries, represented 35% in the same year. While chemicals, iron and steel, and cement together consumed half of industrial energy, emitting 382 $MtCO_2$ in 2021, or more than 71% of all EU emissions. There is potential to rapidly reduce these emissions to reach the short- and long-term EU emission reduction targets (see Figure 3.2).

Figure 3.2 Industry final consumption by subsector



Notes: PJ = petajoule; Industry consumption includes energy and non-energy uses.

Figure 3.3 Industry consumption aggregated under the Decarbonising Energy Scenario, 2050



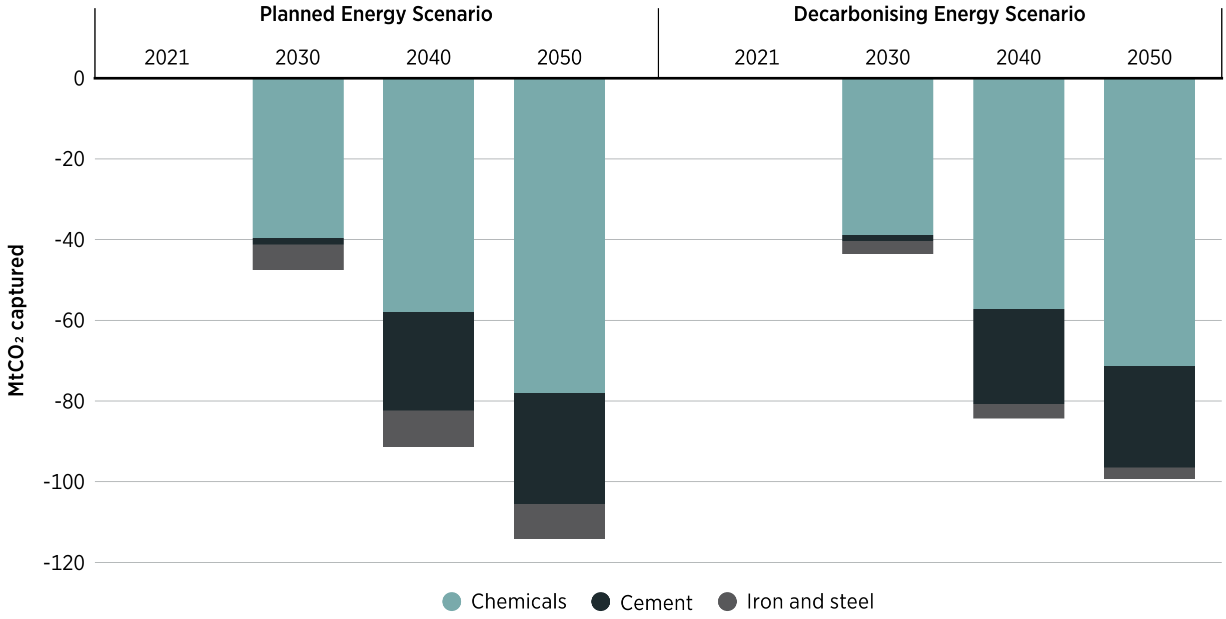
Note: PJ = petajoule.

The five EU countries with the top-consuming industrial sectors – Germany, France, Italy, Spain and the Netherlands – will retain their position in 2050. They will represent 62% of the EU27's total industry energy consumption, as illustrated in Figure 3.3.

Reducing industrial emissions will require radical shifts in how materials are produced, consumed and disposed of. For the European Union to reduce its emissions to at least 55% below those in 1990 – which equals an emission level of 232 Gt by 2030 (European Commission, 2024i) – its industry emissions need to reduce -8.9% every year across 2021-2030. All industry subsectors must expedite efforts to halve their emissions in this decade.

The highly ambitious EU emissions reduction targets can be achieved if industry can immediately transition to low-carbon technologies while implementing rigorous energy efficiency measures in production processes. The circular economy needs to be promoted, and the recycling rate must also be increased to the extent possible. CCS – especially in steel, cement and chemicals – will have to be deployed in the next half-decade and accelerated towards 2050 to further mitigate emissions and reach net-zero emissions by mid-century.

Figure 3.4 Industrial CO_2 emissions captured, by subsector



Notes: Figure shows CO_2 captured from energy and process emissions. $MtCO_2$ = million tonnes of carbon dioxide.

Under the PES, emission reductions of 232 Gt and 76 Gt are achieved in both 2030 and 2040, respectively, showing a very similar trend to the EU Impact Assessment report – emission reductions of 232 Gt and 75.5 Gt in the same year. The implementation of more energy-efficient industrial product use under the DES allows industry to achieve further emission reductions, -4% to -20%, in those same years compared with the PES. Both the PES and DES are projected to allow industry to reduce emissions significantly by 2050, with the demand for CCS more than doubling over 2030-2050. By 2050, industry will capture -114 to -99 Gt of CO_2 under the PES and DES, compared with -137 to -109 Gt of projected CO_2 capture in Impact Assessment S3[8] and under the LIFE scenario for the same year (Figure3.4) (Table 3.3).

[8] *Scenario in Impact Assessment Report to reach a reduction of at least 90% by 2040.*

Table 3.3 Key performance indicators for industry

	HISTORICAL	PLANNED ENERGY SCENARIO			DECARBONISING ENERGY SCENARIO		
	2021	2030	2040	2050	2030	2040	2050
KPI.02 RENEWABLES							
Share of renewables in industry FEC - direct use (%) [1]	10%	18%	20%	20%	18%	20%	20%
Share of renewables in industry FECs - direct and indirect use (%) [2]	20%	47%	58%	65%	43%	67%	81%
KPI.03 ENERGY INTENSITY							
Industry - final consuption (EJ) [3]	12.4	9.4	8.2	7.7	9.0	7.3	6.6
KPI.04 ELECTRIFICATION IN END-USE SECTORS (DIRECT)							
Share of electricity in industry FEC (%)	31%	41%	51%	59%	41%	53%	61%
Electricity consumption in Industry (TWh)	956	930	1 018	1 082	909	946	973
KPI.05 CLEAN HYDROGEN AND DERIVATIVES							
Clean hydrogen consumption in Industry (EJ)	0	0.13	0.23	0.26	0.10	0.19	0.20
Clean hydrogen energy consumption in industry (Mt)	0	1.1	1.9	2.2	0.8	1.6	1.7
KPI.06 CCS, BECCS AND OTHERS							
CCS ($MtCO_2$ captured/year)	0.0	-48	-91	-114	-44	-84	-99
EMISSIONS							
CO_2 emissions with carbon capture and removal ($MtCO_2$/year)	537	233	76	10	223	60	1.5

Notes: CCS = carbon capture and storage; $MtCO_2$ = million tonnes of carbon dioxide; EJ = exajoule; FEC = final energy consumption; GW = gigawatt; KPI = key performance indicator; Mt = million tonnes; All the CO_2 emissions information presented in the KPI table refer to energy and process emissions.

[1] Direct renewable share includes direct use of renewables (bioenergy, solar and geothermal).

[2] Direct and indirect renewable share includes direct use of renewables (bioenergy, solar and geothermal) and of indirect renewables (renewable electricity, hydrogen and district heating).

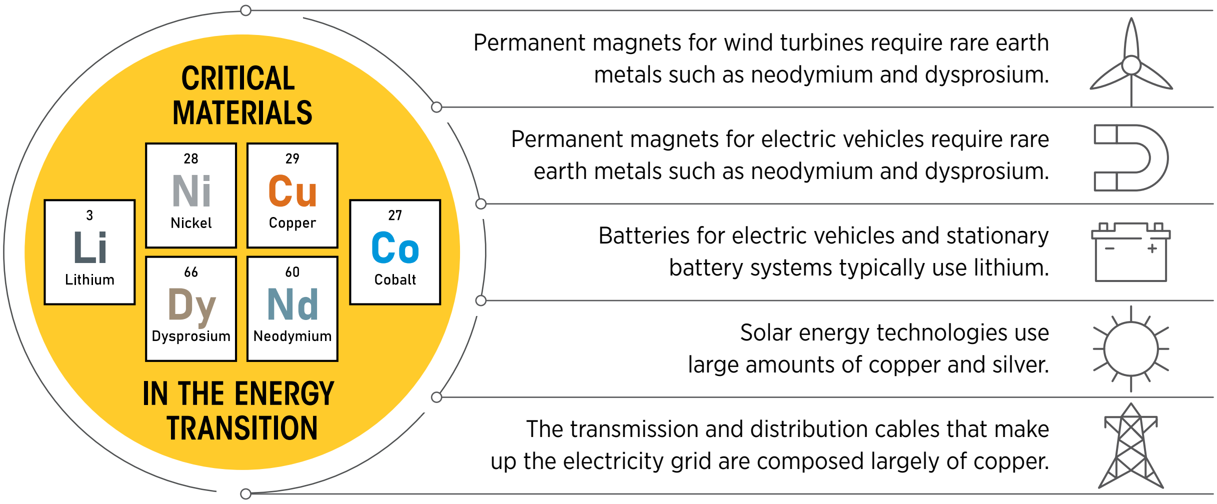
[3] final consumption includes energy and non-energy uses.

3.3 CRITICAL MATERIALS KEY TO THE ENERGY TRANSITION

The European Union is in the midst of a green transformation and has set its energy transition as a key objective of its Green Deal. In 2021, the region committed to reducing GHGs by 55% by 2030, 90% by 2040 and achieving net-zero emissions by 2050 (relative to the baseline year of 1990). These targets are expected to trigger massive increases in the demand for renewable energy technologies for power generation, and electric vehicles in transport.

Supply and critical materials play vital roles in supporting and helping the European Union to realise the energy transition. Under the DES, renewables' share in power generation capacity will reach 87% by 2050, which translates to installed renewables capacity reaching about 2 TW. In the same scenario, 98% of road vehicles will be electric in the very same year. The number of electric vehicles will reach approximately 335 million. This translates into an increased requirement of key technologies, for example, solar panels, wind turbines and batteries, which require critical materials to produce. Figure 3.5 provides an overview of components of the main energy transition technologies driving up critical material demand.

Figure 3.5 Main technologies increasing the demand for critical materials



Growing demand for critical materials locally, regionally and globally has exposed the critical materials supply chain to market disruption. Amid concerns over critical materials supply in the region, the European Union continues to strengthen its policies to address the short- and long-term challenges associated with the related supply chain in the region. Domestic production has been one of the focuses of the European Union, given it has significant reserves of materials like copper, nickel and lithium. International partnerships, including investment in domestic lithium mining and domestic production facilities to help the European Union reduce its reliance on Chinese lithium-ion batteries, are expected to increase economic viability, in turn boosting production within the region. Meanwhile, the EU wind industry's reliance on rare earth element imports poses another challenge to growth since fluctuating prices could hinder expansion.

The European Union acknowledges the importance of critical materials. Led by the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), it has conducted a region-level criticality assessment of a wide range of raw materials. In 2023, the Union recognised 34 types of critical raw materials. Sixteen strategic raw materials were identified, including nickel, copper, lithium and rare earth metals, which drew the most attention due to their relevance and supply challenges (European Commission, 2023n). This assessment will be continuously conducted every three years to ensure the European Union is able to address the challenges and designs a timely action to address its dependency status. This is essential to create resilience and competitiveness in its industries and achieve its climate objectives.

The European Commission estimates that the demand for rare earth metals in the European Union is expected to increase six-fold by 2030 and seven-fold by 2050. For lithium, the demand is expected to increase 12-fold by 2030 and 21-fold by 2050 (European Commission, 2023o). In 2020, the European Commission launched its Action Plan on Critical Raw Materials considering current and future challenges (*e.g.* the region's reliance on other countries, supply diversification, and resource efficiency and circularity improvement; IRENA, 2023a). In October 2017, the Commission launched the European Battery Alliances, which included a project-driven community programme to bring together over 800 industrial and innovation actors from mining to recycling with the common objective of building a strong and competitive European battery industry. The alliance primarily seeks to address industrial challenges to trigger a fast-growing demand for efficient batteries for power, transport and industrial applications for a clean energy transition and a competitive future industry for the European Union.

In 2024, the Commission regulated the European Critical Raw Materials Act with the main targets of strengthening the critical materials value chain and diversifying imports to reduce strategic dependencies. The Act aims to enhance EU capacity to monitor and mitigate risks in the critical materials supply chain, while improving circularity and sustainability. It prioritises actions based on an updated list of essential materials for the EU economy's strategic technologies. By 2030, the Act targets at least 10% of EU annual consumption for extraction, 40% for processing, 25% for recycling and limits reliance on a single third country to 65%. It mandates monitoring and stress testing for the critical raw materials supply chain, co-ordinates strategic stocks, particularly for companies producing key energy transition technologies, and streamlines permitting procedures to reduce administrative burdens while ensuring high social and environmental standards. On the consumption side, it sets targets to improve the sustainability and circularity of critical materials, enhances recycling processes for critical material-rich waste, and establishes recyclability and recycled content requirements for produced technologies. Additionally, it supports international trade by securing diversified trade through agreements, expanding the European Union's trade network with a value chain and sustainability focus, addressing unfair trade practices and strengthening enforcement. The European Union must translate this comprehensive Act into actionable policies and implement them promptly to ensure a smooth energy transition within the region.

3.4 EU IRON AND STEEL

Key Findings

- **Iron and steel can be fully decarbonised before 2050** with decarbonised production modes, reaching -6.5 to -3.1 $MtCO_2$ of emissions captured under the PES and -8.6 to -2.8 $MtCO_2$ captured under the DES, between 2030-2050.
- Energy efficiency and a shift of the energy mix towards renewables drive a **-65% to -76% decline in energy intensity in the iron and steel industry over the base year by 2050**; energy intensity ranges from 61 GJ /million EUR to 43 GJ /million EUR in the PES and DES, respectively.
- Electrification is one of the keys to decarbonising the sector. **Electricity share grows from 25% in the base year to 69% and 81% under the PES and DES, respectively, in 2050**, with 215 TWh and 178 TWh of consumption annually.
- **Hydrogen consumption grows to 1.5-0.8 Mt by 2050,** constituting 15% and 11% of total energy consumption respectively, in the PES and DES, respectively.
- **Increase of circularity and optimisation of potential post-consumer scrap availability** to maximise production using scrap electric arc furnace technology will be key factors in decarbonising the sector. Scrap demand in the European Union will grow by a factor of 1.5 and 1.2 under the PES and DES, respectively, by 2050, from about 76.4 Mt in 2021 to 114.6-94.4 Mt.
- **Annual investment of EUR 2.1-2.6 billion** per year is required to decarbonise the sector; it relates to getting hydrogen DRI production modes and carbon capture and storage (CCS) online by 2050.
- **Different options are employed in the PES and DES for ensuring the supply of DRI for the iron and steel industry.** Under the PES, all low-carbon DRI will be produced locally; production will reach 28.6 Mt annually by 2050. The DES explores potential DRI import of 7.0-11.1 Mt over 2030-2050 from other regions, reducing the low-carbon DRI demand to half that under the PES by 2050. International trade of DRI should be assessed carefully, with competitiveness in mind.
- The DES estimate that, by 2030, 70% of the European Union's DRI iron plants should already be operating using hydrogen, and the remainder using natural gas with CCS. **Germany, Italy and France are the top three steel producers in the region, and the trend is expected to remain unchanged in 2050.**

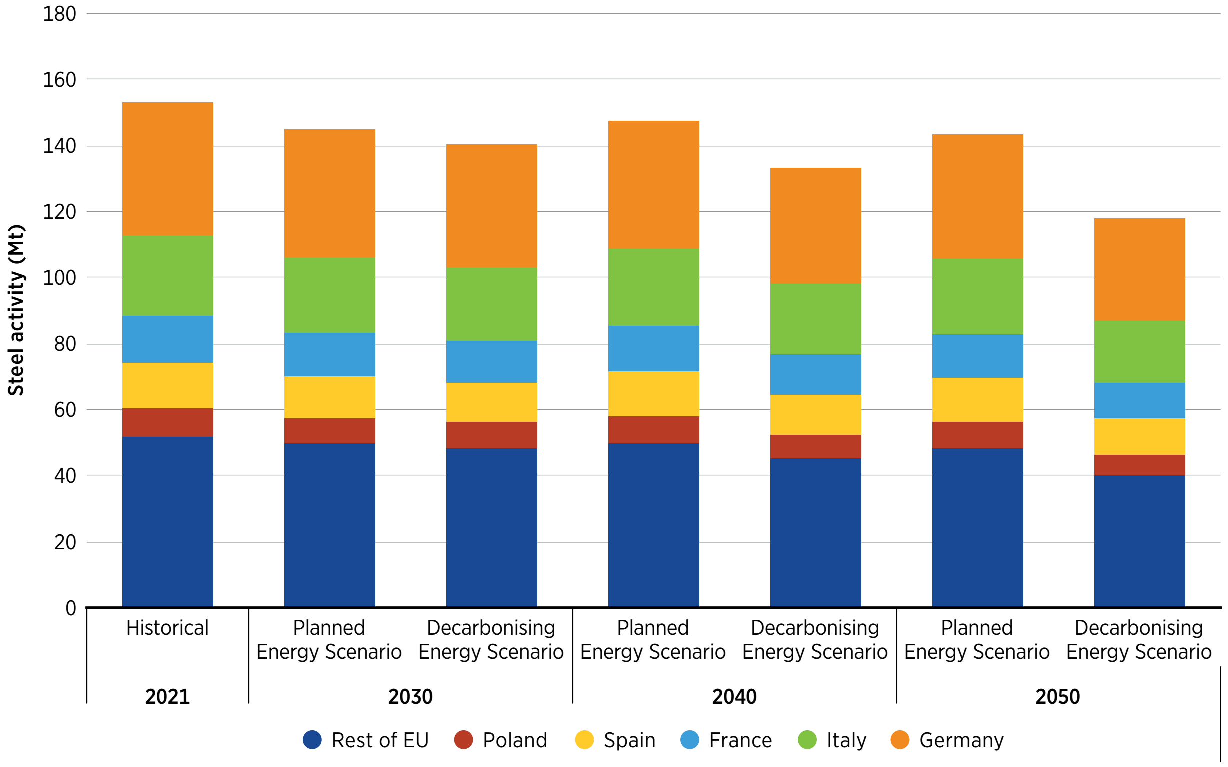
Key Messages

- **The European Union's scrap management and import/export policy should be assessed to ensure the availability of high-quality steel scrap, which is needed in the sector's decarbonised future.** For the European Union to optimise the consumption for high-quality scrap and decarbonise the sector, it needs a stringent policy on standard scrap availability and ensure this scrap is used within the region.
- **A structural shift in iron and steel production is needed, with renewables displacing fossil fuels as energy consumption and reducing agents.** Key innovations such as hydrogen-based direct iron reduction with electric arc furnaces represent a promising, efficient and low-emission technological pathway, complemented by process digitalisation (*i.e.* the integration of Industry 4.0 practices).
- **It is important to accelerate R&D for the roll-out of low-carbon technologies and CCS and establish appropriate fiscal incentive programmes to ramp up their adoption in the sector.** CCS is an alternative to further reduce emissions. The increased use of electric arc furnaces, greater use of hydrogen in iron ore reduction and/or the implementation of natural gas DRI with CCS are the main factors in decarbonising EU steel production.

The iron and steel industry is among the most important in the region. It represented 7% of the global steel production in 2020 (IRENA, 2023a). EUROFER statistics shows that in 2021, EU27 countries produced 153 Mt of steel overall, of which 66% came from the top five producing countries: Germany, Italy, France, Spain and Poland. With industry heading towards an ambitious target of a 55% carbon emission reduction by 2030, iron and steel faces several challenges. This target would compel the industry to transform significantly. Several challenges have arisen, of which high energy prices, strong competition and global overcapacity are key to address immediately. Having experienced its lowest-ever steel production rates in 2023, the European Union needs to have answers on the sector's decarbonisation to ensure it can sustain competitiveness.

The European steel industry has the potential to be the global front-runner in the sector's decarbonisation. According to EUROFER, there are 60 low CO_2 steel industry projects to date that are able to reduce CO_2 emissions by 81.5 Mt per year by 2030 (Figure 3.6). To achieve this, an annual capital investment of approximately EUR 2.6 billion in the PES and EUR 2.1 billion in the DES is planned to decarbonise the sector by 2050. Access to the most competitive low-carbon carriers is essential to decarbonise the sector and maintain industry competitiveness in the global market, especially as the European Union faces energy prices four to six times higher than its competitors.

Figure 3.6 Steel production in the top five producing countries and rest of EU27



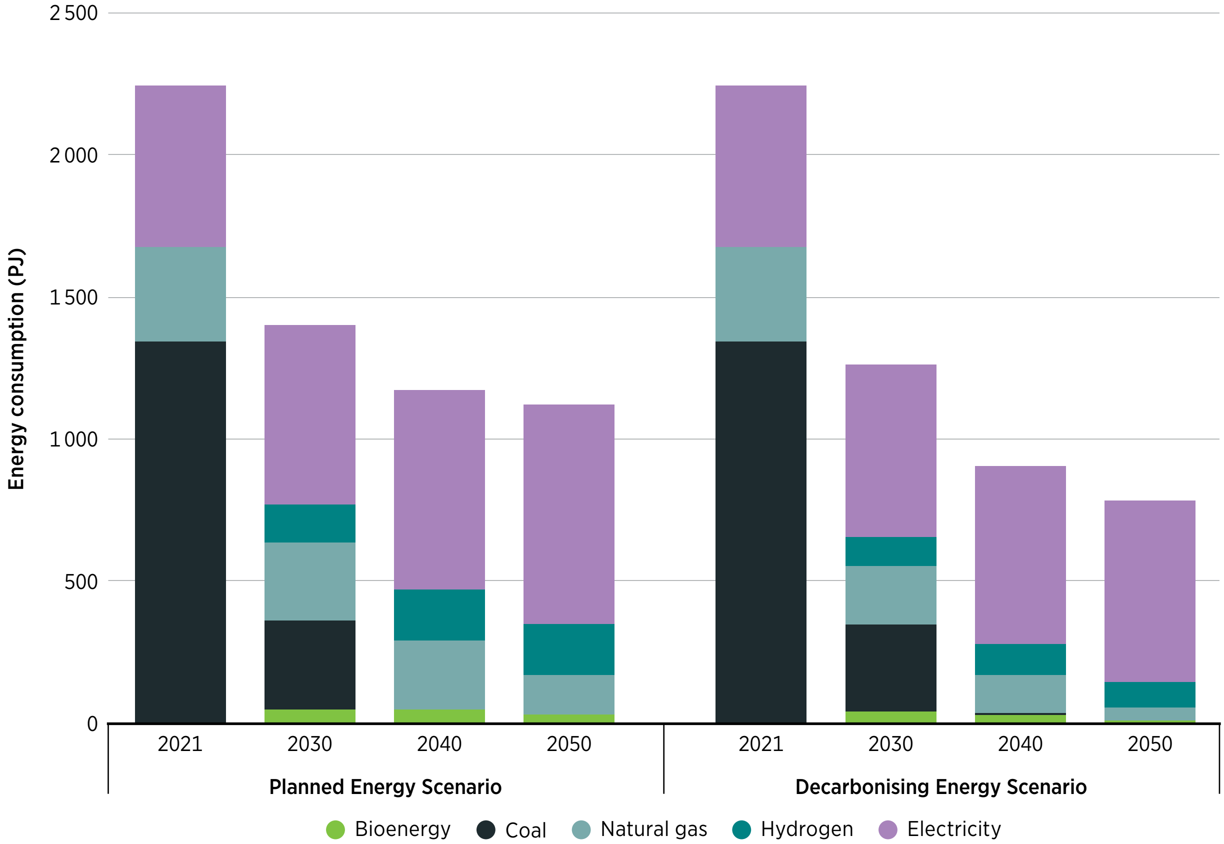
Note: Mt = million tonnes.

In the PES, the iron and steel industry needs to reduce its energy consumption in the short term towards 2030 by -37%. The EU Impact Assessment Study foresees steel production remaining at the current level. This is reflected in the PES, while an increasing recycling rate and an increased share of secondary steel could drive down demand by about 15% in 2050, as reflected in the DES. The sector will be decarbonised via an increased share of electric arc furnaces and through the implementation of hydrogen DRI, whose adoption within these decades should be the industry's priority. Carbon capture technology also needs to be implemented faster within this decade, to capture -6.5 $GtCO_2$ /year by 2030. By 2030, coal and natural gas consumption needs to decline by -77% and -16% over 2021, respectively. The total fossil fuel consumption in 2030 is about 0.5 EJ. Electricity consumption in 2030 needs to increase 111% over the base year value to reach 0.6 EJ.

Hydrogen consumption will increase significantly. It will represent over 9% of the sector's energy consumption within this decade. By 2050, electricity's share of the overall sector energy demand increases to more than two-thirds, leaving about 12% of the residual fossil fuels in the sector. Hydrogen will constitute 15% of the sector's energy consumption (Figure 3.7).

The DES envisions further utilisation of green-hydrogen-based production particularly between 2030 and 2050. Electricity makes up more than 80% of the overall sector energy demand in 2050. Hydrogen constitutes more than 11% of the energy demand in the same year, leaving only 5% of residual fossil fuels in the sector.

Figure 3.7 Iron and steel energy consumption by carrier



Note: PJ = petajoule.

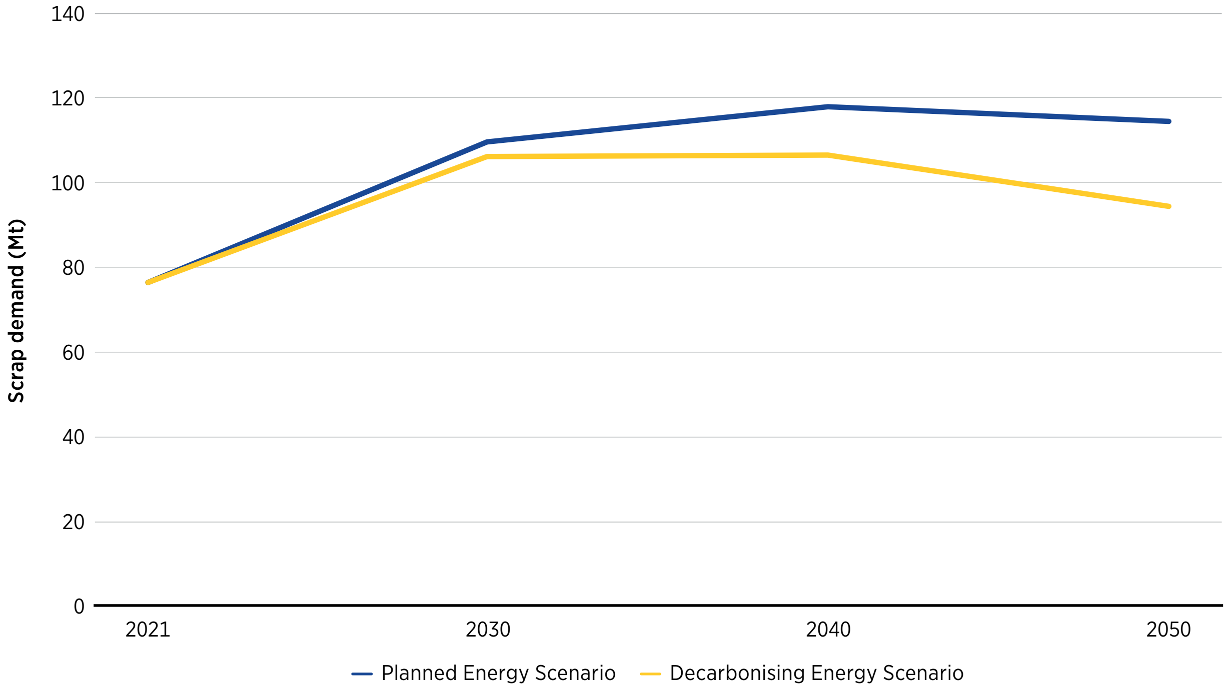
The European Union has been importing DRI. Eurostat data show that the European Union imported 1.69 Mt of DRI between January and July 2024 – an increase of about 4.8% compared with the same period in 2023. The DES considers that the European Union could benefit from importing its hydrogen DRI from other countries and/or regions with high-quality iron ore and low renewable electricity prices. It is estimated that hydrogen DRI imports under the DES will grow, reaching 7-11 Mt in 2030 and 2050.

Secondary scrap steelmaking is vital for reducing emissions of about 1.6 tCO_2eq for every tonne of recycled steel crap (Broadbent, 2016). Today, not all the scrap available in the European Union can be used to produce steel. The EU scrap use rate is 54%-59% (Pothen and Hundt, 2024). The steel produced can be used to manufacture a wide range of products only if high-quality steel scrap, as published in the steel scrap specification of the European Ferrous Recovery and Recycling Federation, is used. EUROFER noted that in 2022, the European Union produced 93 Mt of steel scrap domestically, while importing 3.9 Mt. In the same year, it exported 17.6 Mt of steel scrap, leaving its consumption at the level of 79.3 Mt.

Optimising the EU industry's transition to secondary scrap steelmaking requires focusing more effort on high-quality scrap. The steel scrap input comes from several phases of steel's life cycle – for example, fabrication scrap, which is the leftover metal pieces that are discarded after a manufacturing process at a metal fabrication plant; production scrap, which comes from the unusable material resulting from production; engineering scrap, which still has value when reprocessed; and post-consumer scrap, which comes from products, such as buildings, households appliances and ships, once they reach end of life.

IRENA's analysis determined the potential quantity of post-consumer scrap in the European Union based on the historical steel consumption and the future transition of production mode the region needs to undergo to meet its emissions reduction targets. The PES estimated that the EU post-consumer scrap demand will grow 150% over 2021-2050, reaching 114.5 Mt per year. More efficient steel consumption under the DES reduces the scrap demand by 18% over that in the PES in 2050 (Figure 3.8). An Econstor study on the estimation of post-consumer scrap availability in the European Union estimates that demand will range from 80-105 Mt to 100-105 Mt in 2030 and 2050 (Pothen and Hundt, 2024). This means that appropriate policy implementation should be able to help the European Union address its scrap needs to decarbonise its steel industry without relying on imports.

Figure 3.8 EU post-consumer scrap demand



Note: Mt = million tonnes.

The European Union will have to deploy CCS in the sector to further accelerate emissions reductions. The transition towards DRI production mode in steel would need to combine CCS-equipped hydrogen- and natural-gas-based processes. The demand for carbon captured in the sector needs to reach -3.1 to -6.5 $MtCO_2$ by 2030 under the DES and PES. The carbon captured under the PES by 2050 needs to grow more than 132% over 2030 values. Under the DES, the demand for locally produced green DRI declines, subsequently also reducing the carbon captured in the sector by about -60% compared with the PES in 2040 and 2050.

Iron and steel emissions can be reduced significantly in both the PES and DES. By 2030, iron and steel emissions would decline by almost three-quarters compared with the base year. The industry will release about 38.5 $MtCO_2$ and 37 $MtCO_2$ emissions under the PES and DES, respectively, and will reach net-zero emissions before 2050.

3.5 CEMENT

Key findings

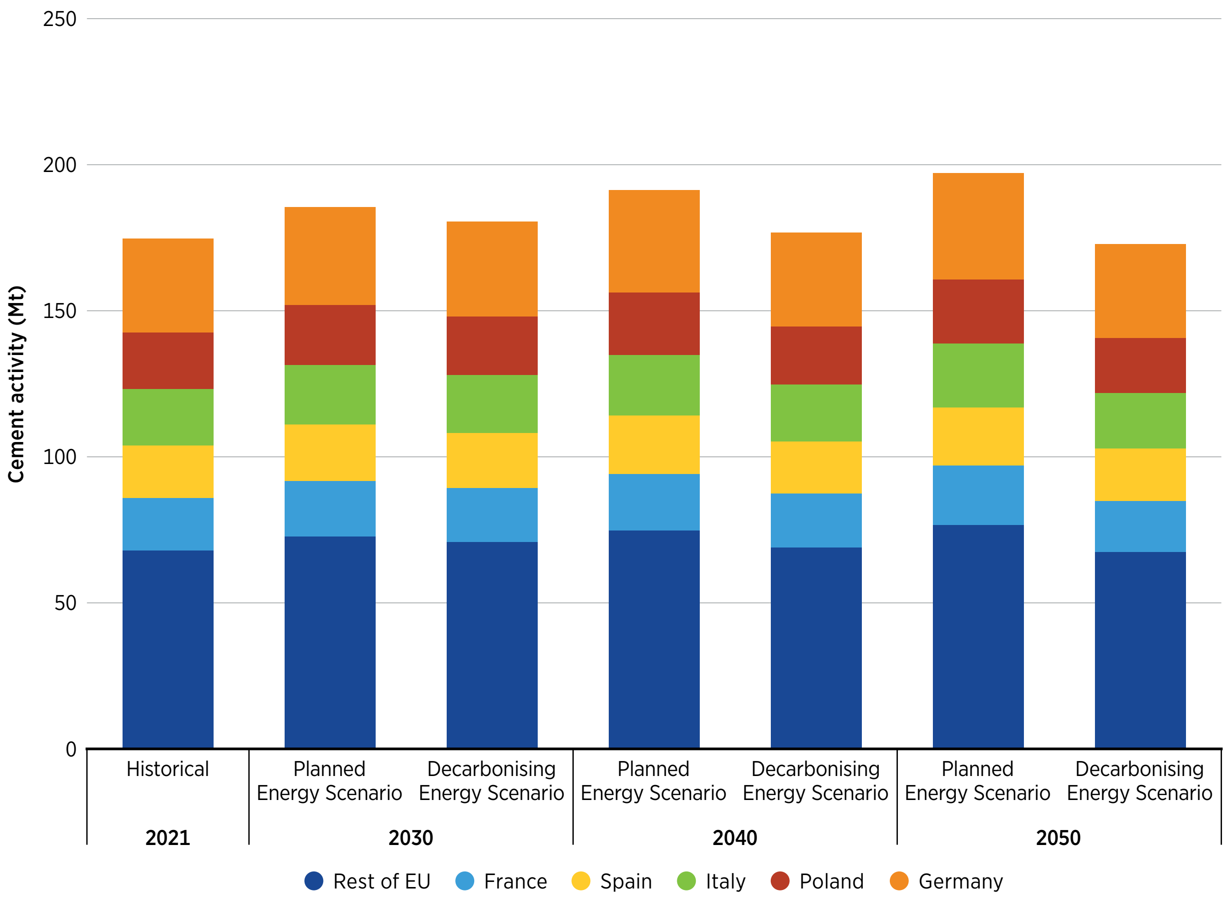
- ★ The cement industry can achieve significant emission reduction in 2050. **Transitioning towards bioenergy and alternative fuel is the key to decarbonise the sector** while capturing -39 to -78 $MtCO_2$ of emissions under the PES and -38 to -71 $MtCO_2$ of emissions under the DES over 2030-2050.
- ★ **The share of bioenergy and alternative fuels increases from 36% at 2021 to about 40% by 2050.** The corresponding energy consumption is 266-194 PJ in the PES and DES. When considering indirect use of renewable electricity, renewable energy accounts for 58%-63% of the sector's energy consumption in 2050.
- ★ **Cement's energy consumption is reduced by -39% to -48% in 2050 over the baseline**, reaching 563 PJ and 482 PJ in the PES and DES, respectively, due to energy efficiency and a carrier transition.
- ★ **The sector's energy intensity reduces at a rate of -3.0% to -3.5% annually until 2050**, from EUR 75 GJ/million EUR in 2021.
- ★ **Annual investment of up to EUR 6.2 billion** is required to decarbonise the sector. This includes the establishment of energy-efficient plants with CCS and retrofit of existing plants with CCS.
- ★ The European Union expects cement production to increase 20% over 2015 by 2050 (relative to 2015), and in the PES, production reaches 197 Mt. Cement demand in the DES can fall to 173 Mt **with the implementation of stricter policies for low-carbon cement alternatives' uptake, an increase in the utilisation and longevity of buildings, and a higher share of recycled cement in concrete.** These measures will drive a 15%-16% energy demand reduction in the top five energy consuming countries by 2050.
- ★ It is estimated that 30% of cement production plants will reach their end of life by 2030 (Agora Energiewende and Wuppertal Institute, 2020). These retired plants need to be replaced with the best available energy-efficient plants with CCS to reach the 2030 emissions target, while another 10% of existing plants have to be retrofitted to adopt CCS. By 2040 and 2050, 30% and at least 45% of existing plants, respectively, have to be retrofitted with CCS in both scenarios. **Policy support is needed to establish a market for CO_2 transport and storage in order to encourage CCS roll-out and more R&D to accelerate the technology's maturity.**

Key messages

- ★ **Cement can increase the use of additives and fillers to substitute for clinker.** These substitutes can include blast furnace slag, coal fly ash, red mud and calcined clay, most of which are waste from other material production processes.
- ★ **The life span of infrastructure made of cement, for example, buildings and bridges, can be lengthened, and waste recycled.** The EU Waste Framework Directive calls for the reuse, recycling or recovery of construction and demolition waste. This circularity would indeed enable the reduction of CO_2 emissions in the building industry. Options for circularity include the reuse of concrete components.
- ★ **Promote efficiency measures in cement production.** A planned greenfield project leverages the best available technology, while integrating CCS technologies to boost energy efficiency and further reduce emissions from the cement production process.

The cement industry predominantly uses thermal processes, which, to date, are satisfied mostly by fossil fuels, while the share of electricity is about one-tenth. The European Cement Association, Cembureau, has set a target of a 60% share of alternative fuels containing 30% biomass in 2030 and a 90% share of alternative fuels with 50% biomass by 2050. Both the PES and DES use this energy carrier transition in the analysis towards 2030 and 2050. The EU Impact Assessment Study estimated that cement production will grow 20% towards 2050 over that in 2015. It will reach about 197 Mt per year in the PES. In the DES, cement demand falls by 25% by 2050, reaching about 173 Mt, due to low-carbon cement alternatives, a high share of recycled cement in concrete, and changes in buildings' lifetime and utilisation rates. About 61% of the region's cement production is dominated by the top five countries, led by Germany, which produced 19% of all EU cement in 2021 (Figure 3.9). The trend is estimated to continue until 2050.

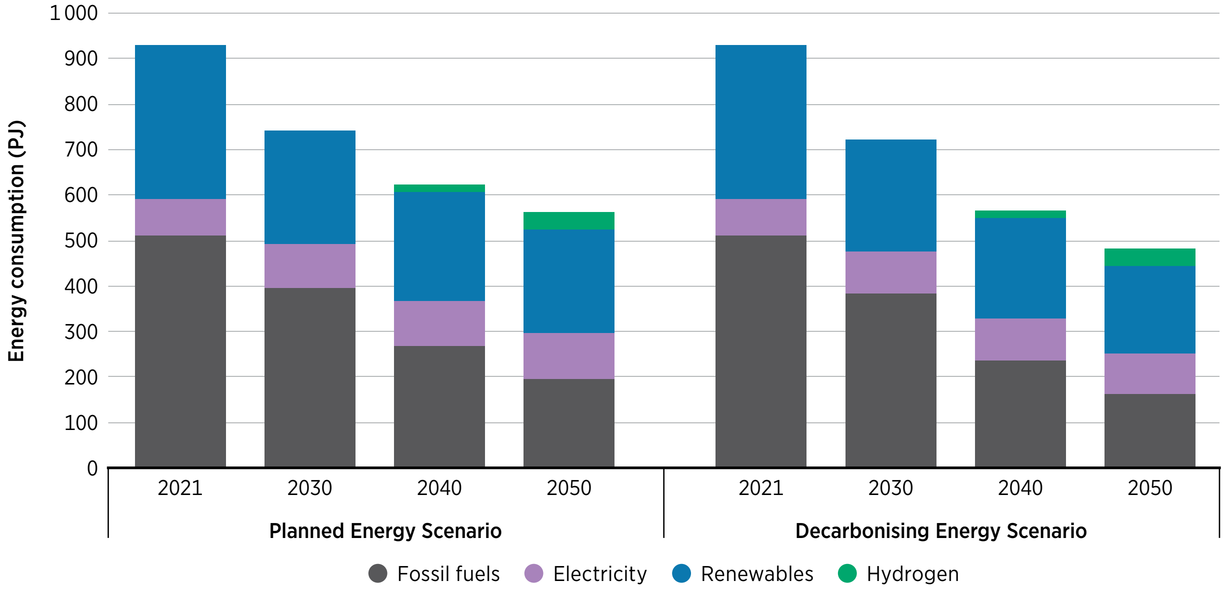
Figure 3.9 Cement production in the top five producing countries and rest of EU27



Note: Mt = million tonnes.

The EU cement industry's energy demand is projected to decline -20% from the baseline under the PES in 2030 and -39% under the PES in 2050, reaching 0.7 EJ and 0.5 EJ, respectively (Figure 3.10). This equals an annual energy consumption reduction of -1.7% in the long term. More efficient materials used under the DES will accelerate energy consumption reduction, at -2.2% annually, in the same period. The energy demand reduction is driven by a carrier transition and a more efficient clinker-to-cement ratio, of 70%, by 2050, and an increase of substitutes, such as granulated blast furnace slag, pozzolanic materials, fly ash, limestone and silica fume. To date, fossil fuels dominate the sector's energy consumption. Renewable energy constitutes a little more than one-third of consumption. By 2050, renewable energy will constitute about 40% of the sector's energy demand. The share of electricity doubles compared with the baseline, reaching 18% of the sector's energy demand. Fossil fuel consumption falls to 0.19 EJ and 0.16 EJ under the PES and DES, respectively, or about a -61% to -68% decline compared with the baseline (Figure 3.10).

Figure 3.10 Cement industry energy consumption by carrier



Note: PJ = petajoule.

CCS has a vital role to play in the sector's decarbonisation given that the sector has limited low-carbon production technology. The DES considers a possible full-scale implementation of CCS in the sector, although this would largely depend on infrastructure development and the subsequent business support. The key is to develop suitable policies to support infrastructure development. Carrier transition, energy efficiency and CCS implementation will allow the sector to reduce emissions by over half by 2030 under the PES and DES to the level of 67 $MtCO_2$ and 65 $MtCO_2$, respectively, while capturing -39 $MtCO_2$ to -38 $MtCO_2$ of emissions. By 2050, emissions under the PES plummet to 1.9 $MtCO_2$, with about -78 $MtCO_2$ being captured. Under the DES, approximately -71 $MtCO_2$ of emissions will be captured, with emissions reaching negative values by 2050.

3.6 CHEMICALS

Key findings

- ★ **The chemicals subsector, including non-energy, consumed about 3.6 EJ in the baseline year 2021, and the sector's energy demand will decline at a rate of -1.0% annually towards 2050,** driven by energy efficiency improvements and a transition towards low-carbon chemical processes in the PES. The sector will consume 2.6 EJ by 2050 in the PES, whereas its demand is 16% lower in the same year in the DES.
- ★ **The share of electricity consumption in the sector increases from about 18% at baseline to about a quarter by 2050 in both scenarios**, with 185 TWh and 159 TWh of clean electricity consumed in the PES and DES, respectively.
- ★ **Bioenergy will constitute almost one-third of consumption in 2050**, with 0.8 EJ and 0.7 EJ consumed in the PES and DES, respectively.
- ★ **Ethylene and ammonia, used to supply the non-energy sector, made up half the sector's consumption in the baseline year.** The two chemical products will continue to make up more than 82% of the sector's demand, with 2.1 EJ to 1.8 EJ consumed in the PES and DES, respectively, by 2050, to meet the increasing demand for them as feedstock in other processes.
- ★ **The transition towards bio-based and electrochemical processes** allows the subsector to reduce emissions by about -58% by 2030 under both scenarios, at about 42 and 40 $MtCO_2$ of emissions in the PES and DES, respectively.

- ★ The sector will need to capture -24 to -23 $MtCO_2$ of emissions by 2040 and -27 to -25 $MtCO_2$ of emissions by 2050 in the PES and DES. **Annual investment of EUR 1.6-1.8 billion** is required to decarbonise the sector; it is related to establishing low-carbon production technologies and CCS.
- ★ An Impact Assessment Study projected that EU petrochemicals will constitute approximately 4% of the global demand. Under the PES, chemical production will increase 25% over the baseline year, whereas **additional measures from demand-side optimisation will save about 15% of chemical production in the DES compared with the PES** in the same year.

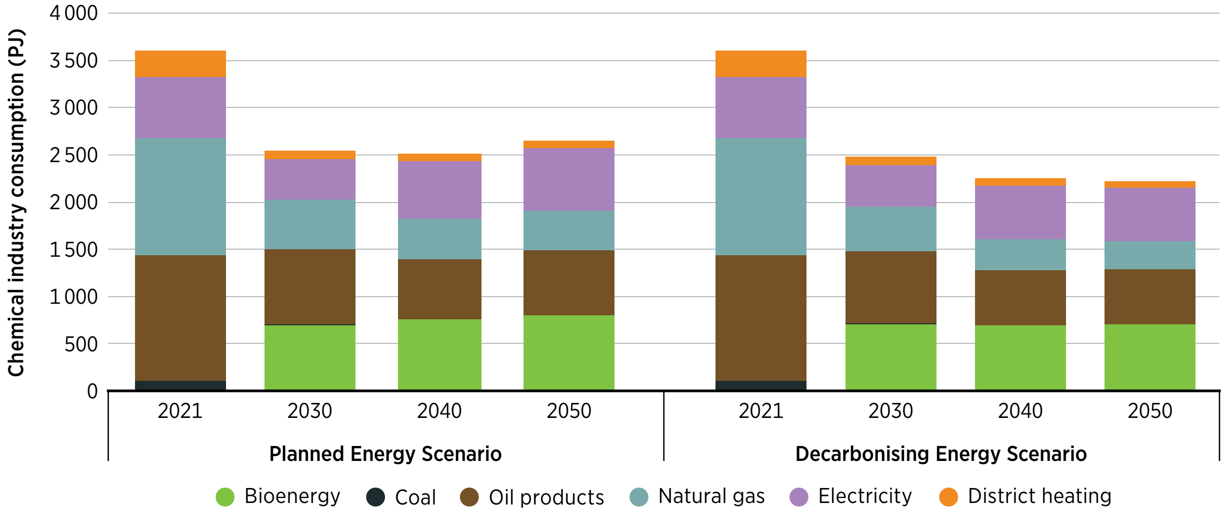
Key messages

- ★ **It is important to increase circular economy measures**, for example, reuse, mechanical and chemical recycling rates, material substitution and the use of sustainable feedstocks for demand reduction. Emissions mitigation consists of demand reduction coupled with recycling and the use of renewables to meet the electricity demand for production processes.
- ★ **The sector needs to transition to electricity and bio-based production methods.** It can achieve net negative emissions reduction when it has undergone a pan-EU transformation towards renewable energy and energy-efficient chemical processes. Emissions mitigation includes renewable solutions for process energy generation and as feedstock, as well as renewable hydrogen, energy efficiency and CCS.
- ★ **Promote the supply chain for low-carbon feedstocks.** The sector's decarbonisation requires support from subsidies and/or tax incentives for low-carbon feedstock, including the sustainable sourcing of bio-based alternatives, or recycled feedstock, to companies.

The chemicals and petrochemicals subsector is a major contributor to global industrial CO_2 emissions. Chemical production released approximately 0.83 Gt of energy- and process-related CO_2 emissions in 2020, when the European Union represented 11% of global chemical emissions. Potential transformative routes for decarbonising the EU chemicals sector include, among others, electrochemical and bio-based chemical production. Four chemicals categories were considered in the analysis – ammonia, methanol, ethylene, chlorine and other chemicals. In 2021, "other chemicals" constituted about 44% of the sector's consumption. Ethylene ranked second, representing one-third of the sector's energy demand in the same year.

Considering also chemicals produced for non-energy sectors, chemicals' energy demand will reduce at a rate of -1.0% annually in the PES, reaching 2.6 EJ by 2050 – a reduction of -26% from the baseline year. In the DES, the energy demand will reduce at a rate of -1.6% annually, becoming 16% less than the demand in the PES. The EU chemicals subsector will continue to be dominated by fossil fuels towards 2050 despite their share declining by over 70% in 2021 to 41%-39% under the PES and DES, respectively. Bioenergy will grow across the time horizon towards 2050 from less than 1% to constitute nearly one-third of the sector's consumption by 2050 under both scenarios (Figure 3.11).

Figure 3.11 Chemicals industry consumption by carrier

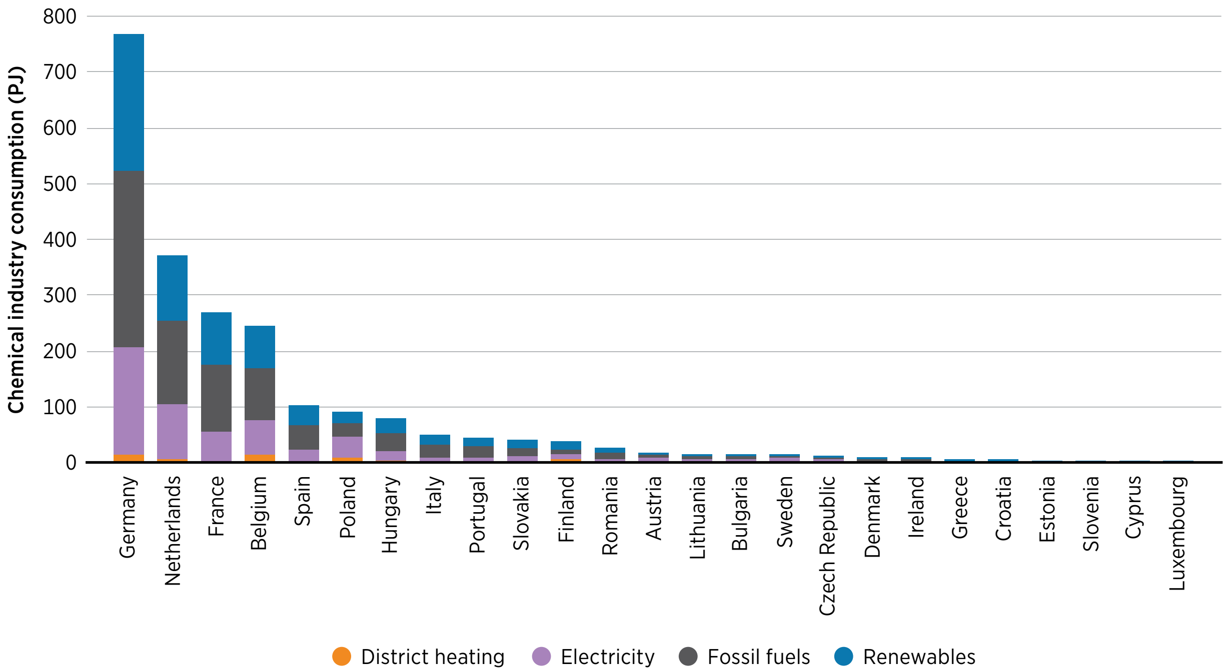


Notes: PJ = petajoule; Chemical industry consumption includes energy and non-energy uses.

The EU chemicals sector emissions under the PES reduce by 58% in 2030, reaching about 42 $MtCO_2$, whereas emissions under the DES reach 40 $MtCO_2$ in the same year. Carriers and more efficient production modes drive these emission reductions. CCS systems will play an important role in the next decade. They will help capture -24 to -23 $MtCO_2$ of emissions and further reduce sector emissions, to 7.5-4.0 $MtCO_2$ under the PES and DES by 2040. By 2050, the chemicals sector will need to capture -27 to -24 $MtCO_2$ of carbon emissions, leaving 4.9 $MtCO_2$ of emissions under the PES and 1.1 $MtCO_2$ of emissions under the DES in the same year.

Germany, the Netherlands, Belgium, France and Poland are the top five consumers in the chemicals industry by 2050. They constitute 78% of the region's energy consumption in the subsector. Ethylene and ammonia production dominate the chemicals industry in these countries, constituting over 85% of the subsector's total consumption (Figure 3.12).

Figure 3.12 Chemicals industry consumption in the DES, 2050

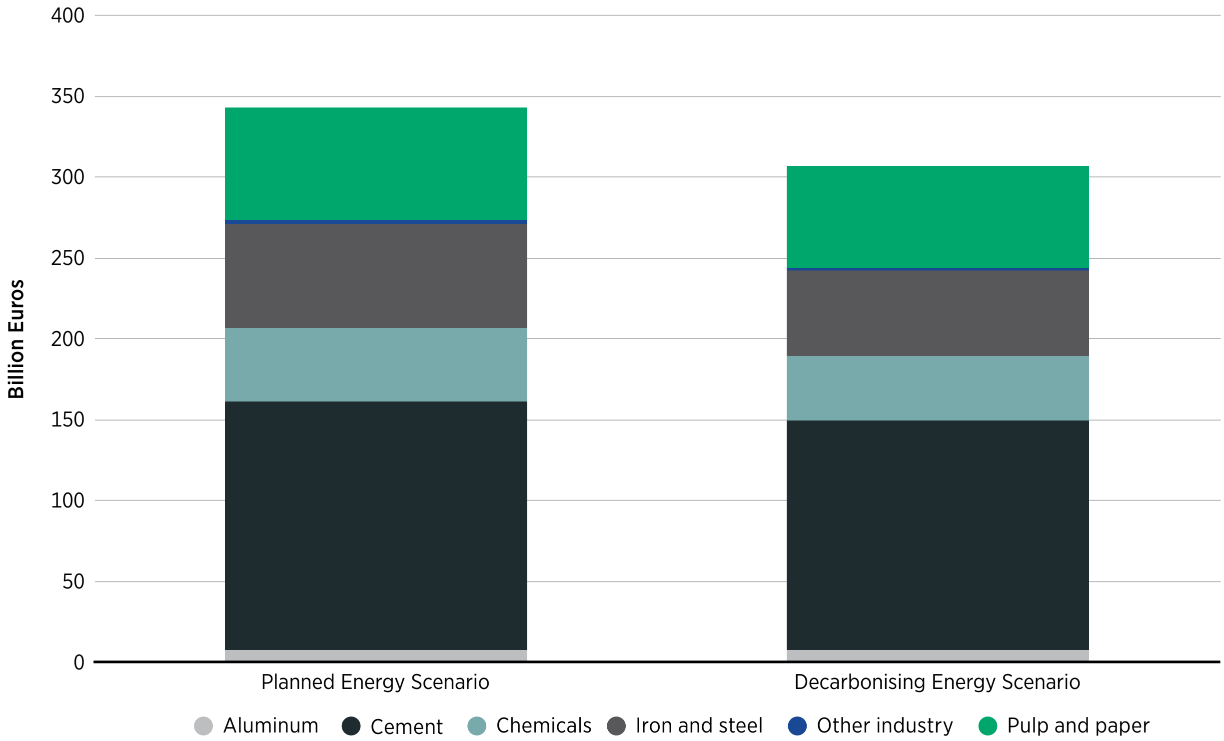


Notes: PJ = petajoule; Chemical industry consumption includes energy and non-energy uses.

3.7 INVESTMENT IN INDUSTRY

Investment in industry is related mainly to newly built equipment or production plants that follow higher energy efficiency standards and incorporate low-carbon technology (*e.g.* a CCS system). For the European Union to transform its industry and reach its emissions reduction targets for 2050, cumulative investments of EUR 307 to 343 billion, or about 3% of the EU27's GDP in 2020, are needed. Annual investments of EUR 13.7 billion and EUR 12.3 billion, about 95% of Malta's GDP in 2022, are needed under the PES and DES, respectively. The PES reflects the European Union's very ambitious plans and regulations to reach the 2030 "Fit for 55" emissions reduction target and net-zero by 2050. The DES adds several measures, for example, the import of low-carbon materials, as well as increased material efficiency. The lower investment number under the DES is because these additional measures lead to lower expected industrial production, and in turn a lower plant capacity, reducing financial pressure. Investments in cement and pulp and paper dominate, at 65% of the total needed for the European Union's industrial decarbonisation (Figure 3.13).

Figure 3.13 Cumulative investment in industry, 2021-2050



By subsector, cement requires the highest total annual investment in equipment, up to EUR 6.2 billion – mainly to build new plants to replace 30% of the cement plants that are reaching end of life by 2030 and equip the new plants with CCS. This represents nearly half of the industry sector's investment needs. The other investments are related to retrofitting the operating plants with CCS to decarbonise their production processes. Pulp and paper has the second-highest annual investment requirement, about EUR 2.8 billion, representing about one-fifth of the industry's investment needs. It is followed by iron and steel at EUR 2.6 billion. The chemicals sector needs investment of EUR 1.6-1.8 billion, whereas aluminium and other industries together need about EUR 0.4 billion annually to decarbonise production.

Investment in CCS constitutes about one-third of the chemicals subsector's annual investment requirement, reaching EUR 0.5 billion to EUR 0.6 billion annually. Cross border public investment within the EU is needed to optimise its utilisation in the region, while private investment needed to be redirected to the clean industry processes and realise the clean industrial deal.

3.8 KEY ACTIONS AND PRIORITIES

The EU industrial sector has the potential to be at the forefront of a low-carbon economy. Technology and resources to reach these targets by 2050 are available. The European Union has also developed many supporting regulations and policies, as well as targets, to stimulate government–private sector dialogue while still maintaining industrial competitiveness and securing regional energy security (Table 3.4).

Table 3.4 Key actions and priorities in industry

OUTCOMES	CURRENT REGULATIONS, DIRECTIVES OR PROPOSALS	ADDITIONAL MEASURES AND ACTIONS SUGGESTED
Comprehensive technical strategies and guidelines for energy-intensive industry processes are needed to ensure the sector maintains its competitiveness amid the push to decarbonise its production processes.	Green Deal Industrial Plan, New Industrial Strategy, EU Clean Industrial Deal	• Create decarbonisation roadmaps, especially for the high-intensity industry processes, for specific industry subsectors with clear short- and long-term targets, milestones and progress-tracking mechanisms for decarbonisation progress. • Plan and co-ordinate the development of the roadmaps among the European Union (EU), the private sector, civil societies and Member States at all levels to come up with the best way to roll out decarbonisation actions and ensure industry stays competitive in the global market. • Implement and monitor the progress of industry decarbonisation, while continuously refining strategies as needed to accelerate the transition over the coming years.
Hydrogen consumption in the industry sector grows 3.1x and 3.5x from 2030 to 2050 under the Planned Energy Scenario (PES) and Decarbonising Energy Scenario (DES), respectively. In the same period, the carbon captured in the sector grows 2.7x and 2.4x. To achieve this, the development of key supporting infrastructure and a skilled workforce is important.	Regulation (EU) 2024/1735, the Net-Zero Industry Act	• Plan and implement key infrastructure projects to support industrial decarbonisation. • Leverage the expansion of renewable energy infrastructure in the form of higher installed renewable energy capacity and improved energy storage to ensure renewable energy remains reliable and ensure its integration to the grid. • Accelerate development of hydrogen infrastructure such as electrolysers, hydrogen transport and storage infrastructure, and hydrogen hubs connecting industrial clusters in the region. • Develop carbon dioxide (CO_2) transport infrastructure and long-term storage sites to ramp up the implementation of carbon capture, utilisation and storage in the industry sector. • Establish a net-zero academy to prepare a sizeable skilled workforce in the region to ensure capacity development through upskilling programmes that impart quality training on the essential skills supporting the energy transition. • Retain a stable and predictable regulatory framework to de-risk investment which is needed to realise industrial decarbonisation and attract long-term capital.

Appropriate financial schemes will determine the success of the industrial decarbonisation.	European Green Deal, Investment Plan, EU Clean Industrial Deal	• Implement a carbon pricing system that is dynamic and adaptable to emerging technologies including potential of "carbon leakage". A robust carbon pricing framework is needed to maintain industry competitiveness. The European Union must develop appropriate financial incentives for industries, especially for first movers, for them to invest in green technologies.
The development of low-carbon production mode technologies is vital. The investment required on efficient production modes, as well as in carbon capture and storage, constitutes about 60% of the investment under the PES and DES.	Horizon Europe, EU Innovation Fund, Net-Zero Industry Act, New Industrial Strategy, that aims to enhance European manufacturing capacity for net-zero technologies and their key components, to address barriers in scaling up production in Europe	• Promote public-private partnerships to encourage research and development in clean and green technologies. • Provide more funding and regulatory support for industries adopting innovation towards green technologies, low-carbon processes, digital transformation and circular economy. • Optimise co-ordination to accelerate the net-zero platform to support and prioritise strategic net-zero projects with a lean permitting process. • Regulate more private capital to increase the share of funding to finance the development of a clean and sustainable industry. • Strengthen international collaboration and trade agreements to secure access to critical raw materials for member states and expand EU-manufactured green industrial products to global market.
There is a potential need for a dedicated body/task force responsible for leading and monitoring the EU's industrial decarbonisation.	–	• Establish a central body to co-ordinate and monitor the implementation of all decarbonisation plans across Member States. • Evaluate the importance of establishing such a government-led body to ensure policy integration among related industry sectors and determine who will lead the involvement of industry partners, associations and trade unions. • Mandate the body to lead the monitoring of EU-wide industrial decarbonisation action plans. • Create clear metrics and monitoring mechanisms to track the progress of industrial decarbonisation across different subsectors and member states, ensuring accountability and effective implementation of the Clean Industrial Deal
Digitalisation can play an important role in the sector's decarbonisation.	New Industrial Strategy, EU Clean Industrial Deal	• Promote close consultation among EU Member States in support of data-driven decision making. • Accelerate industry digitalisation to facilitate the development of continuous measurement, reporting and verification schemes to closely monitor decarbonisation progress, especially in the energy-intensive industry sector. • Encourage policy adjustment based on real-time data and feedback from industry players and help fine-tune regulatory measures and incentives.

4

BUILDINGS

This chapter presents the main outcomes, findings and messages of the buildings sector analysis for EU27. Some of the key questions this section will cover are:

1. What is the status of the ongoing decarbonisation of buildings in the region?
2. Are the existing directives, plans and measures sufficient to deliver net-zero by 2050?
3. Which are the points of attention for policy makers?

KEY FINDINGS

- ★ **As of 2023, the buildings sector was the single largest energy consumer in the EU**, representing approximately 40% of the region's final energy consumption.
- ★ **A significant emissions reduction of almost 100% is reached under the DES by 2050 relative to the emissions in 2021.** The emissions reach 0.4 $MtCO_2$ compared to 112 $MtCO_2$ under the PES 2050.
- ★ **Of the energy used in EU homes, 80% is for heating, cooling and hot water.**
- ★ **Decarbonisation of space heating by 2050 would require an increase in heat pump stock of 7% annually on average between 2025 and 2050.** Only so the emissions reduction of the S3 scenario from the 2040 Climate Impact Assessment report could be achieved.
- ★ **The annual average electrification rate must increase to 0.27% between 2025 and 2050 in DES in order to successfully electrify most of the demand from the heating services.** This will help replace fossil-fuel-driven technologies with others that use electricity to operate, reducing buildings sector emissions to nearly zero by 2050, in line with the S3 scenario from the 2040 Climate Impact Assessment report.
- ★ **Energy demand under the DES decreases at an average annual rate of 2% compared with 1.3% in PES between 2021 and 2050.**
- ★ **Energy demand under the DES is 13% lower than the PES by 2040 and 16% by 2050. Thus, the energy bills for EU households and businesses will see the benefits of building renovation and the adoption of energy-efficient technologies.**
- ★ **Spending for greater energy efficiency and decarbonisation in the buildings sector is expected to reach EUR 4.4 trillion and EUR 5.4 trillion in the PES and DES, respectively.** This spending covers heating and cooling devices, electric appliances and lighting, and is reported in cumulative terms between 2025 and 2050.
- ★ **In both the PES and DES, space heating and water heating would represent approximately two-thirds of overall spending in decarbonisation of the buildings sector**. This is despite higher ambitions achieved in DES through the increased adoption of heat pumps and bioenergy-based solutions.
- ★ **The PES requires EUR 37 billion on average per year for the renovation of the existing buildings stock up to 2050.** The DES, following a much more ambitious pathway targeting a larger stock and deeper renovations, **almost doubles the PES investments, at EUR 75 billion per year**.
- ★ In cumulative terms, improvements in thermal insulation for buildings lead to **expenses of EUR 969 billion under the PES and EUR 2 trillion under the DES between 2025 and 2050. These cumulative investments represent 6% and 11% of 2023 EU GDP respectively.**
- ★ The transition to highly efficient electrical appliances will lead to spending of EUR 1.2 trillion in the DES by 2050. This is approximately 50% more than in the PES (EUR 638 billion).
- ★ The increased use of space cooling as a result of the increasing cooling degree days over time will represent 2% of total spending towards 2050 under both scenarios.

KEY MESSAGES

- ★ **Electrification of the heating services is paramount for decarbonising both sub-sectors** of the buildings sector and must increase at a faster pace.
- ★ **Electrification must be prioritised in the following order depending on resource availability in each Member State: (1) space heating, (2) water heating and (3) cooking.**
- ★ **Reduction of thermal energy consumption (moderation of thermal energy demand or needs)** is mainly achieved through the renovation of the buildings' envelope to achieve greater energy efficiency.
- ★ **District heating networks should be kept (and whenever possible expanded)** and decarbonised to help reduce the sector's emissions and secure the space heating service. The investment costs needed for this are not considered in the analysis of the buildings sector, but rather in the investment analysis of the supply side of the energy system.
- ★ **The use of biomass for space heating should be considered** in case replacing biomass boilers with heat pumps is not economically and/or technically feasible. The sustainability criteria for the use of biomass from the Renewable Energy Directive must be considered and complied with.
- ★ **National governments must accelerate the renovation rates of existing buildings to achieve the current targets for this sector.** These rates depend on the availability of financial resources in each Member State, as well as on the purchasing power of the population and the financial situation of the owners of commercial buildings.
- ★ **Attractive and easily accessible financing mechanisms** must be put in place so that all citizens and business owners have access to them.
- ★ **National and regional governments should work together to create and promote local and regional initiatives, such as municipal building transformation programs.** This will contribute to the sector's decarbonisation and support the decentralised implementation approach often emphasised in EU policy.
- ★ **The definition of a specific set of indicators that all countries need to report on, for instance in the NECPs, would facilitate the monitoring of the buildings sector evolution on its way to meeting the targets defined in the current regulatory framework**. The definition of these specific targets could also facilitate countries understanding the feasibility of meeting them and establishing specific mechanisms if needed so that they can be met.
- ★ **Financing the infrastructure required for the sector's decarbonisation remains one of the main factors determining the successful implementation of renovation and efficiency measures.** In this regard, the legal framework at both the EU and national levels must enable access to affordable financing for owners of households and commercial buildings. Partnerships with the private sector, such as private banks and energy service companies (ESCOs), can also provide a solution through tax reductions (or partial subsidies) for building renovations specifically to reduce energy consumption. In addition, improvement of financing programmes with national development banks and the current EU funds (*e.g.* European Regional Development Fund, Cohesion Fund, Just Transition Fund) could help increase the rate of renovation of buildings and the adoption of efficient technologies for heating services.
- ★ **The definition of a specific set of indicators that all countries need to report on, for instance in the NECPs, would facilitate the monitoring of the buildings sector evolution on its way to meeting the targets defined in the current regulatory framework.** The definition of these specific targets could also facilitate countries understanding the feasibility of meeting them and establishing specific mechanisms if needed so that they can be met.

4.1 BUILDINGS' ROLE IN MEETING EU EMISSIONS REDUCTION TARGETS

The buildings sector plays an important role in both energy consumption and GHG emissions in the EU Member States. Among sectors, it was the single-largest energy consumer in Europe in 2023 (at 40% of the energy consumed in the European Union) and emitted one-third of the EU's energy-related GHG emissions. Additionally, approximately 80% of the energy used in EU homes is for heating, cooling and hot water (European Commission, 2023p). The so-called heating services (space heating, water heating and cooking) represent the largest potential for decarbonising the buildings sector due to the mix of energy carriers (including electricity) that are used to satisfy their demand. Today's energy mix for satisfying these services still includes fossil fuels like natural gas, oil derivatives and coal. Space cooling, lighting and electrical appliances consume electricity as their main energy carrier, so the only way to truly decarbonise their consumption is by generating and using renewables electricity.

The buildings sector includes two subsectors: (1) residential and (2) commercial. The commercial subsector includes not only buildings used for commercial activities but also governmental ones. The residential subsector dominates the buildings sector's energy demand and is the one for which the current European framework establishes already specific decarbonisation targets by 2030 and 2035, such as the 16% reduction of energy use by 2030 and 20-22% by 2035 compared with 2020, as mandated in the Energy Performance of Buildings Directive (EU/2024/1275).

The buildings sector consists of several services: (1) appliances, (2) cooking, (3) lighting, (4) space cooling, (5) space heating, (6) water heating and (7) other uses.

The analysis conducted for this study showed that, to decarbonise the buildings sector, emphasis must be placed on heating services in the following descending order of priority: (1) space heating, (2) water heating and (3) cooking. Member States should then prioritise the service(s) they would like to focus on, depending on the availability of financial, technical and human resources. It is evident that addressing all three services simultaneously will yield the best results in the reduction of energy consumption, increasing energy efficiency and related emissions.

The increase in energy prices since 2022 has made it difficult for people to keep their homes warm during winter. While lowering energy bills for space heating remains essential for the well-being of the European population, it is only one dimension of a broader housing challenge. The Affordable Housing Task Force addresses a wider range of social and market issues, such as the mismatch between income and real estate prices, and the pressure from short-term rentals. Even if energy were free, these structural challenges would persist. Nonetheless, the decarbonisation of heating and cooling and improvements in energy efficiency are still crucial.

The decarbonisation of heating and cooling and an increase in energy efficiency are set as priorities in the Mission Letter to Dan Jørgensen, the Commissioner for Energy and Housing. Bringing down energy prices for households and businesses is also a key element of this Mission Letter and shall be achieved by the recently adopted Action Plan for Affordable Energy Prices[9] (European Commission, 2024j). This reduction is only possible by making households more energy efficient through better insulation and a transition to more efficient heating technologies that use renewable energy sources to operate. In this regard, the rapid deployment of heat pumps is crucial for decarbonising space heating in both subsectors wherever there is no grid for district heating.

[9] *Action Plan for Affordable Energy: Unlocking the true value of our Energy Union to secure affordable, efficient and clean energy for all Europeans - European Commission.*

Successful decarbonisation of the buildings sector depends on several factors, for example, the availability of the required technologies at affordable prices and a legal supportive framework that facilitates their rapid deployment in both subsectors. The legal framework is vital to achieve several targets, such as keeping the European Union competitive as a region for locally producing the required infrastructure, while simultaneously fostering job creation and securing a regional supply of the equipment needed to decarbonise the sector. All these elements will contribute to securing the sector's energy supply for the desired service.

Buildings in the European Union should become carbon neutral by 2050. This is a very ambitious target, especially because it involves the electrification of most of the heating services and the rapid renovation of existing buildings for greater energy efficiency. Electrification of the heating services will have impacts on the power sector, which will need to consider the expansion of the generation, transmission and distribution capacities to accommodate the additional electricity demand required by the buildings sector in the future. The buildings sector is a perfect example of why an energy system must be treated from a holistic perspective as it has implications on other areas too. The Energy Performance of Buildings Directive (EPBD) requires Member States to set out policies and measures for the gradual phase-out of fossil fuels in boilers in 2040.

Scenario analysis using the PES and DES indicates that a greater effort from the Member States is required if the EU wishes to be climate neutral by 2050. In this regard, the PES and DES capture the measures proposed in the EPBD 2024/1275 (European Commission, 2024l) for decarbonising the buildings sector but do not comprehensively include the forthcoming provisions proposed in the so-called building renovation plan (first draft) that must be submitted by each Member State by 31 December 2025. With the current policies and regulations, the buildings sector, under the PES, would still be responsible for approximately 112 Mt of CO_2 emissions in 2050, which is well above the 1 Mt of CO_2 proposed by the S3 scenario from the 2040 Climate Impact Assessment report. Reaching the emissions level proposed by the S3 scenario requires the almost complete elimination of fossil fuels by 2050, the electrification of heating services and improvements in energy efficiency through the renovation of buildings to reduce their thermal demand for space heating. In this regard, the DES reduces more emissions by 2050, at approximately 0.4 Mt, following the S3 scenario from the 2040 Climate Impact Assessment. Nevertheless, the targets of the Energy Performance of Buildings Directive (EU/2024/1275) are met under both scenarios in the residential subsector (16% reduction of energy use by 2030 and 20-22% by 2035 compared with 2020). In this regard, the PES achieves a reduction of 17% and the DES of 24% in 2030, whereas reductions of 22% and 31% are achieved, respectively, under the PES and DES by 2035.

The main regulations, directives, plans and strategies considered in the buildings sector analysis are presented in Table 4.1.

Table 4.1 Buildings: Regulations and relevant documents considered under the PES and DES

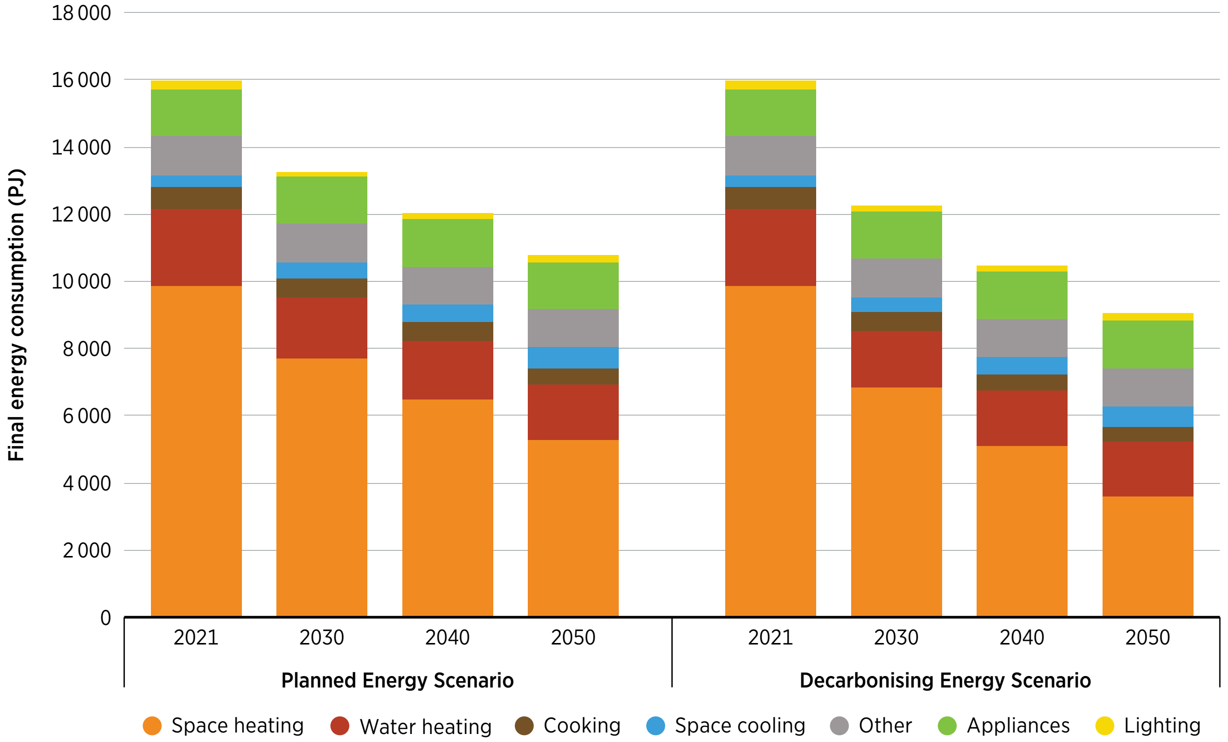
REGULATION / PLAN / STRATEGY	REFERENCE
• Directive (EU) 2023/2413 as regards to the promotion of energy from renewable sources (RED III)	(European Commission, 2023q)
• Energy Performance of Buildings Directive (EU/2024/1275)	(European Commission, 2024l)
• Energy Efficiency Directive (EU/2023/1791)	(European Commission, 2023r)
• Energy Taxation Directive (2003/96/EC)	(European Commission, 2023s)
• EU Strategy for Energy System Integration	(European Commission, 2020c)
• Ecodesign for Sustainable Products Regulation (EU 2024/1781)	(European Commission, 2024m)
• National Energy and Climate Plans	(European Commission, 2024n)
• Europe's 2040 Climate Target and Path to Climate Neutrality by 2050 • Commission staff working document • Impact Assessment report Part 3	(European Commission, 2024o)
• A Renovation Wave for Europe – Greening our Buildings, Creating Jobs, Improving Lives	(European Commission, 2020d)
• Directive on the Common Rules for the Internal Market for Electricity (EU 2019/944) • Article 19	(European Commission, 2019a)
• A Technical Analysis of FTT: Heat – A Simulation Model for Technological Change in the Residential Heating Sector	(Knobloch, 2017)
• EU Challenges of Reducing Fossil Fuel Use in Buildings	(Nijs *et al.*, 2021)
• Heating Market Report 2021 • Association of the European Heating Industry	(Association of the European Heating Industry, 2021)
• European Heat Pumps Market and Statistics 2022	(European Heat Pump Association, 2024)
• The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning	(International Energy Agency, 2018)
• Heat Roadmap Europe 2050: Space Cooling Technology in Europe	(Dittmann *et al.*, 2016)
• Heating Appliances Retrofit Planning. Deliverable 2.2: Building vs Heating Stock (Space and Water) Matrix, EU and Country Level	(Marchetti, 2019)
• Comprehensive Study of Building Energy Renovation Activities and the Uptake of Nearly Zero-Energy Buildings in the EU	(Hermelink *et al.*, 2019)
• The JRC Integrated Database of the European Energy System	(Joint Research Centre Data Catalogue, 2015)
• Country Profiles: Main Energy Efficiency Trends and Policies by Country. ODYSSEE-MURE	(ODYSSEE-MURE, 2024)

Notes: DES = Decarbonising Energy Scenario; EU = European Union; RED III = Renewable Energy Directive III; EC = European Commission; FTT = Future Technology Transformation; JRC = Joint Research Center; PES = Planned Energy Scenario.

4.2 BRIEF OVERVIEW OF THE BUILDINGS SECTOR

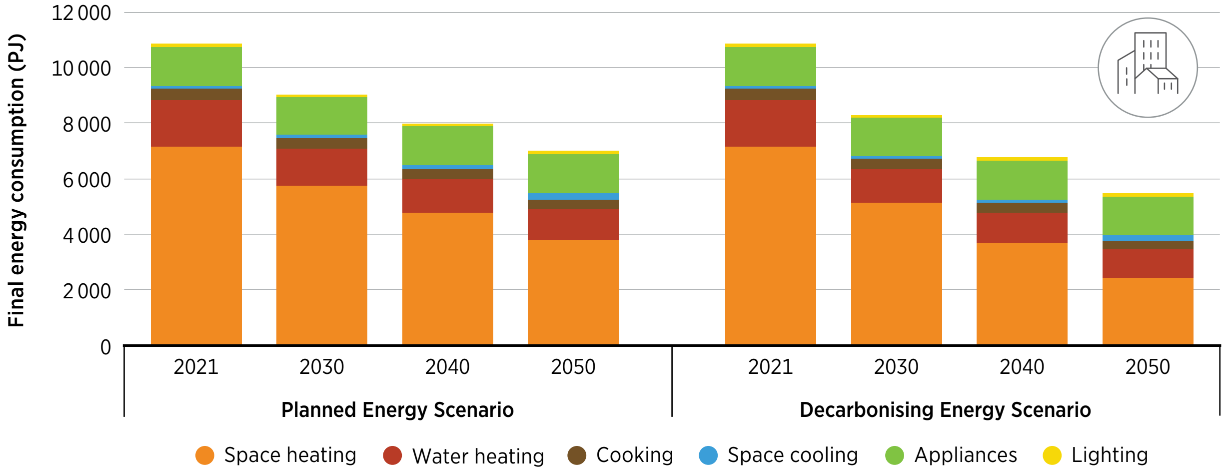
The buildings sector must undergo a deep transformation to become carbon neutral by 2050. This transformation is linked to energy consumption and associated emissions from services that utilise a mix of energy carriers to operate. In this regard, the decarbonisation potential is highest for heating services because (1) they consume the most energy among all services (space cooling, electric appliances, lighting and others), as shown in Figure 4.1 for the entire sector and in Figure 4.2 for each subsector, and (2) they consume a mix of energy carriers including fossil sources (*i.e.* coal, oil derivatives and natural gas). The potential for electrification is also highest for heating services, and electrification would contribute to their decarbonisation if renewable electricity is used to satisfy this new power demand. Concerning the remaining services, it is clear that they mostly consume electricity, leaving little room for their decarbonisation other than through renewable electricity.

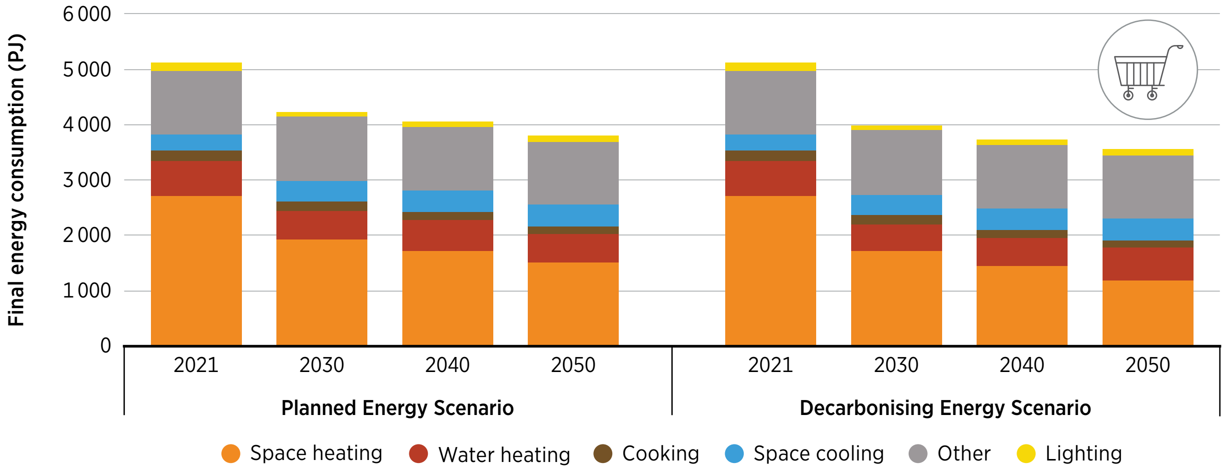
Figure 4.1 Buildings: Final energy consumption by service



Note: PJ = petajoule.

Figure 4.2 Residential (first) and commercial (second): Final energy consumption by service

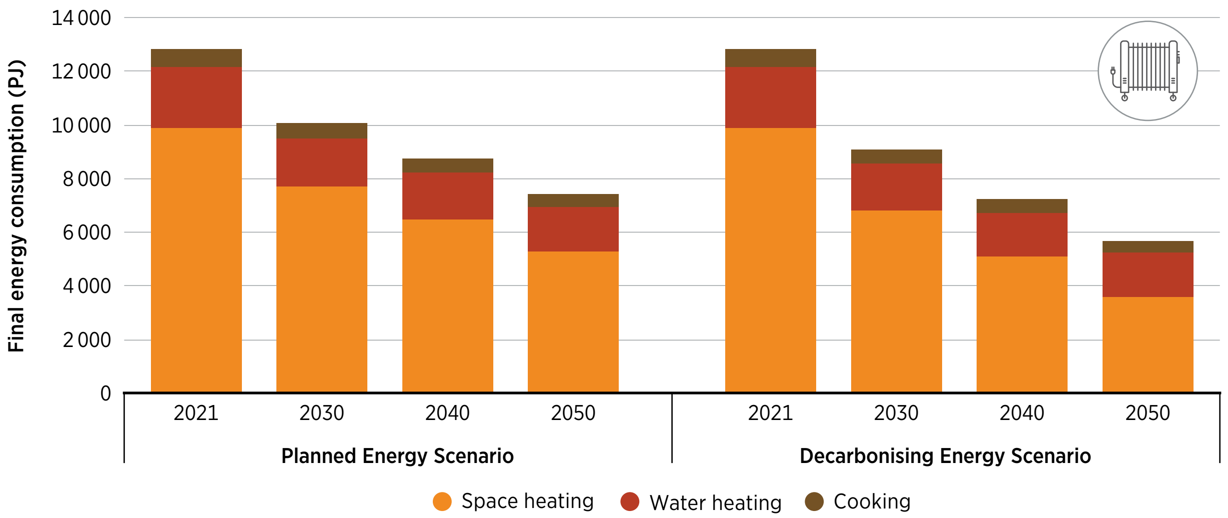




Note: PJ = petajoule.

Figure 4.3 presents the energy consumed by heating services. These services consumed up to 80% of buildings' energy use in 2021, with energy consumption declining to 69% and 63% in PES and DES, respectively, in 2050.

Figure 4.3 Buildings: Final energy consumption for heating services



Note: PJ = petajoule.

The main KPIs presented in Table 4.2 summarise the ongoing transformation of the buildings sector for both scenarios. As can be seen, the share of electricity under both scenarios increases with respect to 2021, reaching 47% in the PES and 60% in the DES by 2050. The difference in this share is mainly due to the higher electrification rate in the DES compared with the PES. The total share of renewables (direct plus indirect uses) also increases in both scenarios throughout the period, reaching 62% in the PES and 88% in the DES by 2050, due to the use of biomass, a biomethane blend in the gas grid and the increasing share of renewable electricity in the grid. Emissions reduce as a consequence towards 2050; almost zero emissions are reached under the DES, as indicated by the S3 scenario from the EU's 2040 Climate Impact Assessment. This is mainly because natural gas consumption in the DES is very small (29 PJ) compared with the PES by 2050 (1 608 PJ).

Table 4.2 Key performance indicators for the buildings sector

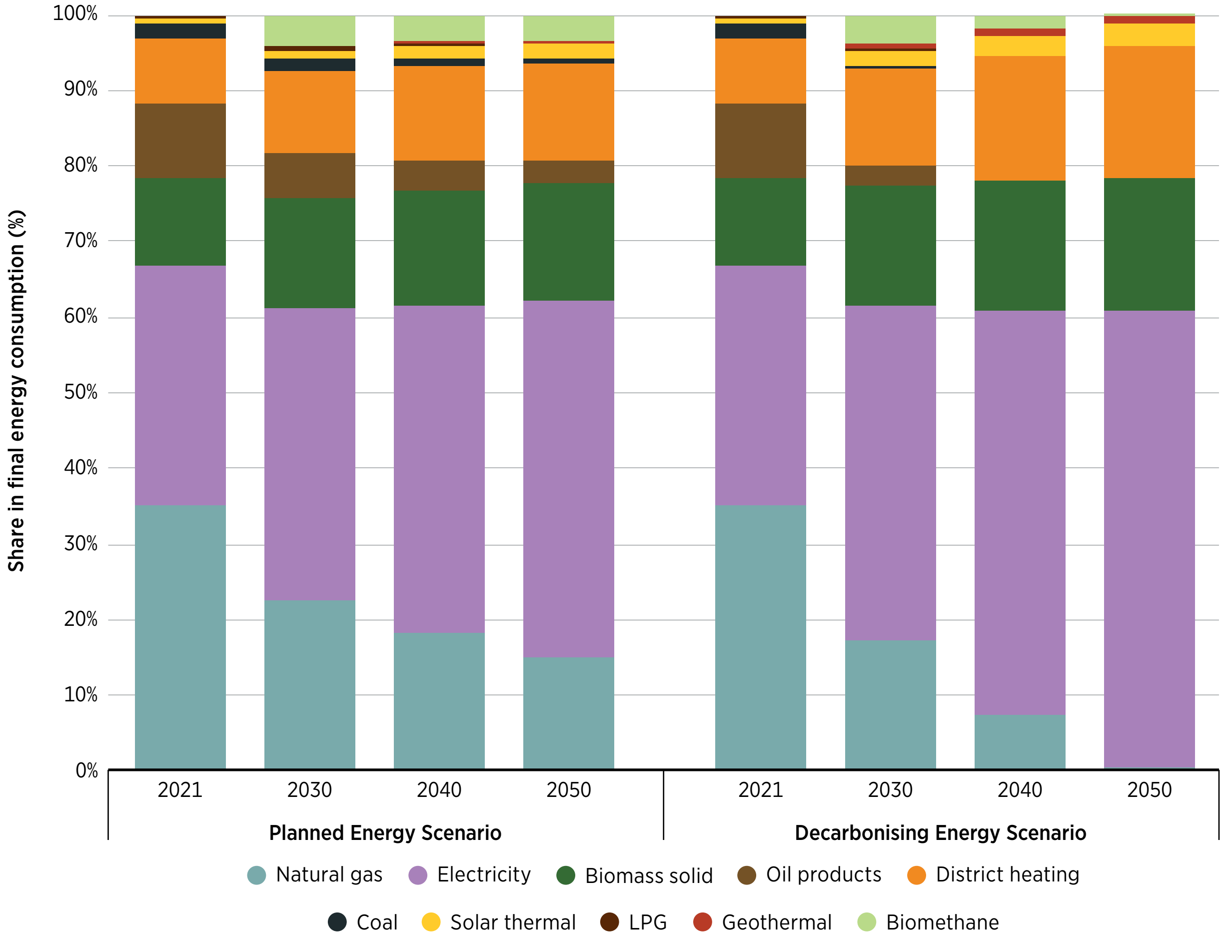
	HISTORICAL	PLANNED ENERGY SCENARIO			DECARBONISING ENERGY SCENARIO		
	2021	2030	2040	2050	2030	2040	2050
KPI.02 RENEWABLES							
Share of direct renewables (%)	12%	20%	21%	21%	22%	22%	21%
Share of direct and indirect renewables (%)	27%	52%	58%	64%	60%	79%	89%
District heat consumption (EJ)	1.4	1.5	1.5	1.4	1.6	1.7	1.6
KPI.03 ENERGY CONSERVATION AND EFFICIENCY							
Total final consumption (EJ)	16	13	12	11	12	10	9
KPI.04 ELECTRIFICATION IN END-USE SECTORS (DIRECT)							
Electricity share (%)	32%	39%	43%	47%	44%	53%	60%
KPI.05 CLEAN HYDROGEN AND DERIVATIVES							
Clean hydrogen consumption (PJ)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EMISSIONS							
CO_2 emissions with carbon capture and removal ($MtCO_2$/yr)	395	212	152	112	129	37	0.4

Notes: DES = Decarbonising Energy Scenario; EJ = exajoule; KPI = key performance indicator; $MtCO_2$ = million tonnes of carbon dioxide; PES = Planned Energy Scenario; PJ = petajoule . 'Direct' use of renewables includes all direct uses of renewable energy sources (bioenergy, solar and geothermal) to satisfy the sector's energy demand. It excludes the use of renewable electricity, renewable hydrogen and district heating. 'Indirect' use of renewables includes the use of renewable electricity, renewable hydrogen and district heating to satisfy the sector's energy demand. The sum of the direct and indirect use of renewables gives the total use of renewable energy in the sector.

4.3 ELECTRIFICATION OF HEATING SERVICES AND THE SECTOR

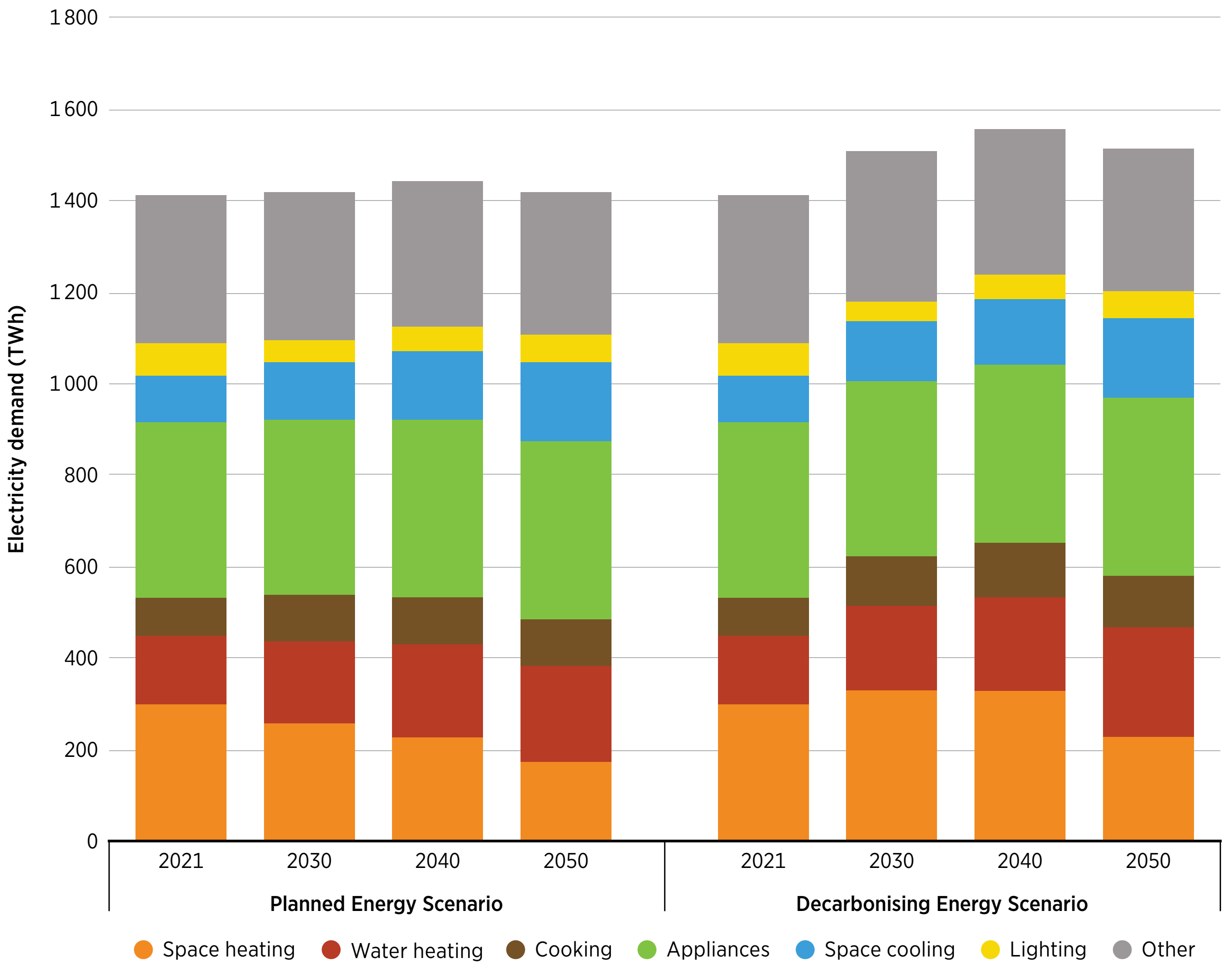
Because the energy demand of heating services is satisfied with a partial mix of fossil energy carriers (coal, natural gas, oil products, LPG), they represent the major decarbonisation potential in the buildings sector as they can be replaced with renewable energy sources. Electrifying the heating services would require that their energy demand is covered as much as possible with renewable electricity. In case this is not economically or technically possible (*e.g.* an old residential building where it is not technically possible to install a heat pump), then other renewable alternatives should be explored, such as biomass (sustainable) boilers or boilers using biomethane instead of natural gas. Figure 4.4 presents the energy carrier mix for the buildings sector. The shares of fossil energy carriers decrease over time until 2050 for both scenarios. Under the DES, the mix has almost no fossil carriers by 2050, mainly because heating services are electrified. A small share of natural gas (0.32%) is still present, which produces approximately 361 ktCO_2.

Figure 4.4 Buildings: Shares of final energy consumption by carrier



The electrification of heating services can also be seen in Figure 4.5, which shows a 60% share of electricity in energy consumption under the DES by 2050, compared with 47% under the PES by 2050. This represents an average yearly electrification rate of 0.27% under the DES compared with 0.01% under the PES between 2025 and 2050. The higher electrification rate in the DES will help reduce the demand for fossil fuels (mainly natural gas) in heating services at a faster rate compared with the PES. This will positively impact the sector's emissions, which will reach nearly zero under the DES by 2050. Nevertheless, this emissions reduction depends on the shares of renewable electricity in the power system. Figure 4.5 summarises the electricity demand under each scenario per decade and shows that the electrification of heating services contributes to a growth of electricity consumption in both scenarios between 2021 and 2040. However, the greater thermal efficiency of buildings and thus a reduction of the thermal energy demand contributes to electricity consumption declining over 2040-2050.

Figure 4.5 Buildings: Electricity demand for all services



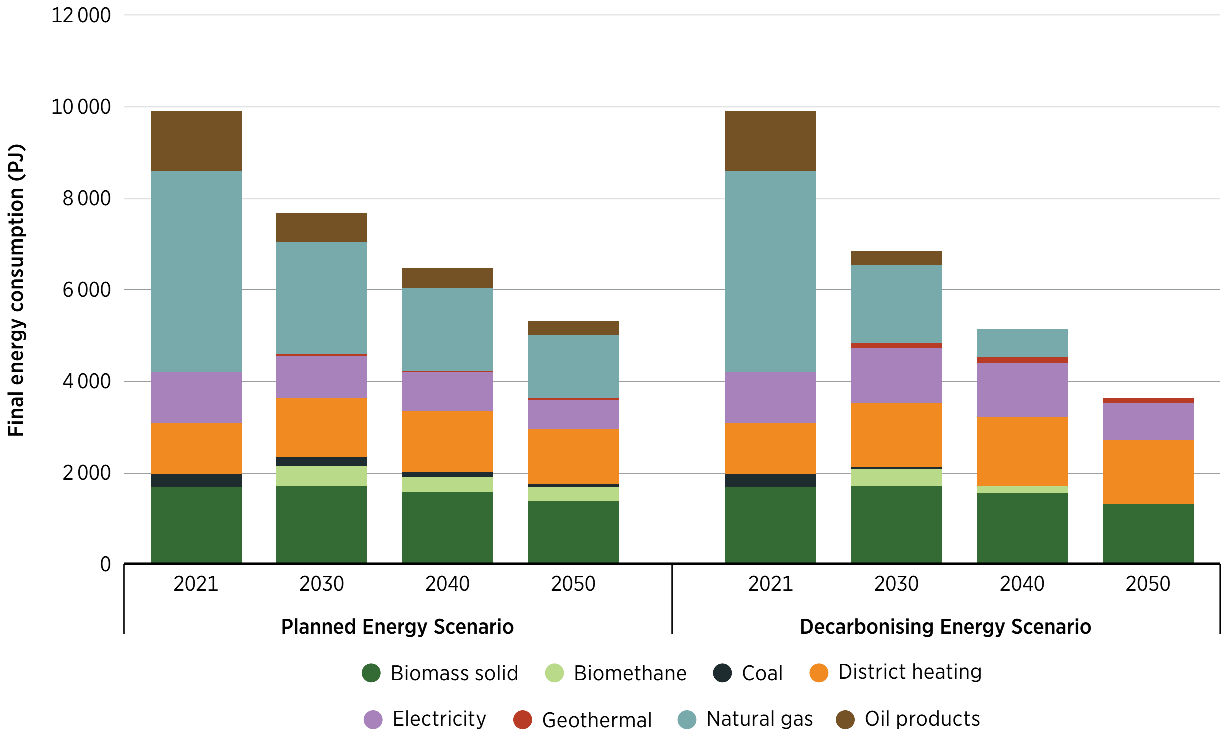
Note: TWh = terawatt hour.

4.4 SPACE HEATING

The role of space heating in the energy demand from heating services is evident from Figure 4.3. Space heating accounts for 64% of the energy consumed by heating services under the DES by 2050, whereas under the PES, it represents 71% by 2050. Water heating follows, with 28% and 22% in the DES and PES, respectively. The decarbonisation potential of space heating lies in the fact that it uses a mix of energy carriers to satisfy its present demand, which could be replaced by other carriers, such as biomethane and renewable electricity (*i.e.* heat pumps).

Figure 4.6 presents the energy consumption by energy carrier for space heating. It can be seen that the use of fossil fuels declines under both scenarios, but DES completely phases out the use of coal by 2040 and drastically reduces natural gas by 2050. This is due to the strong electrification of this service using heat pumps, while biomass use and district heating are maintained.

Figure 4.6 Buildings: Final energy consumption for space heating by carrier



Note: PJ = petajoule.

4.5 SPACE COOLING

Space cooling mainly utilises air-conditioning units, which are powered by electricity. Decarbonisation options for this service are therefore limited due to the constraints in the energy carrier choices available. As it can be seen in Figure 4.1, the energy required for space cooling almost doubles under the DES by 2050 (614 PJ) over that under the PES by 2021 (368 PJ). This represents an increase from 2% to 7% in the sector's final energy consumption. In terms of the sector's electricity demand, the share of space cooling sees growth, from 8% in 2021 to 11% in the DES by 2050. This growth represents an additional 58 TWh that will be consumed by air-conditioning units in 2050. Thus, the main way to decarbonise this service is by increasing buildings' energy efficiency, so as to minimise the cooling load, and by producing more renewable electricity, to satisfy the growing space cooling demand.

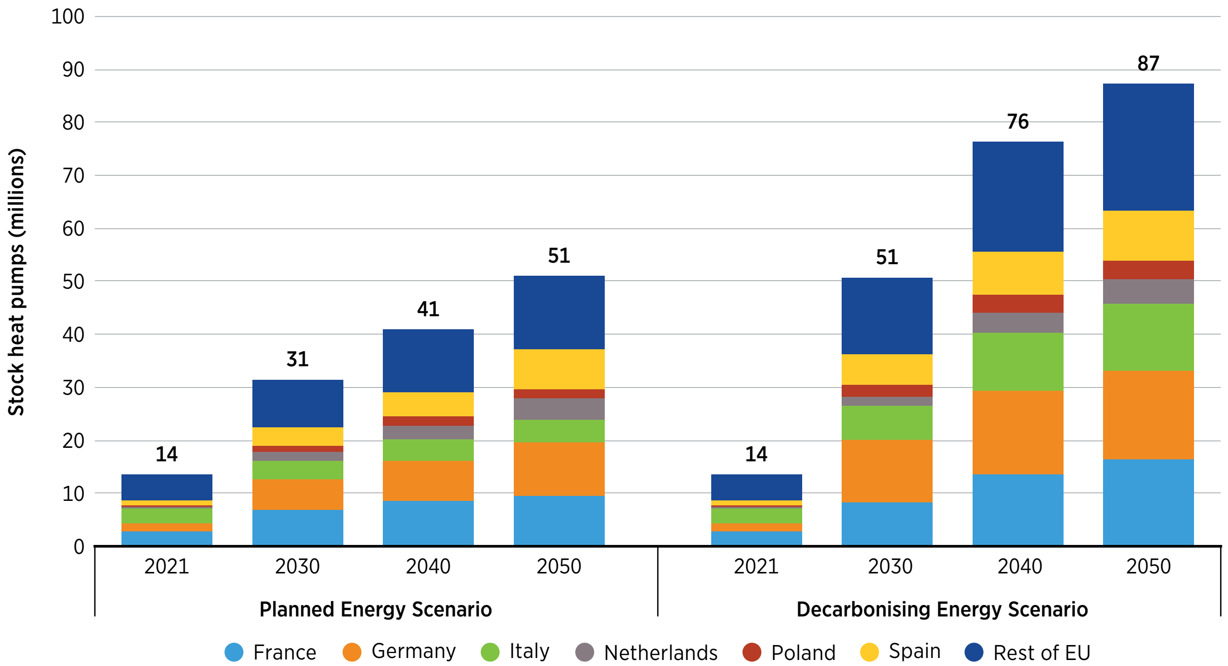
4.6 THE ROLE OF BIOMETHANE AND HEAT PUMPS

Biomethane is chemically identical to natural gas and hence a perfect replacement for it. Considering the EU target of producing 35 billion cubic metre (m^3) of biomethane annually by 2030 (European Commission, 2023t), from the REPowerEU Plan, a blend of natural gas with biomethane was considered in the analysis of both scenarios for reducing natural gas consumption while simultaneously complying with the aforementioned target. In this regard, the EU should consider scaling up the production of biomethane and its injection into the natural gas grid so that it is able to partially satisfy the natural gas demand in the buildings sector. This is especially true for buildings where the installation of heat pumps is not technically feasible due to the additional work that is needed for installing ducts for transporting the heat generated by the heat pump (*e.g.* old residential buildings).

The use of biomethane is relevant for the heating services, especially for space and water heating because both services consume mainly natural gas when boilers are used. The use of biomass for cooking will likely disappear in the future in favour of electric stoves. While it is acknowledged that gas boilers will not be used anymore under the DES by 2050, their role is important as a bridge technology for decarbonisation through the use of a blend of biomethane with natural gas. The analysis showed that the consumption of biomethane will decrease over the years mainly because gas boilers (for space and water heating) will be retired in favour of the electrification of these heating services. In terms of solid biomass, the DES considers it as a renewable energy source that, while not as efficient as a heat pump for space heating, certainly does not have the emissions released by a fossil energy carrier. In this regard, the DES still considers the use of biomass for some heating services (mainly space heating and water heating) in some countries even in 2050, in combination with other efficient technologies, such as district heating and heat pumps.

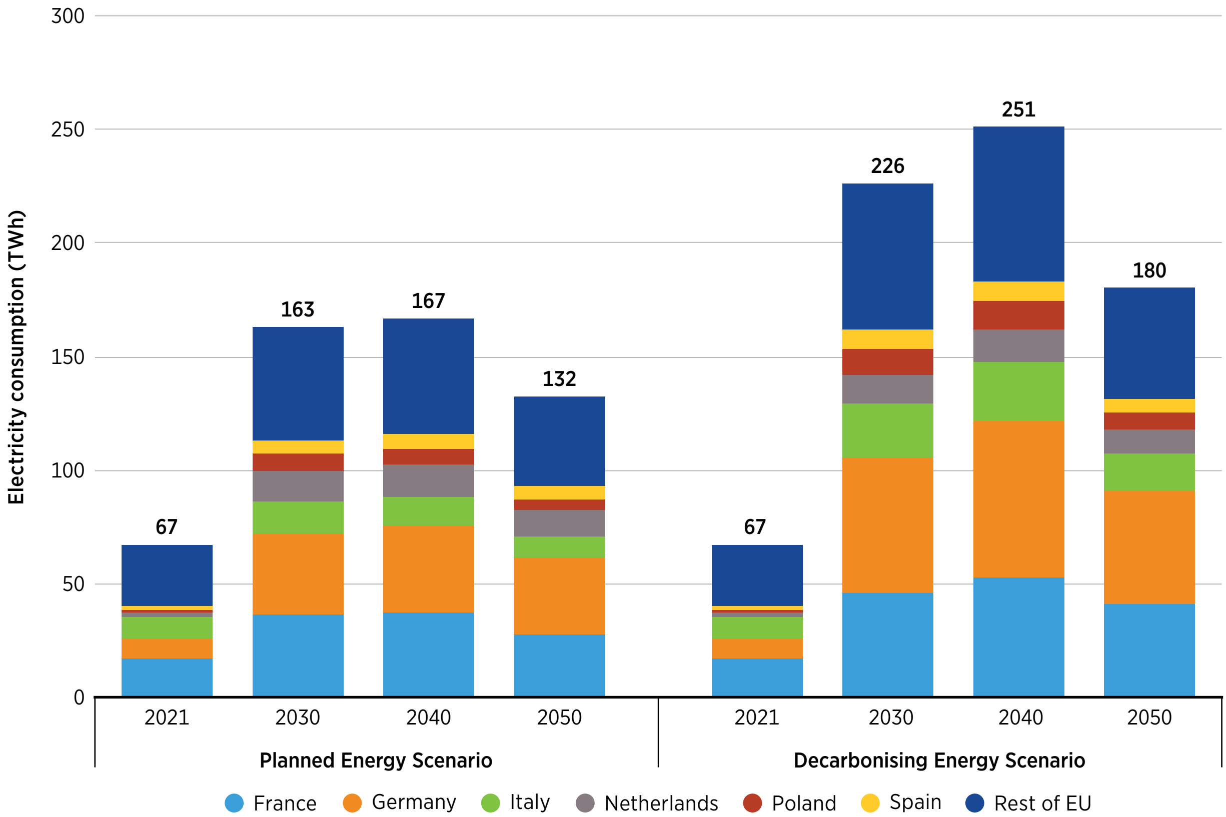
While the use of heat pumps for space heating helps decarbonise the energy demand for space heating, it is faster under the DES, where this technology is adopted at a higher rate, as shown in Figure 4.7. Between 2025 and 2050, heat pumps are adopted at a yearly rate of 5% and 7% under the PES and DES, respectively. Nevertheless, to comply with the EPBD's target of decreasing the average energy performance of the residential building stock by 16% by 2030 over that in 2020, the yearly adoption rate increases to 15% under the PES and 25% under the DES on average for the entire European Union.

Figure 4.7 Buildings: Heat pump stock



The electricity consumed by heat pumps in the buildings sector follows the same increasing trend as the heat pump stock under both scenarios; that is, electricity consumption and stock increase continuously between 2021 and 2040. From 2040 onwards, the trend is the opposite for the electricity demand under both scenarios, as shown in Figure 4.8. This is because buildings become more energy efficient so that their thermal energy demand reduces from 2040 onwards. Energy consumption grows at an average yearly rate of 17% under the PES and 23% under the DES between 2025 and 2030. This is something that must be carefully considered from both financial and technical perspectives because buildings must be adapted to accommodate heat pumps and the power grid must also have sufficient capacity to generate, transmit and distribute the additional electricity demand in the future.

Figure 4.8 Buildings: Electricity consumed by heat pumps

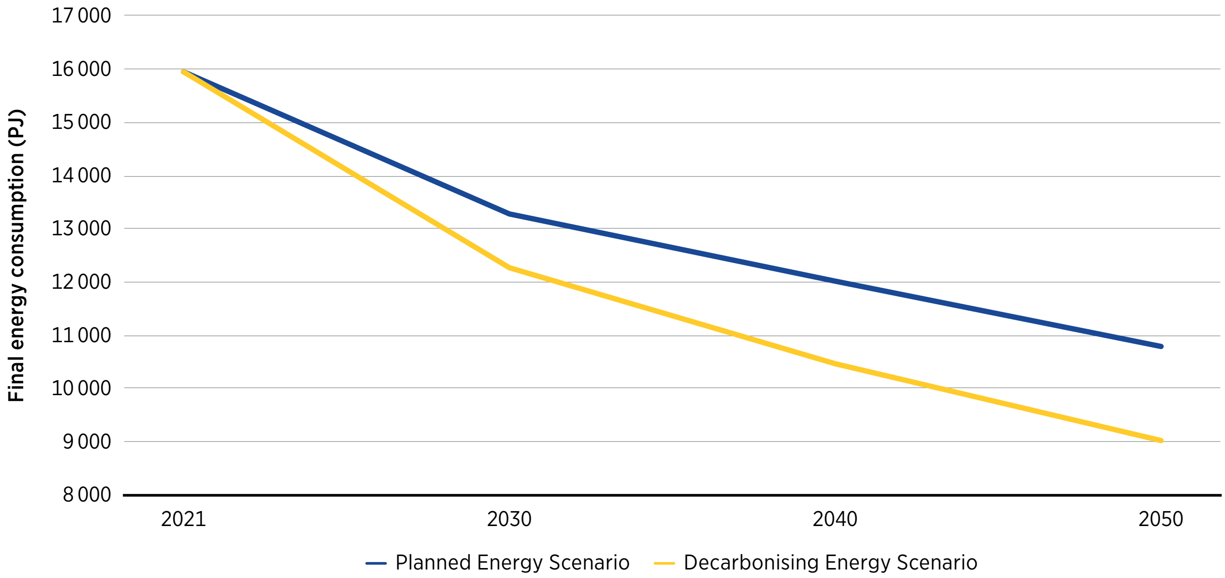


Note: TWh = terawatt hours.

4.7 ENERGY EFFICIENCY

Electrification of heating services is not the only way to decarbonise the buildings sector. Improvements in the energy efficiency of the building envelope must be combined with improvements in technology for a given service. In this regard, we can see a reduction of energy consumption in the buildings sector between 2021 and 2050 for the PES and DES as shown in Figure 4.9. The difference between the scenarios is due to a higher renovation rate and the introduction of a higher share of heat pumps for space heating under the DES. Relative to 2021, the energy savings by 2030 account for 8% under the PES and 17% under the DES, and in 2040 they are of 25% under the PES and 34% under the DES. Achieving the net-zero target in the buildings sector by 2050 requires 43% energy savings relative to the consumption in 2021, more than the 32% savings under the PES. Reaching these levels of energy savings in the DES requires an annual average reduction rate of 2.6% by 2030, 2.1% by 2040 and 1.9% by 2050 relative to the consumption in 2021. The percentage efficiency improvements reduce over time as higher impact efficiency measures are prioritised for implementation first with lower yielding measures subsequently implemented.

Figure 4.9 Buildings: Final energy consumption

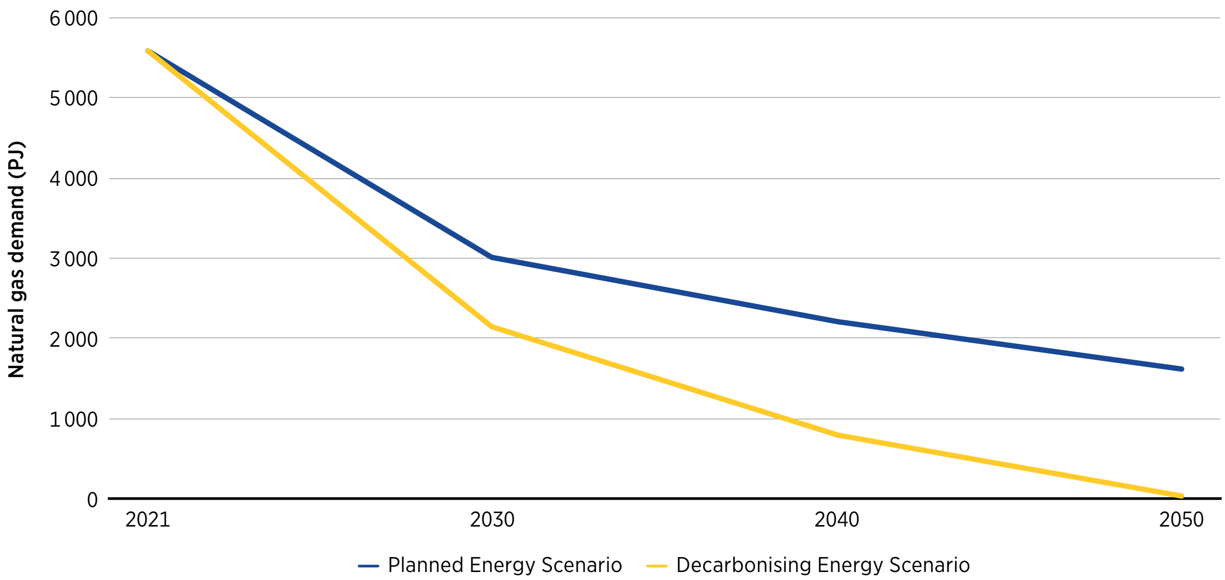


Note: PJ = petajoule.

4.8 THE ROLE OF NATURAL GAS IN THE BUILDINGS SECTOR

The reduction of natural gas imports is paramount for the European Union. Figure 4.10 presents the natural gas consumption in the buildings sector. It can be seen that the trend towards 2050 is negative. The difference between the scenarios in 2050 is due to several factors, such as greater electrification of heating services (mainly space heating and water heating), the use of biomethane in the gas grid and the reduction of the thermal demand for space heating (due to better thermal insulation of buildings). In this regard, the natural gas demand declines at an average yearly rate of 16% under the DES compared with 4% under the PES. This translates to a demand of 1 608 PJ in the PES and 29 PJ in the DES in 2050. Finally, in the PES, 3 005 PJ and 2 206 PJ of natural gas are consumed by 2030 and 2040, while 2 134 PJ and 788 PJ are consumed by 2030 and 2040 in the DES, respectively.

Figure 4.10 Buildings: Natural gas demand



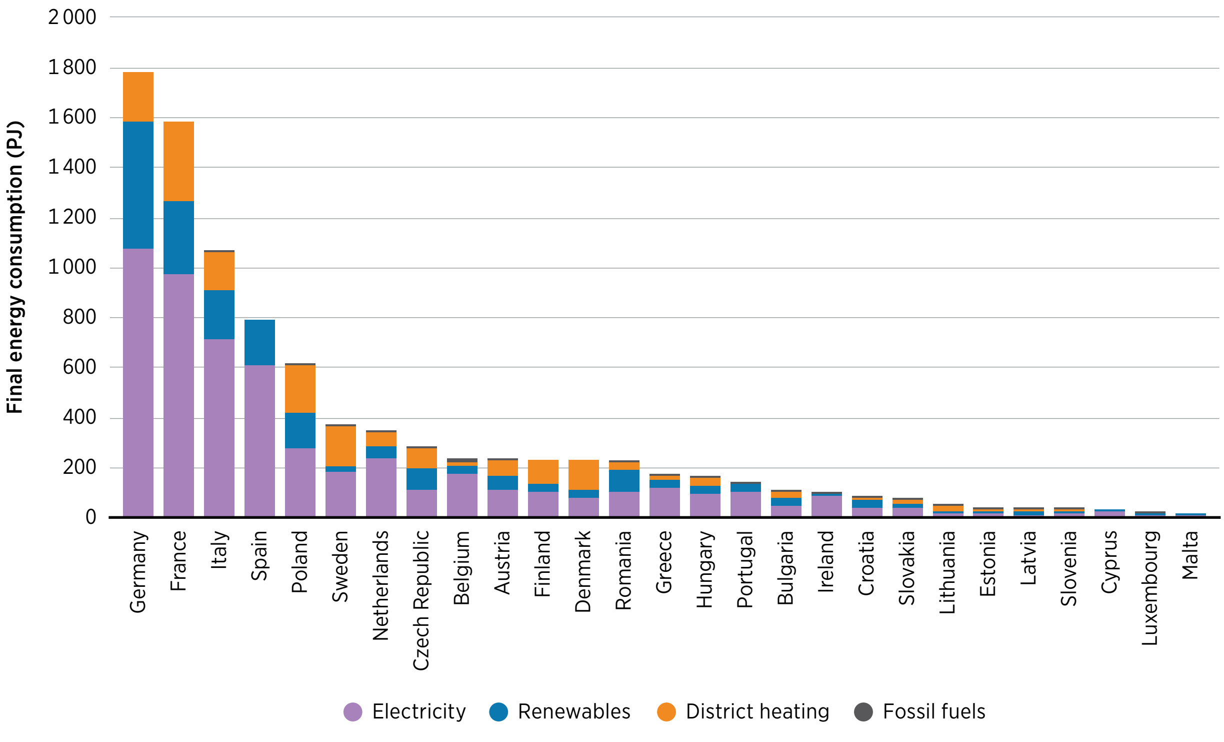
Note: PJ = petajoule.

4.9 RENEWABLE ENERGY IN THE BUILDINGS SECTOR

The share of renewables (direct plus indirect uses) increases under both scenarios. Renewable electricity used in the sector is accounted for in the indirect uses of renewables. The PES reaches a share of 41% in renewable electricity compared with 67% in the DES by 2050. The total share of renewables in the buildings sector reaches 62% in the PES, compared with 88% in the DES, by 2050. The difference between the scenarios is due to the use of biomethane and the electrification of heating services, together with an increasing share of renewable electricity in the European power system.

Figure 4.11 presents a breakdown of final energy consumption under the DES by 2050, highlighting the share of renewables in the buildings sector by country. A small fraction of fossil energy is natural gas, which remains for water heating and cooking (29 PJ in total). Natural gas will no longer meet the thermal demand for space heating in 2050. This has a direct impact on the significant reduction of the sector's emissions of 0.4 Mt. Regarding renewable energy consumption in the buildings sector under the DES by 2050, Germany (506 PJ), France (290 PJ), Italy (200 PJ), Spain (188 PJ) and Poland (139 PJ) are the largest consumers in the European Union.

Figure 4.11 Buildings: Final energy consumption by Member State in the DES, 2050



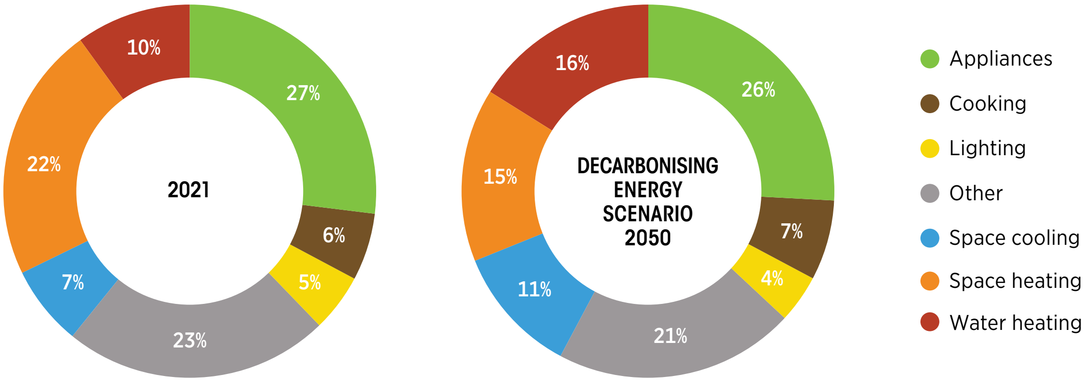
Notes: DES = Decarbonising Energy Scenario; PJ = petajoule.

4.10 ELECTRIC APPLIANCES, LIGHTING AND COOLING

The future energy demand of other services such as space cooling is also important to address, even though it does not contribute as much to the final energy consumption when compared with heating services. Space cooling is a service that mostly utilises air-conditioning units, which use electricity as an energy carrier to operate. The only options for decarbonising this service are the use of renewable electricity, installation of efficient air-conditioning units and improvement of the buildings' thermal insulation. As can be seen from Figure 4.12, the share of space cooling in electricity consumption increases from 7% in 2021 to 11% under the DES by 2050. This represents an increase of 58 TWh in the electricity demand from air-conditioning units.

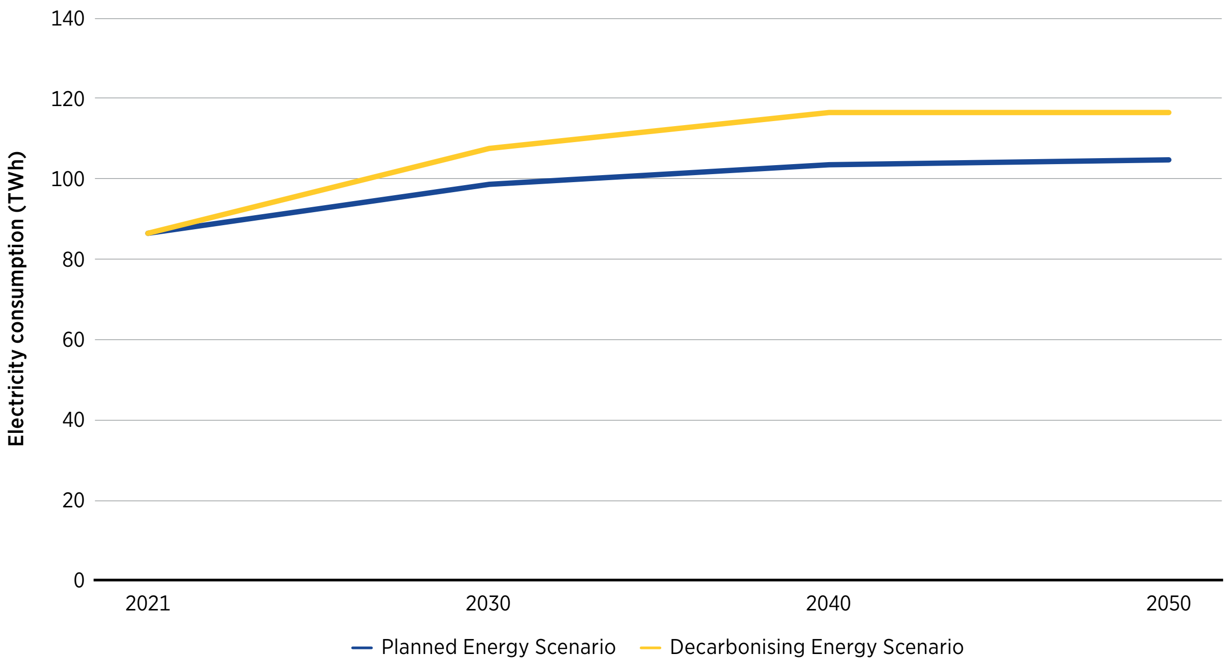
Even if the electricity powering the air-conditioning units is not renewable, Member States must be prepared to adapt their power sector to accommodate the additional electricity demand that will be produced by the increasing use of air-conditioning units in buildings. This is due to an increase of cooling degree days in the future, the combined effect of more hours of cooling, a higher ownership rate and an increase of floor area in the residential subsector. It is important to stress that the electricity used for operating air-conditioning units must be produced with renewables; otherwise, a vicious cycle will be created, where high ambient temperatures lead to an increased use of grey-electricity-powered air-conditioning units, which in turn leads to climate change.

Figure 4.12 Buildings: Share of electricity consumption by service in 2021 and 2050



Another topic that is relevant to address is the electrification of the cooking service. While it represented 6% in 2021 and increases to 7% under the DES by 2050 of the sector's electricity consumption, its additional electricity demand (30 TWh) must be compensated by the power sector. The yearly average electrification rate for cooking is 0.77% and 1.2%, respectively, under the PES and DES between 2025 and 2050. This represents a difference of 11 TWh between the scenarios in 2050, as shown in Figure 4.13.

Figure 4.13 Buildings: electricity consumption for cooking



Note: TWh = terawatt hours.

Finally, as can be seen in Figure 4.12, the share of electricity consumption of appliances increases 1% between 2021 and 2050 in the DES, representing a difference of 6.4 TWh. This increase in electricity demand is due to an increase of floor area in the residential subsector and higher ownership of appliances. Nevertheless, the increase in electricity demand is limited by the higher efficiency level of the equipment used. For lighting, the share in electricity consumption decreases by 1%. This represents a reduction of 18 TWh under the DES by 2050 compared with 2021, and results from the increased efficiency of lighting technology despite the increase of residential floor area.

Future electrical appliances must be designed following the Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2024m) to accelerate the transition to a circular economy mode. The circularity, energy performance, recyclability and durability of the appliances used in buildings will have to be improved. Following the ESPR will, among other benefits:

1. Make products more energy and resource efficient;
2. Increase the products' recycled content;
3. Make products easier to remanufacture and recycle;
4. Improve products' durability, reusability, upgradability and reparability; and
5. Increase the possibility of product maintenance and refurbishment.

In this regard, the Digital Product Passport proposed by the ESPR will make it easier and more transparent for consumers, manufacturers, and authorities to make more informed decisions related to sustainability, circularity and regulatory compliance.

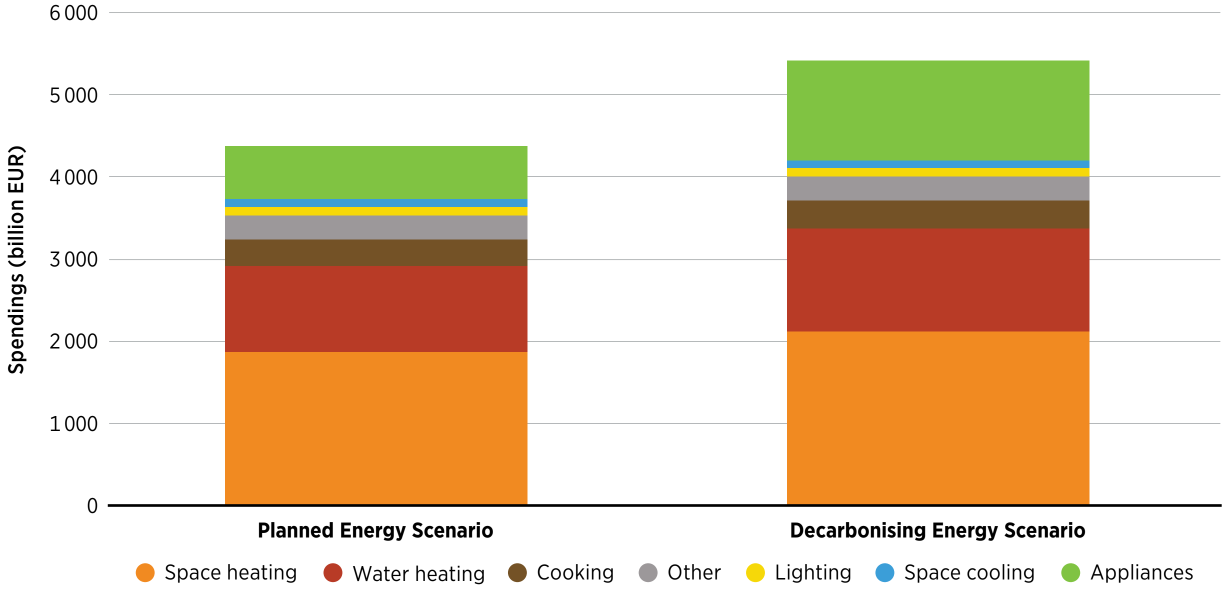
4.11 INVESTMENT IN BUILDINGS

The energy transition of the EU buildings sector, as envisaged in the PES and DES, with its ambitious targets, would require significant efforts in spending and investments from homeowners, commercial businesses and other actors. Key measures, as previously stated, involve greater electrification of all heating end uses in combination with improvement of the thermal efficiency of buildings' envelopes through increased renovation.

Overall spending on end uses, including for heating/cooling devices, electric appliances and lighting, is expected to reach EUR 4.4 trillion and EUR 5.4 trillion in the PES and DES, respectively, in cumulative terms over 2025-2050. This is equivalent to approximately 25% and 31% of the 2023 EU GDP, respectively.

Figure 4.14 presents a breakdown of sectoral spending by end-use service over 2025 to 2050. In both scenarios, the measures implemented in heating would absorb approximately two-thirds of the overall spending in buildings, despite higher ambitions achieved under the DES mainly through massive adoption of heat pumps. Transitioning towards highly efficient appliances leads to EUR 1.2 trillion in spending under the DES, approximately 50% more than in the PES, and representing 15% and 22% of the overall cumulative spending in the PES and DES, respectively. Lastly, as increased cooling degree days and floor area drive up cooling needs across Member States, more air-conditioning units are installed over time, representing 2% of the overall spending in both scenarios.

Figure 4.14 Buildings: Cumulative end-use spending, 2025-2050

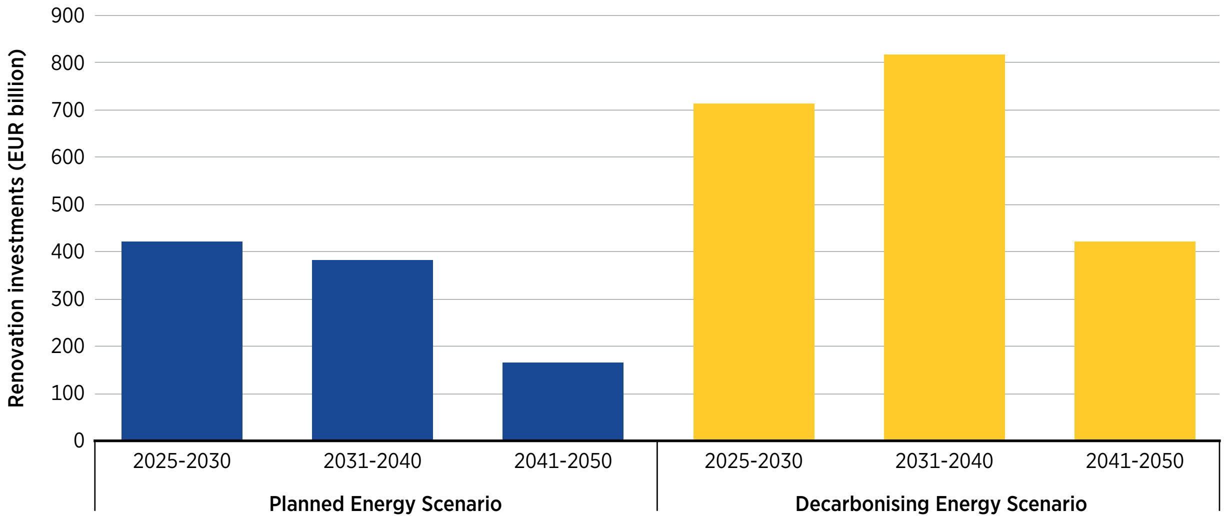


Note: EUR = Euros.

Achieving the list of measures outlined under the DES requires a set of instruments to facilitate a successful transition, mainly related to financing for final consumers (considering the local income level), as well as addressing the specific energy requirements of individual buildings.

Regarding renovation, residential and commercial buildings will require different efforts, considering the share of stock targeted and renovation level (from light to deep), as can be seen in Figure 4.15. Under the PES, aligned with current policies, renovation investments increase up to 2030, following which renovation rates as well as upgrade levels follow a downward trend, requiring an average of EUR 37 billion/year up to 2050. Under the DES, yearly investments almost double compared with those under the PES (EUR 75 billion/year) because a much more ambitious pathway is pursued; the share of building stock targeted expands and the level of renovations grows until 2040. Improvement of buildings' insulation leads to EUR 969 billion in cumulative spending in the PES and EUR 2 trillion in the DES between 2025 and 2050. These cumulative investments represent 6% and 11% of 2023 EU GDP in the two scenarios.

Figure 4.15 Buildings: Renovation investments by scenario and decade



Note: EUR = Euros.

The process of gradually enhancing the entire EU building stock would not be timely and efficiently achieved without the required workforce and construction services, and without facilitating institutions that will make plans a reality. In line with the required efforts, instruments such as the Renovation Wave Strategy (European Commission, 2020d) defined by the European Union deliver a common framework for building renovation, defining key actions and timelines for effective deployment in each Member State. The Strategy acknowledges that renovation requires labour; creates jobs and draws investments, often to the benefit of local supply chains; generates demand for equipment that is highly energy and resource efficient; and brings long-term value to properties. It further recognises that, by 2030, the European Union could see an additional 160 000 green jobs created in the construction sector through a renovation wave. This can be valuable for a sector where more than 90% of the operators are small and medium enterprises, which were hit hard by the economic impact of the COVID-19 crisis.

According to the European Commission, offering private financing jointly with innovative renovation services will be an increasingly attractive business proposition. In this regard, energy service companies, utilities and private banks can support property owners with ideas and financing in all phases of the renovation process. They can also promote the aggregation of small projects, offer favourable conditions for complex projects with long payback times, and gather the stakeholders involved in making decisions related to the renovation of buildings.

The overall transformation of the buildings sector towards carbon neutrality, therefore, would require a combination of efforts including (1) clean and efficient end-use technologies, (2) investment in building renovation and (3) an appropriate legal and regulatory framework that promotes affordable financing. This translates into a requirement of EUR 205 billion a year on average under the PES (18% share for renovation), which escalates to EUR 283 billion/year under the DES due to higher levels of renovation (27% share for renovation). In this regard, the EU funding programmes (*e.g.* Regional Development Fund, Cohesion Fund and Social Climate Fund) are good sources of funding for ensuring a just energy transition in the buildings sector while aligning with the EU funding priorities and not affecting vulnerable households.

Table 4.3 Key actions and priorities in the buildings sector

OUTCOMES	CURRENT REGULATIONS, DIRECTIVES OR PROPOSALS	ADDITIONAL MEASURES AND ACTIONS SUGGESTED
Reduce energy consumption in the national residential building stock beyond 16% by 2030 and beyond 22% by 2035, relative to 2020.	Energy Performance of Buildings Directive (EU/2024/1275)	• Provide additional incentives for making buildings more energy efficient through higher renovation rates and the electrification of heating services.
		• Create skills development and training programmes to build a skilled workforce capable of delivering large-scale building renovation and energy efficiency projects.
An annual heat pump adoption rate of 7% between 2021 and 2050 DES compared with 4% PES to decarbonise the buildings sector by 2050. An annual heat pump adoption rate of 13% between 2021 and 2030 under the DES compared with 6% under the PES for complying with the energy performance targets for the residential sector in 2030.	Energy Performance of Buildings Directive (EU/2024/1275)	• Create affordable financing mechanisms and business models for financing the rapid adoption of heat pumps in both subsectors, with special emphasis on the residential subsector.
		• Create an awareness-raising campaign targeting homeowners that conveys transparent information on the advantages of substituting their current heating system with a heat pump. Clarify that due to the technology's nature, heat pumps consume less energy than other technologies such as gas boilers or even electric heaters. This translates into lower costs for households with the right electricity-gas price ratio.
		• Create skills development and training programmes for installers, and increase productivity of installations.
		• Reduce the retail price ratio between electricity and gas.
Reduction in the consumption of natural gas by 2050: 1 921 PJ under the PES versus 160 PJ under the DES, resulting in a difference of 92% between the scenarios.	N/A	• Increase the consumption of biomethane by gradually substituting natural gas with it. This is conditioned to the scale-up of biomethane production and its injection into the natural gas grid.
		• Gradually phase out stand-alone gas boilers (conventional and efficient/condensing) and replace them with heat pumps for space heating, even if they partially use biomethane to operate.
Decarbonisation of space heating through a complete phaseout of fossil-fuel-driven boilers by 2040.	Energy Performance of Buildings Directive (EU/2024/1275)	• To completely phase out fossil fuel boilers by 2040, subsidies must end for stand-alone units from 1 January 2025, and a ban on future sales of fossil fuel boilers should be implemented. Additionally, the service provided by these units must be replaced with heat pumps and, wherever possible, by expanding the district heating network.
Specific targets for the deployment of solar photovoltaic and solar thermal equipment on the rooftops of buildings (residential and non-residential), as highlighted by Article 10 (3) of the EPBD.	Energy Performance of Buildings Directive (EU/2024/1275)	• Article 10 (3) of the Energy Performance of Buildings Directive includes some targets for the deployment of solar energy installations that are based on the floor area for non-residential buildings (including public buildings).
		• To improve the decarbonisation efforts, it is advisable that Member States refine those targets, taking into account their national circumstances, with objectives in installed capacity based on their annual energy consumption, both electric and thermal. Solar photovoltaic and solar thermal technologies must be a part of those objectives.

Notes: DES = Decarbonising Energy Scenario; EPBD = Energy Performance Buildings Directive; EU = European Union; PES = Planned Energy Scenario; PJ = petajoule; PV = photovoltaics.

5

THE POWER SECTOR AND GREEN HYDROGEN

KEY FINDINGS

★ **Total renewable capacity nearly triples by 2030, quadruples by 2040 and expands more than five-fold by 2050 (relative to 2021) in the DES.** Capacity grows from 491 GW in 2021 to nearly 1 250 GW by 2030 in both scenarios marking a crucial step towards the achievement of tripling renewables capacity. By 2050, renewables capacity reaches 1 993 and 2 456 GW, respectively, in the PES and DES, highlighting the significant investment needs in solar and wind power. This growth in capacity, corresponds to reaching a renewable power generation capacity share of 79% by 2030 in both scenarios, 87% and 91% by 2050 in PES and DES respectively, which is a significant increase beyond the 2021 share of 52%. This massive renewable capacity expansion represents a significant market opportunity for EU-based manufacturers of solar PV, wind turbines, and related components, directly supporting the objectives of the Net-Zero Industry Act to build domestic clean technology industries and enhance EU competitiveness in these strategic sectors.

- ★ **Variable renewable energy (VRE) capacity as a percentage of total capacity increases from 37% in 2021 to 70% by 2030 (in the PES and DES) and reaches 84% in the DES by 2050**. Renewables will account for about 70% of electricity generation by 2030 in the PES and DES, up from 37.8% in 2021. By 2050, this share grows to 78% (PES) and 88% (DES).
- ★ **Coal-fired generation decreases from about 450 TWh in 2021 to 18 TWh in the PES by 2050, while a complete coal phaseout is achieved by 2040 in the DES. Nuclear power, a stable low-carbon resource, declines moderately over the period,** falling from approximately 750 TWh in 2021 to 617 TWh (PES) and 522 TWh (DES) by 2050. As VRE increases, nuclear power faces growing operational challenges, including greater flexibility needs in operation and economic pressure from intermittent energy sources, necessitating a careful assessment of its role in the future energy mix.
- ★ **System flexibility is a key avenue of focus for policy makers.** Grid deployment, energy storage, demand-side management (DSM) and sector coupling can help ensure system flexibility, linking electricity with heating, cooling and transport. Natural gas underpins system reliability during periods of low renewables-based generation.
- ★ **Solar photovoltaic (PV) capacity grows exponentially, tripling by 2030 from 161 GW in 2021 to 651 GW.** By 2050, it dominates the renewable mix, reaching 1 443 GW under the DES, solidifying its role as the largest renewable technology. Solar PV also dominates renewable technology investments, reaching EUR 273 billion (2025-2030) under both scenarios, then declining to EUR 205 billion (DES) and EUR 140 billion (PES) for 2031-2040, and culminating at EUR 262 billion (DES) and EUR 217 billion (PES) by 2050.
- ★ **Wind capacity shows robust growth.** Onshore wind capacity rises from 173 GW in 2021 to 349 GW by 2030, further increasing to approximately 515 GW by 2050 under both scenarios. This growth requires over EUR 200 billion (2025-2030) in investments across both scenarios, increasing sharply under the DES to EUR 163 billion (2031-2040) and EUR 275 billion (2041-2050). Offshore wind expands rapidly, growing from 15 GW in 2021 to about 100 GW by 2030, with levels reaching 216 GW (PES) and 303 GW (DES) under 2050, highlighting offshore wind's pivotal role in decarbonisation. Cumulative investments in offshore wind total EUR 225 billion (2025-2030), EUR 306 billion (2031-2040) and EUR 421 billion (2041-2050) under the DES, highlighting the high capital requirements for deep-sea infrastructure.
- ★ **Hydropower remains a stable contributor,** growing from 105 GW in 2021 to 116 GW by 2050. **Biomass plays a transitional role,** with capacity peaking at 38 GW by 2030, before stabilising at 33 GW by 2050, reflecting sustainability constraints and shifting priorities in decarbonisation strategies.
- ★ **Robust renewable capacity investments are needed; at EUR 750 billion for 2021-2030 under the PES and DES,** shifting to EUR 677 billion (PES) and EUR 885 billion (DES) in 2031-2040, and to EUR 910 billion (PES) and EUR 1 204 billion (DES) in 2041-2050, reflecting the higher scaling needed under the DES to meet the ambitious decarbonisation targets.
- ★ **Hydrogen electrolyser capacity scales up significantly to meet green hydrogen demand, which will be mostly served by domestic sources though imports will also be needed**. Capacity reaches approximately 6 GW by 2030 under both scenarios to produce 1 Mt (PES) to 2 Mt (DES) of green hydrogen, 128 GW by 2050 (PES) to produce 12 Mt or 120 GW by 2050 (DES) to produce 16 Mt.
- ★ **Battery capacity expands from near-zero in 2021 to 46 GW under the PES and DES by 2030, supporting the early integration of VRE.** By 2050, installed capacity reaches 227 GW (PES) and 240 GW (DES) to meet grid stabilisation needs, corresponding to an average rollout of around 9 GW/year. Battery storage capacity requires significant near-term investments of EUR 34 billion (2025-2030) under both scenarios, increasing to EUR 120 billion in the medium term (2031-2040) under the DES, before reducing to EUR 70 billion (2041-2050), highlighting the key role of utility-scale batteries.

- ★ **Cross-border transmission capacity grows from nearly 100 GW in 2021 to approximately 144 GW and 209 GW under the DES by 2030 and 2050**, respectively, reflecting enhanced regional inter-connectivity. EUR 408 billion will be required by 2030 under DES to expand and modernise grids, facilitating the seamless integration of growing renewable energy capacity. Investments in grid upgrades, expansion and modernisation are crucial to accommodate VRE. Investments total EUR 2.2 trillion and EUR 2.5 trillion to 2050 under the PES and DES, respectively.
- ★ **Wholesale electricity prices in the EU27 shift significantly across the milestone years, with an initial decline by 2030 due to renewables expansion,** followed by an increase under both scenarios by 2040 owing largely to the remaining fossil fuel reliance. A more decarbonised system in the DES leads to a more stable long-term price trajectory (~EUR 66 /megawatt hour [MWh] by 2050), whereas a more fossil-dependent pathway in the PES results in higher and more volatile prices (~EUR 79 /MWh). The difference reflects the cost advantage of renewables as well grids interconnections in the long run.

KEY MESSAGES

- ★ **Achieving a 1.5°C-compatible future requires immediate and co-ordinated efforts to decarbonise the EU power sector.** Transmission planning would benefit from being more centralised, and a faster renewable energy deployment and fossil fuel phase-out require mechanisms for enforcing the implementation of priority projects. National energy strategies must be better aligned with EU targets, and permitting processes streamlined to fast-track renewable projects which are now the most cost-competitive form of new power generation and essential for lowering electricity prices for EU consumers and industries, as prioritised in the Action Plan for Affordable Energy.
- ★ **Renewables, especially solar and wind, are the foundation of the transition.** Country-specific renewable energy targets should be defined and linked to funding mechanisms. For instance, Germany, Spain and Italy can be supported in expanding solar capacity, while Poland and Germany focus on onshore wind. Enhanced regional inter-connections are critical for balancing supply and demand, incentivised through joint funding or collaborative investment frameworks.
- ★ **High levels of VRE necessitate significant investment in energy storage, grid modernisation and DSM to maintain system reliability.** This can be achieved by:
  - ★ Establishing **regional funds** to promote energy storage projects;
  - ★ Setting **binding targets** for grid upgrades and the deployment of smart technologies; and
  - ★ Developing **market mechanisms** such as flexibility services and demand-response programmes to ensure system reliability.
- ★ **Cross-border collaboration is essential to optimise resources, reduce costs and accelerate the energy transition.** Binding frameworks for regional energy planning can encourage countries to pool renewable energy resources. Clear timelines for inter-connector construction, with penalties for delays, would help ensure improved regional energy integration.
- ★ **Harmonised policies and streamlined permitting processes are essential for unlocking the full potential of renewable energy.** Actions should include:
  - ★ Expanding existing initiatives to fast-track permitting and requiring regular progress reports from national authorities;
  - ★ Designing capacity markets that reward flexibility and storage, such as hybrid renewables storage projects; and
  - ★ Ensuring better co-ordination between energy and market policies to prevent inefficiencies in system expansion.

- **The electrification of transport, heating and hydrogen production will drive significant demand growth but proactive planning to scale renewable and transmission power capacity will be needed**. This can be addressed through:
  - Developing sector-specific electrification roadmaps for transport, industry and heating;
  - Promoting joint renewable capacity auctions to meet cross-border electrification needs; and
  - Aligning national plans with EU targets to avoid bottlenecks and ensure sufficient capacity expansion.
- **Achieving the ambitious EU targets demands unprecedented levels of investment in renewable energy, transmission infrastructure, and emerging technologies like green hydrogen and storage.** Achieving climate neutrality by 2050 requires over EUR 5 trillion in investments across renewable power capacity, grid modernisation, storage systems and hydrogen infrastructure. Delaying clean energy investments results in higher long-term electricity wholesale pricing. A renewables-based market with enhanced flexibility measures – grid upgrades, storage and DSM – helps to ensure price stability and affordability.
- **Achieving a decarbonised and resilient energy system requires combined investments of EUR 2.8 trillion (2025-2050, DES) in grids and flexibility.** Upgrades to transmission and distribution networks, smart grids and cross-border inter-connections are essential for accommodating high shares of VRE. Simultaneously, scaling up 240 GW of mostly utility-scale battery storage and other technologies like pumped hydro will ensure system stability, enable DSM and support the integration of renewable energy into the EU power sector. Additionally, maintaining a portion of the existing gas capacity – even with reduced utilisation – could serve as a critical backup for system flexibility. This requires policy frameworks to partially retain gas infrastructure, promote the use of green gases and establish dedicated storage facilities for such purposes. Key actions to deliver this could include setting binding targets for the grid upgrades and smart technologies needed to integrate high renewables shares, incentivising deployment through financial instruments and implementing cost-sharing agreements to equitably distribute infrastructure costs.
- The analysis has shown that there are several key priorities for planning power sector components essential to the European Union's energy transition, here outlined by time frame:
  - **Immediate priorities (2021-2030):** Drive the rapid expansion of solar PV and onshore wind capacity, complemented by substantial investments in early-stage energy storage, including improved hydropower solutions, and grid upgrades. Ensure that regulation and market design, especially pricing systems to promote effective market participation, are optimised in advance to facilitate effective sector coupling solutions and the integration of energy storage technologies. Prioritising the electrification of key sectors, such as transport and heating, will drive a demand for renewables and energy efficiency improvements. Additionally, upgrading existing power generation units can further support these efforts. These measures are critical to achieving the target of tripling renewable energy capacity by 2030.
  - **Medium-term priorities (2031-2040):** Focus on scaling offshore wind deployment and battery storage, alongside significant grid modernisation investments to support the growing demand from electrified transport, industry and buildings. Strengthen inter-connections with other regions through cross-border inter-connectors and collaborative initiatives to optimise resource sharing and grid stability. These actions will ensure that the targets of renewable energy capacity tripling are successfully met and further build upon them, while simultaneously supporting widespread electrification and efficiency improvements across sectors.
  - **Long-term priorities (2041-2050):** Complete advanced grid modernisation; deploy large-scale, long-duration storage solutions; and establish a fully mature green hydrogen economy. This will require far-sighted investment in research and development to support enabling technologies like long-duration energy storage and grid forming inverters. A deeply electrified energy system powered by renewable sources will deliver sustained energy efficiency gains and ensure resilience, while achieving net-zero emissions and renewables targets.

5.1 THE POWER SECTOR'S ROLE IN MEETING EU EMISSIONS REDUCTION TARGETS

Achieving the ambitious electrification rates outlined in the preceding chapters requires the transformation of system planning, expansion and operation. This chapter examines how these actions can be taken across the EU27, providing insights on opportunities and challenges. The aim is to maximise the benefits of the energy transition, ensuring a robust, equitable and low-carbon power sector capable of meeting future electricity and green hydrogen demand.

Achieving a 1.5°C-compatible future requires a transformative shift in the EU power sector. Several possible 1.5°C-consistent pathways were examined considering long-term capacity expansion, operational flexibility, and improved regional and national integration in an energy system with an increasingly large share of renewables. Importantly, this analysis assesses ways to ensure that the EU power system aligns with climate objectives while safeguarding energy security and affordability.

The analysis provides a roadmap for developing a sustainable, efficient and resilient power system across the EU27, ensuring secure operation amid capacity expansion. Table 5.1 provides an overview of the scenario definition that was explored in the analysis.

Table 5.1 Scenarios definition in the power sector

Planned Energy Scenario	Decarbonising Energy Scenario
The Planned Energy Scenario represents a transition pathway in line with latest European Commission and Member State plans, and latest submitted NECPs, where there is significant scaling up of renewable capacity.	The Decarbonising Energy Scenario outlines an ambitious pathway that seeks to expand and assess existing plans with a view toward near-complete decarbonisation. This scenario aggressively phases out coal and oil while incorporating advanced technologies enabling a high-reliability, low-carbon energy system.

Scenario analysis is at the core of this analysis, exploring interactions between technological, economic, and policy factors. Such factors are inherently uncertain and scenario analysis can show how different factors impacts results for more informed and robust planning. To this end, results were assessed in terms of sensitivity to a wide range of factors, in terms of system expansion and short-term operation.

This section strives to answer several key questions shaping the future of EU power system development. These questions include:

- What is the status of the ongoing decarbonisation of the EU power sector?
- Are the existing directives, plans, and measures sufficient to deliver net-zero emissions in the power sector by 2050?
- At the time of publication, how are member states' National Energy and Climate Plans (NECPs) aligning with achieving EU-wide targets?
- What are the critical focus areas for policy makers in the transition to a decarbonised power system?
- What priorities should member states address in their domestic policies and regulations over the next decade?
- What role does regional integration play in achieving decarbonisation targets?
- How can the EU balance decarbonisation with energy security and affordability?

This approach highlights the importance of co-ordinated planning and market design to accelerate the deployment of renewable technologies and unlock their full potential. The findings derived from this assessment seek to guide policy makers and stakeholders in achieving deep decarbonisation and understanding how a lower-cost, effective and fair system expansion can be delivered.

The European Union and Member States lead in renewable energy integration in the power sector. The European Union has a history of successive strong and ambitious policies and targets, for example, the European Green Deal, Fit for 55 and the REPowerEU Plan, which have to date been important in driving significant investments in renewable energy, inter-connection and electrification across the bloc, ensuring the electricity sector remains on track to meaningfully contribute to EU decarbonisation ambitions. Given the role of electrification in delivering energy efficiency targets across energy end-use sectors, it is crucial that the rising electrification rate is matched by a corresponding increase in clean and renewable electricity generation.

Renewable energy capacity has grown substantially. Solar PV and wind dominate the installed capacity mix. By 2023, renewables accounted for over 50% of total installed capacity, most of it wind and solar PV. At the same time, fossil fuel capacity continues to decline as the European Union phases out coal and reduces its reliance on natural gas. This transformation is reflected in the electricity generation mix, where renewables now deliver a growing share of power, significantly reducing emissions intensity and in 2023 reached a renewable share of 45%.

EU power sector emissions have fallen significantly, driven by this increasing share of renewables. Key to this has been EU and national policy, which have prioritised renewables expansion, as well as the EU Emissions Trading System, which incentivises the shift away from fossil fuels by making them costlier than CO_2-emission-free alternatives. While the emissions reduction trajectory in recent times aligns broadly with the 2030 and 2050 targets due to significant progress, achieving these long-term goals will require maintaining trends in renewable deployment and systemic energy market reforms.

Table 5.2 Power and hydrogen regulations and relevant documents considered in the PES and DES

REGULATION / PLAN / STRATEGY	REFERENCE
• **European Green Deal.** Seeks to make Europe the first climate-neutral continent by 2050; focuses on a clean energy transition and decarbonisation of all sectors of the economy	(European Commission, 2023l)
• **Fit for 55 Package.** A comprehensive policy package to reduce greenhouse gas emissions by at least 55% by 2030, including revisions of the Renewable Energy Directive and Energy Efficiency Directive	(European Commission, 2024p)
• **Electricity Market Design Directive (2024) (Directive EU/2024/1711)**	(European Commission, 2024r)
• **Directive (EU) 2023/944 on common rules for the internal market for electricity (Revised Electricity Directive).** Strengthening market design and flexibility to support renewables and energy security	(European Commission, 2019a)
• **Affordable Energy Action Plan: Addressing Energy Price Volatility and Consumer Protections**	(European Commission, 2025c)
• **Recommendation on Energy Storage: Enhancing Deployment within the EU Energy Market**	(European Commission, 2024r)
• **A hydrogen strategy for a climate-neutral Europe**	(European Commission, 2020e)
• **Delivering on the EU offshore renewable energy ambitions**	(European Commission, 2023u)
• **National Energy and Climate Plans.** Member State strategies for meeting the 2030 energy and climate targets	(European Commission, 2024n)
• **Clean Energy for All Europeans Package.** A legislative package seeking to achieve a clean, secure and efficient energy transition by 2030	(European Commission, 2019b)
• **EU Solar Strategy.** Targeting 600 gigawatts (GW) of installed solar capacity by 2030, emphasising rooftop installations and integration	(European Commission, 2022c)
• **Offshore Renewable Energy Strategy.** Plans to achieve 300 GW of offshore wind and 40 GW of ocean energy by 2050	(European Commission, 2020f)
• **REPowerEU Plan.** Accelerating the transition to renewable energy and reducing reliance on fossil fuels, especially Russian imports	(European Commission, 2022d)
• **Electricity Market Stability Regulation (2024) (Regulation EU/2024/1747)**	(European Commission, 2024s)
• **European Union Reference Scenario**	(European Commission, 2020g)
• **ENTSOE/G Ten-Year Network Development Plan 2024**	(ENTSOE and ENTSOG, 2024)

Note: ENTSOE/G = European Network of Transmission System Operators for Electricity/Gas.

Cross-border inter-connections are a key part of the EU energy strategy and enable a collaborative approach to system development that unlocks economies of scale. The benefits of such inter-connections extend beyond expanding power transmission, unlocking significant renewable energy potential across the European Union; they also facilitate the sharing of system services that are essential for a reliable system. The 2030 target of at least 15% inter-connection seeks for greater energy security and the optimisation of renewable energy utilisation, and to support the creation of a unified electricity market. Reliable inter-connections have reduced the risk of blackouts, minimised the need for new power generation capacity and improved the integration of VRE sources. By making the regional sharing of surpluses and deficits possible, inter-connections boost resilience, reduce consumer costs and lower reliance on fossil fuel imports. Evolving market structures are also prioritising flexibility and ancillary services to better integrate renewable energy. These will be crucial to reducing the costs of effective system operation and renewables' integration.

These priorities are presented in the 2024 Mission Letter from European Commission President Ursula von der Leyen to the Commissioner for Energy and Housing, Dan Jørgensen. The letter emphasises advancing energy system integration, improving locational price signals, removing flexibility barriers, decarbonising heating and cooling, and increasing energy efficiency (European Commission, 2024c). Similarly, the Mission Letter to the Executive Vice-President for a Clean, Just, and Competitive Transition, Teresa Ribera Rodríguez, highlights the need to develop a climate and energy diplomacy vision and to build on the pledges made at the 28th Conference of the Parties (COP28) to triple renewable energy and double energy efficiency (European Commission, 2024a). These priorities align with the European Union's ongoing efforts to lead in renewable energy integration and meet its decarbonisation targets through comprehensive policy frameworks and strategic initiatives.

5.2 ELECTRICITY DEMAND PROJECTIONS

Future system expansion will need to not only displace old and less efficient capacity with new clean units, but will need to do so while meeting a growing need for electrification. This implies a need for a paradigm shift in how electricity is supplied today – transitioning to a renewables-dominant system while at the same time simultaneously meeting rapidly growing electricity demand.

Electricity demand is expected to increase steadily, driven by the electrification of transport, heating and industry; the growth of green hydrogen production; and economic expansion across EU Member States. Projections under the PES as well as the DES show a clear upward trend in electricity consumption out to 2050. This trend highlights the transformative shifts in energy consumption patterns that are needed and driven by the electrification and decarbonisation of the economy under both scenarios. In addition, the increasing consolidation of electricity as the key energy carrier in much of the economy will make system reliability ever more crucial. Each sector presents distinct implications for EU energy and power systems, infrastructure and resource management.

Transport is projected to be the fastest-growing sector, with electricity consumption increasing from 56 TWh in 2021 to over 970 TWh by 2050 under the DES. This dramatic increase reflects the widespread adoption of electric vehicles and electrified public transport. The scale of this growth signals a fundamental reshaping of electricity demand profiles, likely creating new peak demand patterns and could place significant pressure on grid infrastructure.

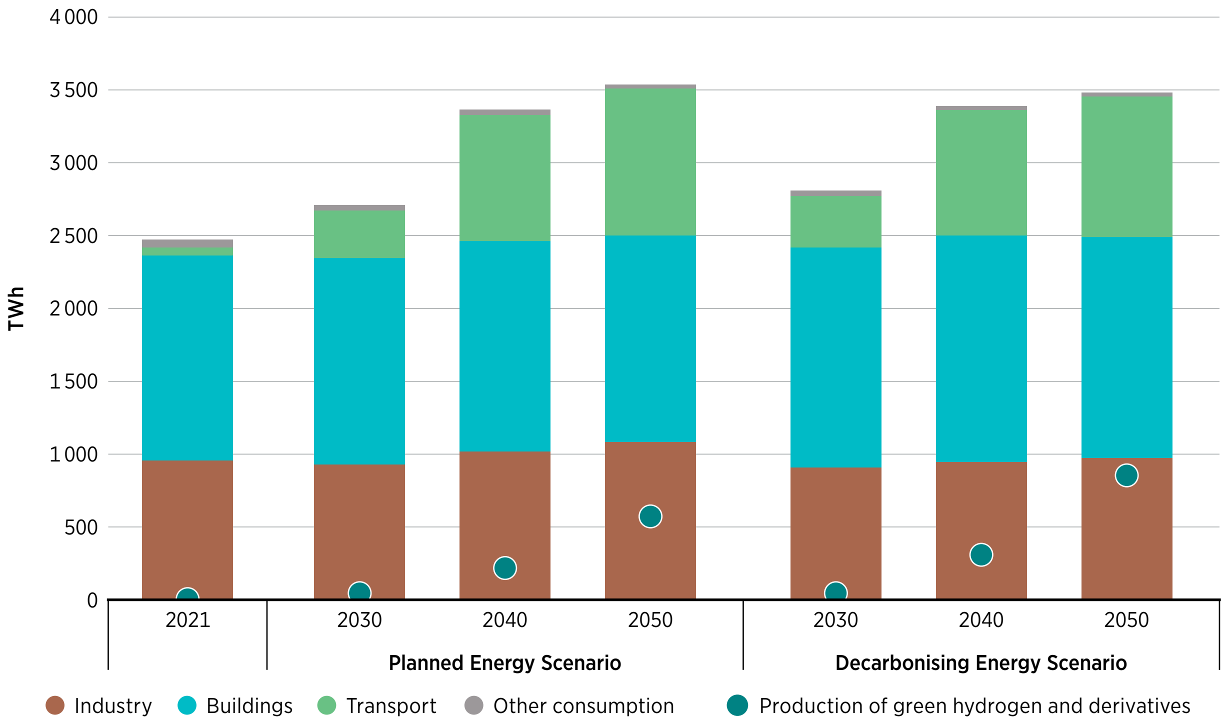
Electricity demand from buildings is similarly expected to increase, although much more steadily, reaching 1 518 TWh by 2050 under the DES. The growing use of electricity for heating and cooling systems in residential and commercial buildings will amplify the variability of seasonal demand. This trend highlights the need for the energy system to accommodate fluctuations in consumption levels throughout the year while delivering energy needs at greater efficiency than legacy heating and cooling systems.

Industrial electricity demand shows a mixed expansion of electricity needs. Modest declines are projected by 2030, followed by an increase to 1082 TWh and 973 TWh by 2050 under the PES and DES, respectively. This long-term trend of electricity consumption remains broadly consistent with today's levels and reflects the growing use of electricity-intensive processes and increasing efficiency, such as those required for clean manufacturing technologies. It raises important questions about the capacity of supply to sustain industrial productivity while meeting decarbonisation targets.

One of the most significant new areas of demand is production of hydrogen and its derivative fuels, where electricity consumption is expected to rise from modest levels in 2021 to 570 TWh and 851 TWh by 2050 (approximately 13% and 18% of total electricity generation needs) under the PES and DES, respectively (these values include additional energy needed for e-fuel production). This sharp increase highlights the crucial role of green hydrogen in decarbonising hard-to-electrify sectors. The scale of this demand introduces substantial challenges for electricity generation capacity. This is because hydrogen production will represent an increasingly large share of overall electricity use, although this growing share will be supported by the flexibility hydrogen can potentially offer in terms of both power demand and supply, both of which will be crucial in the long term.

Electricity consumption either grows modestly or is relatively stable for smaller categories, such as other consumption and heat plants (Figure 5.1). While these categories are not the primary drivers of demand growth, they play a key role in some Member States and are important in meeting a range of energy needs in these cases.

Figure 5.1 Electricity consumption by end-use sector nd for production of green hydrogen and derivative fuels



The future EU power sector will be shaped by its high ambition for electrification and renewables integration. The key performance indicators for the EU power sector (Table 5.3) demonstrate transformative pathways under both the PES and DES, outlining steps to achieve climate neutrality by 2050.

Total renewables capacity is projected to grow from 491 GW in 2021 to up to 1993 GW under the PES and to 2 456 GW under the DES by 2050. Renewables will represent 87% and 91% of the total capacity under the PES and DES, respectively, by 2050. Variable renewables, such as solar and wind, dominate this expansion. Solar capacity increases nine-fold to 1 443GW, while wind capacity reaches nearly 820 GW under the DES by 2050.

Electricity generation nearly doubles by 2050, reflecting rapid electrification across sectors, particularly transport, for which the electrification rate jumps from 2% in 2021 to 81% under the DES, through policies which address vehicle adoption, infrastructure, energy supply and market incentives. An increasing need for green hydrogen supply is also a prominent driver of increased generation needs, which reach 13 Mt and 16 Mt in the PES and DES, respectively, by 2050. Supporting this transition, electricity storage expands from 5 GW to over 240 GW and grid inter-connection capacity grows to 209 GW, ensuring system flexibility and resilience.

These few high-level indicators emphasise the scaling required in renewable energy, electrification and infrastructure to align with the European Green Deal and REPowerEU. They provide policy makers with a clear roadmap to integrate clean energy, meet growing demand, and build resilient and decarbonised energy and power systems.

Table 5.3 Key performance indicators for the energy transition in the EU power sector: Tracking progress towards 2050

	HISTORICAL	PLANNED ENERGY SCENARIO			DECARBONISING ENERGY SCENARIO		
	2021	2030	2040	2050	2030	2040	2050
Total renewable capacity (GW)	**491**	**1 246**	**1 717**	**1 993**	**1 247**	**1 919**	**2 456**
Renewables' share in capacity (%)	52	79	86	87	79	88	91
Share of variable renewables in capacity (%)	37	70	78	80	70	81	84
Renewables' share in generation (%)	38	71	75	78	71	82	88
Capacity by technology – solar (GW)	161	651	937	1 109	651	1 098	1 443
Capacity by technology – wind (GW)	188	446	625	724	446	650	819
Capacity by technology – hydro (GW)	105	108	111	116	108	111	116
Total annual electricity generation (TWh)	**2 720**	**3 176**	**3 913**	**4 548**	**3 196**	**4 034**	**4 837**
Industry electrification rate (%)	31	41	51	59	41	53	61
Buildings electrification rate (%)	32	39	43	48	44	53	60
Transport electrification rate (%)	2	13	51	77	14	54	81
Annual green hydrogen production (Mt)	<1	1	6	12	2	7	16
Battery storage capacity (GW)	5	46	227	227	46	232	240
Grid international inter-connection capacity (GW)	90	140	164	164	144	190	212
Of which is intra-EU (GW)	56	85	85	98	98	98	89
Of which is extra-EU (GW)	34	55	59	66	91	66	111

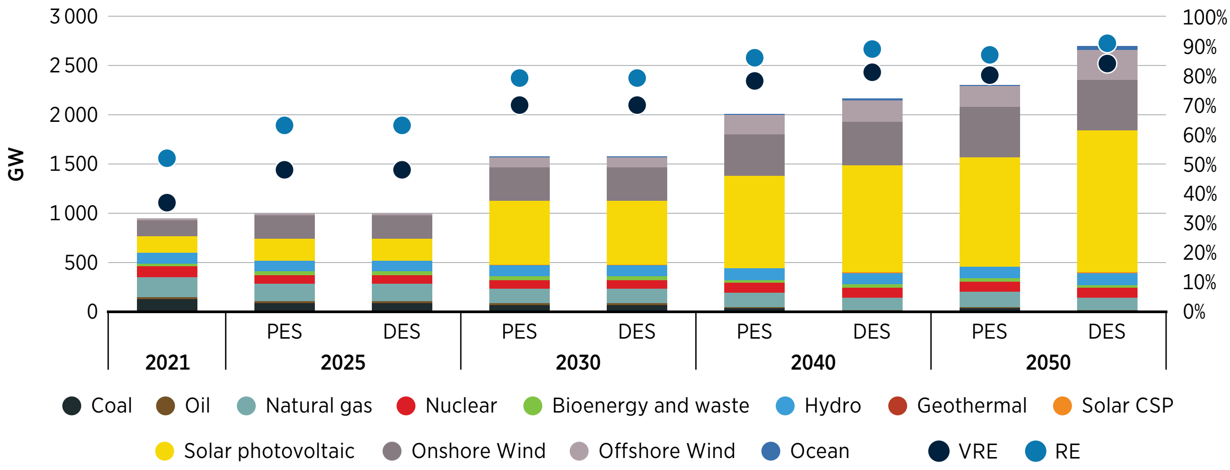
Notes: DES = Decarbonising Energy Scenario; GW = gigawatt; KPI = key performance indicator; Mt = million tonnes; TWh = terawatt hours.

5.3 POWER SECTOR CAPACITY EXPANSION

Transforming the EU power sector will necessitate a comprehensive capacity expansion strategy to meet rising electricity demand while achieving decarbonisation objectives. A mismatch between the two could frustrate efforts for effective renewable integration if demand is lower than expected and frustrate clean electrification if renewable roll-out is lower than anticipated.

By 2050, electricity generation needs will grow substantially, due to widespread electrification across sectors. To address this, renewable energy technologies, led by solar PV and onshore wind, will form the bulk of new capacity additions, as indicated in Table 5.2. However, realising this transformation requires overcoming significant challenges, including integrating variable renewables, modernising grid infrastructure and phasing out fossil-fuel-based generation without compromising energy security, adequacy or affordability. Regional co-operation, through improved inter-connection and integrated planning, will be crucial for effectively unlocking the full potential of renewables while reducing overall system costs and emissions with effective and lower-cost distribution of power sector infrastructure.

Figure 5.2 Installed power generation capacity by technology and scenario



Notes: GW = gigawatt; CSP = concentrated solar power; VRE = variable renewables (right Y-axis); RE = renewables (right Y-axis).

The analysis reveals a profound transformation in Europe's power sector, characterised by a dramatic shift from fossil fuels to renewable energy across both distinct scenarios: the PES and the DES (Figure 5.2).

The traditional fossil fuel landscape undergoes a dramatic reconfiguration. Coal capacity, once a central component of European power generation, plummets from 120 GW in 2021 to a mere 33 GW in the PES by 2050, with a complete phaseout in the DES by 2040. Oil-fired capacity declines more gradually, from 26 GW in 2021 to 14 GW in the PES and 12 GW in the DES by 2050. Natural gas maintains a relatively stable presence, declining from 202 GW in 2021 to 147 GW by 2030 in both scenarios, and reaching 159 GW and 137 GW in the PES and DES, respectively, by 2050. The capacity decline is gradual particularly from 2030 onwards due to its role envisaged in system flexibility. The existing natural gas fleet will remain essential during the energy transition in DES. It will provide critical system flexibility and seasonal energy services, and complement VRE sources like solar PV and wind due to its fast ramping capabilities in tandem with other flexible technologies. The fleet will thus help address variability challenges and ensure energy security. In both the PES and DES, natural gas shifts from playing a stronger role to a backup role. It supports the supply-demand balance and seasonal fluctuations. Natural gas can be further aligned with the European Union's 2050 decarbonisation targets by retrofitting plants with technologies that prepare them for integrating hydrogen. This aggressive phase-out of coal and significant reduction in overall fossil fuel reliance directly contributes to the EU's energy security objectives, decreasing dependence on imported fossil fuels and mitigating exposure to volatile global energy markets, a key priority outlined in the Clean Industrial Deal for enhancing EU resilience.

Nuclear energy remains a consistent contributor. Nuclear energy remains stable, at 98 GW, throughout the longer term under both scenarios, with no expansion beyond existing national plans, which is modestly lower than the 105 GW online in 2021.

The analysis demonstrates the complex technical and economic dynamics of power generation assets. It reveals how different fossil fuel technologies have varying decommissioning rates and how baseload nuclear generation evolves during the renewable energy transition. Renewable energy technologies emerge as the definitive future of EU power infrastructure. They grow rapidly across both scenarios.

The most dramatic transformation is in solar PV, where capacity expands from 161 GW in 2021 to an impressive 1 109 GW in the PES and 1 443 GW in the DES by 2050. This remarkable trajectory underscores solar power's critical role in decarbonisation efforts.

Wind energy complements this growth with robust expansion. Onshore wind capacity rises from 173 GW in 2021 to 517 GW under the DES by 2050. Equally compelling growth occurs in offshore wind, with capacity rising from 15 GW in 2021 to 303 GW under the DES by 2050, highlighting offshore wind's increasingly strategic importance in the renewable energy mix.

Hydropower provides a stable foundation. Hydropower capacity increases modestly, from 105 GW in 2021 to 116 GW by 2050 in both scenarios. Geothermal, concentrated solar power and bioenergy maintain consistent, albeit smaller, contributions to the overall energy landscape.

Both scenarios demonstrate the unprecedented scale of renewable energy infrastructure deployment, highlighting the technological learning curves, capacity factors, and potential for grid integration challenges associated with large-scale expansion of solar and wind generation. The pace and co-ordination needed in this deployment within and between Member States will require careful planning but presents a major opportunity. This capacity roll-out translates into correspondingly large increases in renewables' share in power generation capacity. By 2050, renewables account for 87% of the capacity under the PES and an astounding 91% under the DES, transforming the sector. VRE technologies alone account for 80% and 84% of the overall capacity under the PES and DES, respectively, by 2050. These capacity shares are a simple metric, which provides critical insights into the system-level transformation. They demonstrate the high-level technical feasibility of high-penetration VRE scenarios, but also the associated integration challenges that will have to be addressed while meeting the needs of these scenarios.

In short, the power system under both the PES and DES will evolve to accommodate more renewables and be more integrated across the European Union, while fossil fuel capacity will fall to play a more marginal role in terms of energy supply but remains critical in maintaining security of supply during low-renewables periods. Nuclear power is anticipated under both scenarios to remain at levels similar to 2025s. Member States differ substantially in the distribution of infrastructure and capacity to deliver these scenarios, but there are many common factors that will be integral to their effective roll-out.

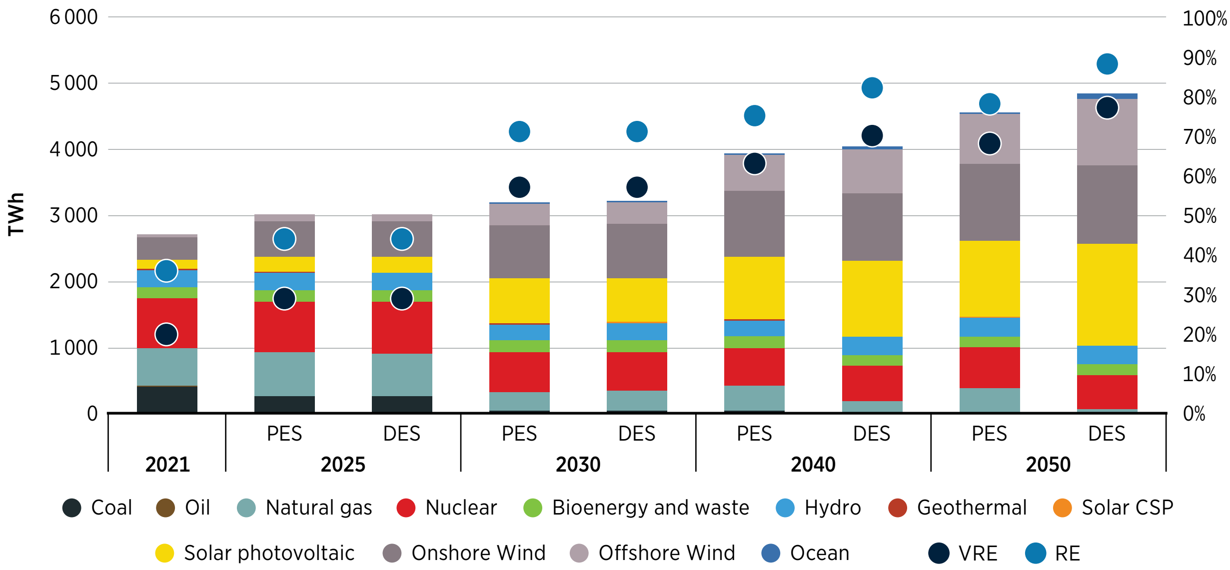
To fully benefit from such a capacity roll-out, Member States will need an integrated roll-out of technical grid modernisation and emerging flexibility solutions while accounting for the systemic inter-dependencies between generation, transmission and market design. In this vein, grid modernisation to accommodate VRE, advanced energy storage solutions, streamlined permitting processes and improved cross-border inter-connections will all be crucial, and market mechanisms must evolve to support and integrate high proportions of renewables-based generation.

The trajectories of both the PES and DES embody the ambitious EU vision for a climate-neutral power sector by 2050. In both trajectories, decarbonisation objectives will have to be balanced strategically with energy security and economic considerations to be effective for the delivery of electricity as the increasingly dominant energy carrier.

5.4 POWER GENERATION MIX

The changes in installed generation capacity in both scenarios can be seen to transform the power generation mix. They have profound implications for how electricity is supplied across the European Union. Climate neutrality by 2050, along with rising electrification will require decarbonising the electricity generation mix. A shift away from coal and other fossil fuels will induce the bloc to rely on renewable energy sources, with solar PV and wind projected to dominate the generation mix consistent with their capacity growth. By mid-century, these technologies combined are expected to supply between 68% and 77% of total electricity, supported by hydropower and bioenergy (Figure 5.3). Flexible generation and storage solutions will be essential to manage resource variability, ensure a reliable supply and enable the phaseout of carbon-intensive technologies. Driving this transition requires co-ordinated policies and market frameworks to encourage co-ordinated investment in renewables while maintaining system resilience and economic competitiveness.

Figure 5.3 Power generation by technology and scenario



Notes: TWh = terawatt hours; CSP = concentrated solar power; VRE = variable renewables (right Y-axis); RE = renewables (right Y-axis).

Renewable energy emerges as the largest source of future power generation. It represents 78% of the generation mix in the PES and an ambitious 88% in the DES by 2050. Solar PV leads this transformation, expanding from about 150 TWh in 2021 to 1150 TWh in the PES and 1540 TWh in the DES by 2050. In terms of variable renewables' shares, they grow remarkably, reaching 68% in the PES and 77% in the DES by 2050, demonstrating an increasing reliance on solar and wind technologies. This metric clarifies the scale and pace of the renewable energy transformation, especially quantifying the shift towards VRE technologies, which will transform power sector operation. This dominance of renewable energy in the future power generation mix is not only crucial for decarbonisation but also for enhancing the long-term competitiveness of EU industries. Renewable electricity provides a stable and increasingly affordable energy source, insulating EU businesses from the price volatility associated with fossil fuels, a key factor for industrial competitiveness highlighted in the Competitiveness Compass.

Wind energy complements solar's growth. Onshore and offshore wind both increase substantially. By 2050, onshore wind reaches 1171 TWh in the PES and 1184 TWh in the DES, while offshore wind grows to 751 TWh in the PES and 1008 TWh in the DES. Hydropower and bioenergy provide critical dispatchable renewable resources. Their contributions remain stable, with slight increases. All of this serves to demonstrate that while wind and solar are the most prominent generation sources in the mix, all renewable sources combine to meet power generation needs reliably across the year and diversify the power generation mix, boosting resilience.

Nuclear power, a stable low-carbon resource, declines moderately over 2021-2050. It declines from around 750 TWh in 2021 to 617 TWh (PES) and 522 TWh (DES) by 2050. As VRE increases, nuclear power faces growing operational challenges, including greater flexibility needs in operation of nuclear units and economic pressures from reduced revenue from bulk energy supply, necessitating careful assessment of its role in the future energy mix. When considering the role of renewables and nuclear together, by 2050, clean power reaches a 91% and 99% share of the EU power system under the PES and DES, respectively.

Fossil-fuel-based generation declines steeply, with each fuel type following a distinct trajectory. Coal generation plummets to a mere 18 TWh by 2050 in the PES and is completely phased out by 2040 in the DES. Oil-fired generation reaches near zero under both scenarios by 2050 but continues to meet capacity needs during some parts of the year. Natural gas demonstrates a more nuanced transition, gradually decreasing from over 550 TWh in 2021 to 374 TWh in the PES, and falling more dramatically to 60 TWh in the DES, by 2050. These results serve to illustrate the systematic and strategic reduction of fossil fuel generation in line with the EU commitment to decarbonising the power sector through a deliberate and phased approach.

The scenarios highlight the necessity of comprehensive system adaptations and strategic interventions. The roll-out of renewable power generation capacity will require system expansion to integrate renewables. Grid modernisation requires significant infrastructure investments and improved inter-connection capabilities to deliver and distribute power. Energy storage solutions, especially battery technologies, are vital for managing supply-demand variability and ensuring system reliability so that power can be stored and mitigate increased supply-side variability and grid congestion, thus preventing renewable curtailment. Supportive policy frameworks and market designs are essential to accelerate clean technology roll-out and facilitate its integration. Co-ordinated action between capacity and infrastructure roll-out to meet a rising electrification need is essential for maximising the benefits of the system transformation.

5.5 GRID INFRASTRUCTURE, STORAGE AND SYSTEM FLEXIBILITY

A secure and decarbonised EU power system requires a combined effort across grid expansion, storage and DSM. Stronger transmission supports large-scale renewable integration, while storage stabilises fluctuations and DSM shifts demand to match supply. Together, they reduce curtailment, enhance system resilience, decrease reliance on older and less efficient fossil-fuel-based generation, and mitigate the risk of system blackouts. These investments in grid infrastructure, storage, and DSM not only ensure a secure and decarbonised power system but also create significant market opportunities for EU companies specialising in grid technologies, smart grid solutions, and energy storage manufacturing, supporting the development of EU-based value chains in these growth sectors, as targeted by the Net-Zero Industry Act.

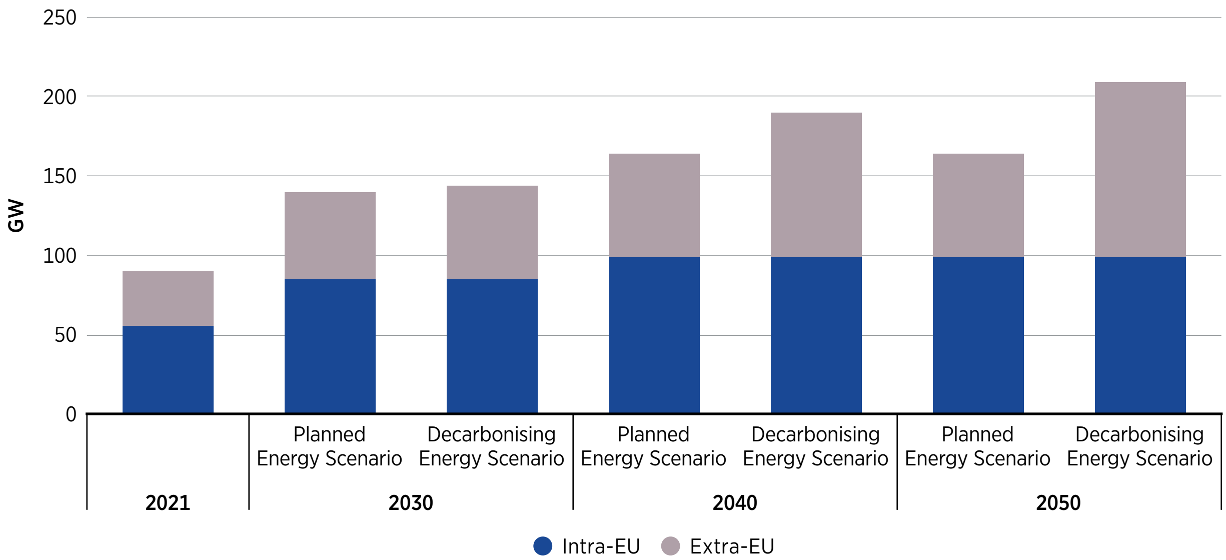
EU power system decarbonisation requires expanding international transmission to support the large-scale integration of solar and wind power as outlined in the earlier sections on power generation capacity and power generation. This enables surplus electricity to flow to regions with a higher demand. Curtailment is thus reduced, the use of renewable resources is maximised, and the system becomes more resilient through the provision of alternative electricity pathways and cross-border balancing. Strengthened inter-connection lowers the overall system costs and reduces the reliance on fossil fuels by supporting cross-border energy sharing. It also advances a unified EU energy market, fostering competitive pricing, improving energy security and enabling market coupling for more efficient electricity flows. Beyond decarbonisation and energy security, these enhanced interconnections are fundamental for completing the EU's internal energy market, fostering greater price convergence across Member States, and creating a more competitive electricity market that benefits EU industries and consumers alike, a key objective for enhancing EU competitiveness as highlighted in the Competitiveness Compass.

However, realising these benefits requires overcoming significant challenges. Expanding transmission infrastructure demands substantial investment and co-ordinated planning across Member States. Fair cross-border electricity trade requires regulatory harmonisation, while sustained system stability and the efficient management of increasing electricity flows requires deploying advanced technologies (*e.g.* high-voltage direct current [HVDC] lines and digital grid management systems). Addressing these challenges takes a concerted effort to streamline permitting processes for cross-border interconnector projects, as emphasied in the Net-Zero Industry Act and the Clean Industrial Deal. Accelerated permitting, along with enhanced regulatory harmonisation and co-ordinated planning, is crucial to unlock the full economic and energy security benefits of these vital infrastructure projects and ensure the EU remains on track to meet its ambitious decarbonisation targets.

Transmission capacity in the EU27 is set to grow substantially over the coming decades (Figure 5.4). From approximately 90 GW[10] in 2021, capacity is projected to reach approximately 140 GW by 2030 in both scenarios, reflecting early efforts to enhance cross-border electricity flows. By 2040, as the need for renewables' integration intensifies, capacity will expand further, reaching roughly 165 GW in the PES and 190 GW in the DES. By 2050, with deep decarbonisation in progress, capacity is expected to peak at about 164 GW in the PES and at 209 GW in the DES, supporting pan-Europe renewable energy sharing at high levels. Both intra-EU and extra-EU inter-connection will be crucial. The role of extra-EU trade will increase over time, especially under the DES, among Eastern EU Member States and their neighbours. The increasing role of extra-EU interconnection, particularly with close regions of the wider Mediterranean, Africa and the Eastern Partnership countries, is strategically vital for diversifying the EU's energy supply sources and enhancing energy security, as emphasised in the REPowerEU plan and the EU's broader geopolitical strategy to reduce dependence on single suppliers and volatile energy markets.

The benefits of this expansion are far reaching. A well-connected European grid will drive down electricity costs, boost energy security and create a more resilient power system. Increased inter-connection will facilitate a smoother transition to a renewables-based electricity mix, ensuring flexibility and reliability even with high shares of VRE. It will also promote economic growth by enabling more efficient electricity markets and attracting investments in clean energy infrastructure. Ultimately, a stronger, smarter transmission network is a crucial part of Europe's path to a decarbonised and competitive energy future.

Figure 5.4 International transmission capacity expansion for the power sector



Notes: GW = gigawatt; EU = European Union.

[10] *This refers to the sum total of net power transfer capacity that can be simultaneously transferred between countries.*

In combination with inter-connection, batteries play a crucial role in integrating renewable energy sources. They are particularly important for alleviating grid congestion, balancing supply and demand, and ensuring grid stability. Batteries can provide critical services, such as frequency regulation and voltage support, and serve as reserve capacity as fossil-fuel-based generation declines.

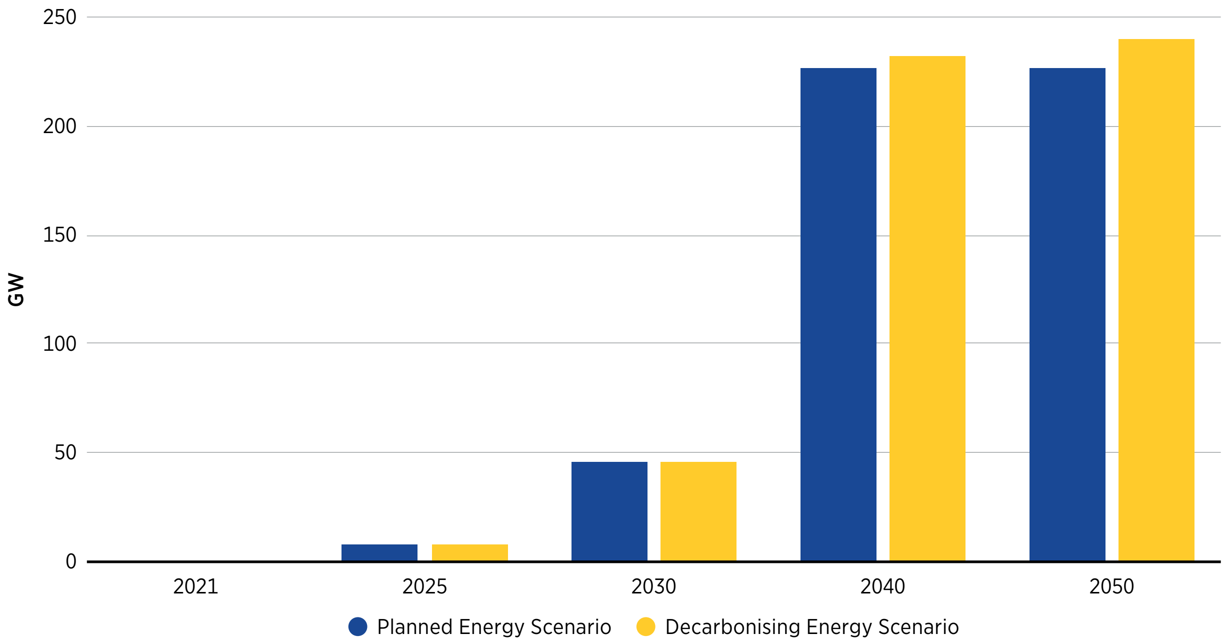
Battery deployment is set to expand rapidly under both the PES and DES (Figure 5.5). In 2021, the installed capacity was minimal, reflecting its early role in the power system. By 2030, battery capacity increases substantially, to about 46 GW under both the PES and DES, marking the start of large-scale adoption. By 2040, as renewables take on a larger share of the generation mix, the installed capacity will reach approximately 227 GW and 232 GW under the PES and DES, respectively. By 2050, batteries will be a central part of reliable power system operation. They will help ensure a flexible and reliable system, with capacity reaching 227 GW under the PES and 240 GW under the DES. Growth in battery capacity between 2040 and 2050 is modest but enabled by greater system flexibility more broadly.

However, scaling deployment requires addressing key challenges. High upfront costs, supply chain constraints and market barriers must be tackled through targeted investment, regulatory clarity and incentives for energy storage. Policies should support battery manufacturing, alternative chemistries and fair market participation to unlock their full potential.

Batteries reduce grid strain, help manage peak demand and enable energy time shifting to minimise renewable curtailment. The growing use of electricity in transport and heating is set to increase the peak demand, putting more pressure on the system. Batteries can help enable a more flexible system to mitigate this. They also support cross-border electricity flows and improve market efficiency. Measures such as flexible tariffs, capacity remuneration and clear rules for behind-the-meter storage are useful tools to drive expansion.

The benefits of such expansion are clear and could be far reaching if roll-out is successful. Batteries improve grid stability, reduce operational costs and can help maximise renewables' integration. With the right policies – investment support, market incentives and streamlined regulations – they can accelerate decarbonisation, boost energy security and drive economic growth in a low-carbon future as assessed under the PES and especially under the DES.

Figure 5.5 Battery expansion of the power sector



Note: GW = gigawatt.

Equally important is DSM, which remains underutilised despite its potential to improve system flexibility. Shifting electricity consumption to periods of high renewables-based generation reduces the strain on grids and storage, lowering overall system costs. Industrial consumers, for example, can adjust operations to match supply conditions, while smart technologies and pricing mechanisms can encourage households to reduce demand during peak hours. DSM is a cost-effective way to improve grid efficiency, but it requires the right market incentives and regulatory support to reach its full potential.

Smart charging, in particular, plays a vital role in DSM. Corporate electric vehicle fleets, which typically exhibit predictable charging behaviour and can be easily aggregated, are especially well-suited for bi-directional charging applications. Vehicle-to-grid (V2G) functionality allows these fleets to not only draw power but also inject electricity back into the grid, providing valuable flexibility services and generating new revenue streams. To fully realise these benefits, however, appropriate market incentives and supportive regulation are essential. As corporate fleets allow for aggregation and generally have predictable charging behaviour, they are highly relevant for bi-directional charging functionalities.

A strategic mix of inter-connection, storage and DSM is essential for delivering a decarbonised power system that is both affordable and resilient. Policy makers would benefit greatly from an integrated approach, ensuring that investments in infrastructure, technology and market design work together to support a flexible and secure energy transition.

5.6 GREEN HYDROGEN AND ITS DERIVATIVES

Green hydrogen is an essential pillar for achieving deep decarbonisation across the EU energy system. Its role is especially crucial in hard-to-abate sectors, where direct electrification is not feasible (*e.g.* aviation, shipping, and energy-intensive industrial processes like steel and chemical production). These industries require high-temperature heat and energy-dense fuels that hydrogen can provide without emitting CO_2. While hydrogen also has the potential to support reliable power system operation during extended periods of low renewables-based generation (commonly known as Dunkelflaute), its primary value lies in supporting deep emission reductions in sectors that currently have limited alternatives for decarbonisation.

Table 5.4 Key performance indicators for hydrogen production

	PLANNED ENERGY SCENARIO			DECARBONISING ENERGY SCENARIO		
	2030	2040	2050	2030	2040	2050
Total electrolyser capacity (GW)	**7**	**41**	**128**	**6**	**38**	**120**
Hydrogen production from electrolysers (Mt)	1	6	12	2	7	16
Share of green hydrogen in total hydrogen production (%)	20%	55%	81%	23%	58%	81%
Share of power generation needed for green hydrogen (%)	1%	5%	12%	1%	5%	11%
Imports as a share of consumption (%)	22%	49%	58%	22%	42%	44%

Notes: GW = gigawatt; Mt = megatonne.

By 2050, the total electrolyser capacity is expected to reach 128 GW under the PES and 120 GW under the DES, a dramatic increase from just 7 GW and 6 GW in 2030 under the PES and DES, respectively, and from a modest installed capacity today. This expansion underlines the necessity of a robust and flexible power system that can accommodate growing hydrogen demand while maintaining reliability. The projected hydrogen production from electrolysers rises from 1 Mt and 2 Mt under the PES and DES, respectively, in 2030 to up to 16 Mt under the DES by 2050, illustrating the scale of transformation required. With the share of green hydrogen in the total hydrogen production projected to increase from 23% to 81% over the same period under the DES, this delivery will require cost competitiveness and scalability (Table 5.4). In PES and DES scenarios, the share of RFNBO hydrogen (including imports) in industrial hydrogen consumption reaches 34% and 36%, respectively by 2030 which is just below the RED III target of 42%. These total quantities are notably lower than those assessed in the European Commission Impact Assessment Report for the 2040 Climate Target Communication. Dedicated pipelines and port facilities will also be critical to facilitate hydrogen trade and distribution, ensuring a resilient and inter-connected supply chain. However, most EU consumption of hydrogen and its derivative fuels is set to be served by domestically produced hydrogen and derivative fuels.

To meet the additional energy demand for hydrogen production, the European Union must significantly scale up its renewables-based power generation capacity. Green hydrogen production requires a large and sustained supply of renewables-based power. The share of power generation required for green hydrogen is projected to grow up to 12% in the PES and 11% in the DES by 2050 (excluding additional energy needed for production of hydrogen derivatives), necessitating a carefully co-ordinated approach that aligns energy policy, industrial strategy and investment planning. Electrolysis must be flexibly integrated into the power system, ensuring it can operate efficiently alongside other electricity demands. Solar PV, wind and other renewable capacity will have to expand significantly to provide enough electricity for electrolysis while meeting other growing electricity demands.

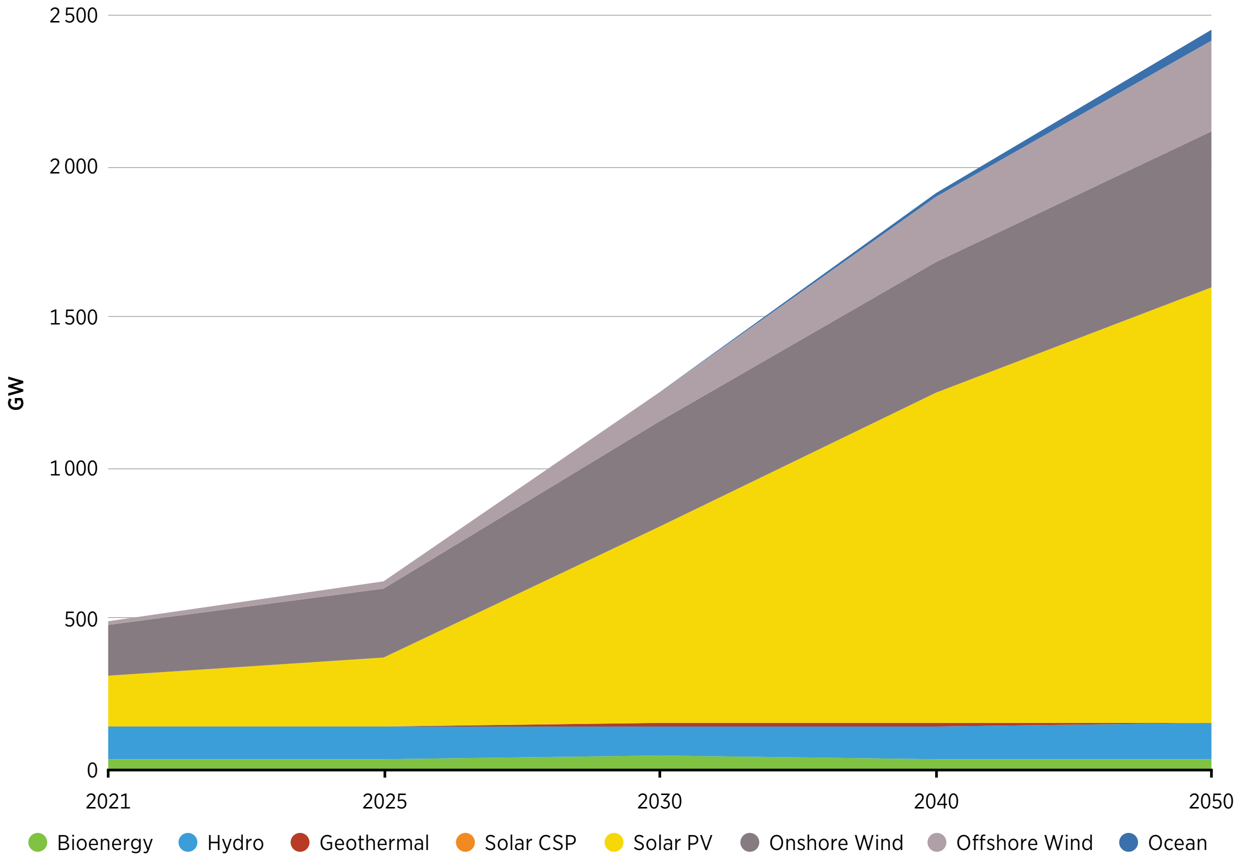
Despite its potential, hydrogen faces several challenges, which must be addressed through co-ordinated policy action. High costs remain a significant barrier for green hydrogen, which is currently more expensive than fossil-based alternatives. Substantial investment and regulatory support are needed to establish a comprehensive hydrogen production, transport and storage network. Policy and market gaps must also be addressed, and there must be an integrated framework providing clarity for investors and ensuring cross-sector alignment. The European Union remains the only region with a comprehensive legal framework for hydrogen. However, further efforts are needed to ensure market uptake and close the price gap between green and conventional hydrogen. Strengthening the regulatory environment, with clear long-term signals, robust certification schemes for green hydrogen, and mechanisms for market integration,will be critical to unlocking investment and scaling up electrolyser deployment.

5.7 REGIONAL INTEGRATION

Renewables are set to be scaled up significantly in Europe, driven by growing power generation capacity, expanding international transmission networks, increasing storage deployment and a growing demand for green hydrogen. These factors, combined with the decarbonisation ambition, technological progress and regional co-operation, will redefine the continent's electricity system in both the PES and DES.

By 2030, in both scenarios, overall, solar PV and onshore wind will dominate new capacity due to lower costs and supportive policies. By 2050, offshore wind and large-scale solar will play a stronger role, while hydropower and bioenergy provide flexibility across the horizon (Figure 5.6). A co-ordinated approach aligning policies, infrastructure and market integration is essential to fully unlock Europe's renewable energy potential.

Figure 5.6 Renewable technology expansion in the DES, by technology and key milestone years



Notes: GW = gigawatt; PV = photovoltaic; CSP = concentrated solar power.

5.8 ROLE OF INTER-CONNECTIONS IN A UNIFIED ENERGY MARKET

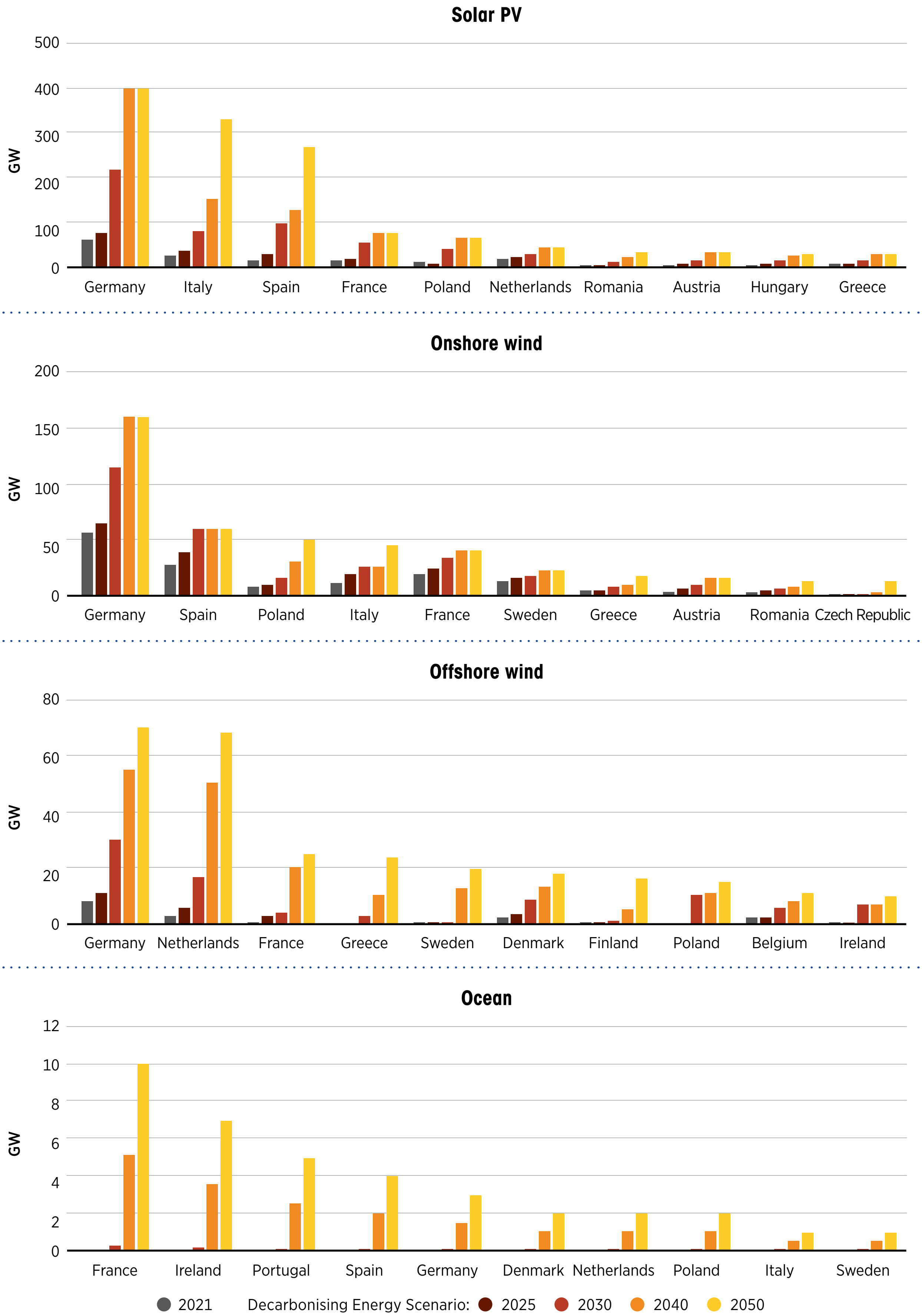
A well-connected European energy market is essential for efficiency, resilience and decarbonisation. Enhanced cross-border electricity trade allows renewables-rich regions to balance supply and demand across Europe, reducing curtailment and reliance on fossil fuel capacity. Northern Europe's offshore wind surplus can support Central Europe during peak demand, while Southern Europe's solar output complements seasonal hydropower fluctuations in the Alps and Scandinavia. These synergies boost energy security by diversifying the supply of resources, reduce costs and accelerate progress towards EU decarbonisation targets. HVDC corridors and smart grids will be crucial for integrating large-scale renewable energy across borders. A well-integrated grid fosters competition, boosts system resilience and ensures efficient resource utilisation. A regionally collaborative approach that recognises the distinct strengths of each region is needed to achieve this.

Each region in the EU brings unique strengths and faces distinct challenges in the energy transition:

- **Northern Europe.** Offshore wind in the North Sea is a vital potential asset in power system decarbonisation. The supporting grid infrastructure is mature but aging. Upgrades are vital to accommodate large-scale renewables' integration.
- **Southern Europe.** The Mediterranean's high solar irradiance makes solar PV a primary energy source. Seasonal hydro resources offer a buffer, although variability and limited storage capacity present challenges.
- **Eastern Europe.** As an emerging renewables market, Eastern Europe offers opportunities for rapid renewable energy growth due to its significant biomass and onshore wind potential. While overall biomass capacity varies across the region, it plays a particularly important role in smaller systems, such as those in the Baltic states, where even moderate capacities can have a sizable impact. Grid modernisation remains essential to ensure the smooth integration of these resources.
- **Western Europe.** Advanced markets, such as Germany and France, have already achieved high levels of renewable integration. Ongoing investments in grid flexibility and storage technologies will enable further expansion of its rich renewable resources, especially wind power.

These regional insights illustrate the need for co-ordinated efforts to harmonise energy policies and infrastructure investments across Europe. Figure 5.7 demonstrates the breadth and depth of the action needed at a Member State level for several key renewable technologies.

Figure 5.7 Installed power generation capacity trajectory for key renewable technologies in milestone years under the DES



Notes: GW = gigawatt; PV = photovoltaic.

5.9 ADDRESSING CHALLENGES IN RENEWABLE CAPACITY DEPLOYMENT

Regional co-operation and inter-connected markets, discussed in the previous section on EU regional integration, provide the foundations for successfully integrating renewable energy into Europe's power system. As highlighted by earlier chapters, achieving a decarbonised energy future demands a co-ordinated effort to scale up generation capacity, expand transmission infrastructure and improve storage solutions. However, despite significant progress, the pace of renewables' deployment remains constrained by systemic challenges that impact grid stability, market efficiency and investment signals. Addressing these barriers is essential for Europe to fully leverage the benefits of its increasingly inter-connected power sector and ensure a resilient, affordable and sustainable energy transition.

The pace of renewable energy integration is contingent on overcoming several systemic challenges:

- **System reliability and renewable integration.** High shares of VRE, like wind and solar, introduce complexities in maintaining system reliability. Inadequate investments in grid modernisation, storage and DSM compound the risk of reliability issues, leading to higher ancillary service costs and an increased likelihood of large-scale blackouts if market design and grid expansion continue to lag renewable deployment. Bottlenecks in grid infrastructure curtail renewable energy generation, where transmission limitations prevent the use of excess energy. A system with high shares of renewables will always have an element of economic curtailment of renewables that is cost effective. Excessive curtailment beyond economic levels, however, not only undermines the economic viability of renewable projects, it also potentially leads to a reliance on fossil fuel backups in certain periods, counteracting decarbonisation efforts. Addressing these challenges a reassessment of market mechanisms to prioritise and adequately compensate essential system services - such as inertia, frequency response, and grid-forming capabilities—rather than just energy volume.
- **System inertia and resilience.** The transition to renewable energy reduces system inertia, which is traditionally provided by synchronous generators in conventional power plants. This diminished inertia makes the grid less resilient to disturbances, increasing the likelihood of blackouts. Bottlenecks further amplify this insecurity by concentrating stress on specific nodes in the grid, limiting the ability to distribute energy effectively. Investments in technologies like grid-forming inverters, fast-frequency response systems and battery storage can help address these challenges. Batteries, especially when configured with grid-forming capabilities, can improve system stability by providing an inertia-like behaviour to the system by rapidly injecting or absorbing power to stabilise frequency fluctuations. Co-ordinated efforts and further research and development are required to ensure that grid infrastructure evolves alongside the increasing penetration of renewables.
- **Pricing disparities.** Infrastructure bottlenecks create significant pricing disparities across regions. Areas with high renewables-based generation but insufficient inter-connection capacity often experience negative pricing or very low wholesale electricity prices during high-output periods. Conversely, prices are higher in regions with limited access to renewable energy, highlighting the uneven distribution of benefits. Such disparities discourage investment in renewable projects and hinder equitable access to affordable clean energy across Europe. Enhanced grid inter-connections and market integration are crucial to mitigate these effects and facilitate a more balanced distribution of resources.
- **Innovation and cybersecurity.** Improved grid flexibility and resilience require integrating digital technologies to manage high renewable energy shares. Innovations such as advanced forecasting, AI-driven demand management and digital twins can significantly improve grid operations. However, the increasing reliance on digitalisation introduces critical cybersecurity challenges. Addressing these risks through robust cyber defences, resilient systems and EU-wide cybersecurity standards is important to ensure the secure operation of a modernised energy grid. Large-scale co-ordinated investment in cybersecurity defences is a pre-requisite for a digitalised, renewables-heavy grid.

- **Policy variability.** Diverging political will and regulatory frameworks across Member States slow progress in some regions. The European Union requires a region-wide harmonised policy framework to align national efforts. However, conflicting national interests often introduce bottlenecks in cross-border infrastructure projects, delaying much-needed inter-connections. Better collaboration and streamlined permitting processes to address these policy disparities will help the EU deployment critical infrastructure faster and unlock the full potential of renewable energy.
- **Infrastructure investments.** Boosting renewable capacity requires substantial investments in inter-connections, flexible grids and energy storage systems. Without these investments, the ability to transport renewable energy from surplus-generation to high-demand regions will continue to be constrained. Such limitations increase curtailment rates, reducing the overall efficiency of the energy system. Furthermore, inadequate infrastructure hinders the integration of emerging technologies, such as green hydrogen production and vehicle-to-grid solutions, which are essential for a sustainable energy transition.

Box 5.1 European Union inter-connection: Bottlenecks and congestion, 2030

Inter-connectors are a vital element of Europe's energy security and power market efficiency. By 2030, they could transport about a third of all EU electricity demand. However, congestion and under-investment could threaten inter-connectors' potential, driving up electricity prices, introducing inefficiency and slowing down power sector decarbonisation. Inadequate interconnection can also contribute to energy insecurity, leaving regions vulnerable to blackouts during periods of high demand or supply disruptions. Strengthening interconnections enhances system resilience by allowing electricity to flow where it is most needed, mitigating the risk of shortages and instability.

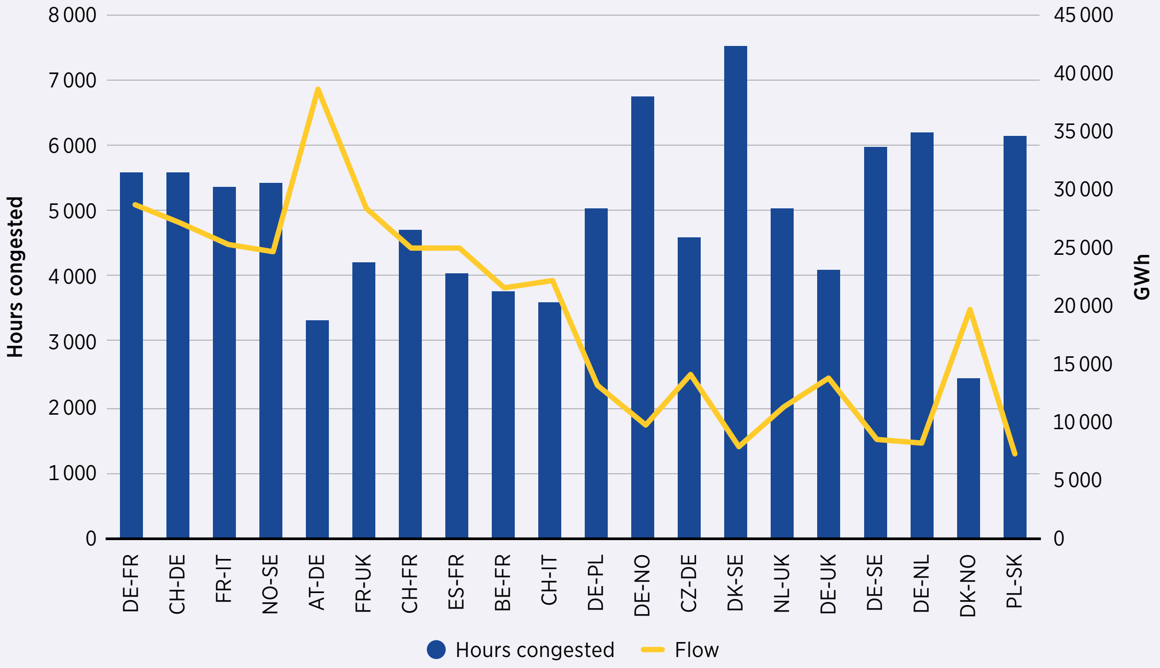
To understand how the EU power system will operate in 2030 based on current plans and projections, a supplementary analysis using an hourly dispatch model was performed for the continental European power system, which broadly follows the operation of the day-ahead electricity market. The most cost-optimal operation for the European power system is determined using model simulation of the system's hourly operation considering key operational constraints, generation costs and transmission capacities. This analysis highlights widespread congestion along several key European lines (defined as the number of hours lines run at full capacity between countries), as highlighted by Figure 5.8, which shows the congestion and the total electricity flow in several lines, which correspond to about 12% of the total electricity demand in 2030.

Spain's inter-connection with France experiences over 4 000 hours of congestion annually. This restricts Iberian renewable exports and imports of nuclear power. Expansion of these inter-connectors in particular are slow due to permitting delays and local resistance (POLITICO, 2024). In Northern Europe, Norway's increased inter-connection with several countries has led to domestic price volatility in Norway (Lyu *et al.*, 2024), demonstrating that while inter-connectors are necessary, they require balanced policies to avoid unintended consequences.

Without action, price disparities will widen, and renewables-rich regions like Scandinavia and Iberia will struggle to optimise generation. During crises, weak inter-connections could expose regions to shortages and instability. Capacity expansion will improve market integration, lower prices and support renewables, but it requires streamlined permitting and strong regulatory co-ordination.

Inter-connectors are more than infrastructure; they are key to a resilient and decarbonised power system. Addressing bottlenecks now will help to secure an efficient, competitive and sustainable energy future for Europe. This requires integrated system planning to align investments with future grid needs, alongside other flexibility enablers such as storage, demand response, and sector coupling to reduce congestion. Failure to address these issues can lead to higher electricity prices and inefficiencies in cross-border electricity flows, hindering the full benefits of market integration.

Figure 5.8 Interconnector operation in the PES for select lines in 2030



Notes: GWh = Gigawatt-hour; AT = Austria; BE = Belgium; CZ = Czech Republic; DK = Denmark; FR = France; DE = Germany; IT = Italy; NL = Netherlands; NO = Norway; PL = Poland; SK = Slovakia; ES = Spain; SE = Sweden; CH = Switzerland; UK = United Kingdom.

5.10 EU27 INTEGRATION WITH NEIGHBOURING MARKETS

Integration with neighbouring regions presents a significant opportunity for the European Union to accelerate the energy transition by enabling a wider deployment of renewable energy, making systems more stable and achieving cost-effective decarbonisation. However, realising these benefits requires tailored, collaborative approaches to address the unique opportunities and challenges of each partnership. Insights from the T-MED initiative, which modelled inter-connection scenarios between the European Union and North Africa in 2030 using merchant lines and in 2050 under full market integration, underline the transformative potential of such strategic infrastructure development.

Each neighbouring region offers distinct opportunities and challenges based on its resource availability, market structure and geopolitical context. The following provides a closer look at the roles and implications of these partnerships:

- **Nordic countries** contribute greatly to EU energy ambitions with their abundant hydropower and wind resources, which enhance low-carbon flexibility and boost system reliability. These resources are vital for balancing the variability of renewables within the European Union. At the same time, the financial demands from the high costs of inter-connections and differing market frameworks requires close co-ordination to maximise shared benefits.
- **The United Kingdom** brings advanced capabilities in offshore wind and energy markets, which complement the European Union's renewable integration and energy security strategies. However, evolving regulatory frameworks and political uncertainties in the post-Brexit context require thoughtful dialogue and co-operation to ensure smooth and mutually beneficial collaboration.
- **Countries in the EU's eastern neighbourhood,** including Türkiye and Eastern Partnership countries such as Ukraine and Georgia, offer significant opportunities for the diversification of the EU energy mix through their substantial potential in wind, solar, and hydropower. These partnerships could strengthen energy resilience region-wide, although long-term and sustainable co-operation will require addressing political uncertainties and supporting the development of local energy markets.
- **North Africa** offers vast potential for solar energy generation, creating opportunities for low-cost, clean energy exchanges with the European Union through HVDC power lines. Two-directional inter-connectors could make not only renewable energy imports to Europe but also electricity exports to North Africa possible, making systems more flexible and boosting energy security on both sides (IRENA, 2023b). Deeper energy system integration could improve grid stability, help optimise resources and increase market efficiency, among other benefits, although this also introduces challenges, including a need for co-ordinated infrastructure investments, regulatory harmonisation and geopolitical considerations. Strong, stable and equitable partnerships will be essential to unlocking these opportunities.
- **The Middle East** provides opportunities for co-operation on system operation and to collaborate on large-scale solar energy projects and green hydrogen production, supporting the long-term EU decarbonisation agenda. Realising these opportunities will require addressing geopolitical complexities and ensuring that the necessary infrastructure is developed in a manner that benefits all parties involved.

These regional partnerships highlight the strategic role of inter-connections in achieving EU energy and climate objectives. Trust, alignment of regulatory frameworks and investments in shared infrastructure can support the European Union in collaborating with its neighbours to build a resilient, secure and sustainable energy future.

5.11 INVESTMENT IN THE POWER SECTOR

The investment requirements of the European Union's energy transition, as detailed in previous sections, underscore the critical role of the power sector infrastructure in achieving climate neutrality. These investments align with the scenarios presented – both the PES and DES – highlighting the scale and focus of financial efforts needed to deliver on 2030 and 2050 EU targets (Table 5.5).

Table 5.5 Cumulative power sector infrastructure investment needs for both scenarios across key periods (EUR, billions)

	2025-2030		2031-2040		2041-2050		2025-2050	
	PES	DES	PES	DES	PES	DES	PES	DES
Renewable Energy	**749**	**753**	**684**	**852**	**882**	**1 128**	**2 314**	**2 732**
Solar PV	273	273	140	205	217	262	**629**	**740**
Onshore Wind	202	202	148	163	280	272	**630**	**637**
Offshore Wind	225	225	285	306	265	421	**775**	**952**
Batteries	**34**	**34**	**117**	**120**	**64**	**69**	**215**	**224**
Grids	**329**	**408**	**966**	**1 075**	**888**	**999**	**2 183**	**2 482**
Total investment for renewable capacity, grids and flexibility	**1 118**	**1 201**	**1 806**	**2 088**	**1 906**	**2 273**	**4 830**	**5 562**

Notes: DES = Decarbonising Energy Scenario; PES = Planned Energy Scenario; PV = photovoltaic.

These substantial investment figures, particularly the significant allocation to renewable energy capacity and grid modernisation shown in Table 5.5, underscore the EU's commitment to directing financial resources towards strategic areas that drive both decarbonisation and industrial competitiveness, aligning with the investment priorities outlined in the Clean Industrial Deal and the EU's broader economic strategy for sustainable growth.

Overall, cumulative investment needs in the EU power sector for renewable capacity, grids, and flexibility are expected to total EUR 4.8 trillion under the Planned Energy Scenario and EUR 5.6 trillion under the Decarbonising Energy Scenario by 2050, equivalent to an average of EUR 193 billion and EUR 223 billion per year, respectively, reflecting the magnitude of financial mobilisation required to deliver a resilient, low-carbon power sector.

Renewable energy capacity expansion. The EU's renewable energy capacity must grow exponentially to meet increasing electricity demand and replace fossil fuel generation. Investments in solar PV and wind technologies dominate the forecast:

- **Solar PV.** Reaching up to 1 443 GW by 2050 under the DES, requiring cumulative investments exceeding EUR 740 billion by 2050.
- **Onshore wind.** Expansion to 517 GW in the DES necessitates robust financial commitment, particularly in Northern and Eastern Europe. Investment reaches EUR 637 billion by 2050.
- **Offshore wind.** Scaling up to 303 GW by 2050 in the DES will demand high capital investments, particularly for turbine manufacturing, offshore grid connections and deep-sea infrastructure reaching EUR 952 billion by 2050 in the DES.

Domestic and international grid modernisation and expansion. The integration of high shares of VRE necessitates investments in grid upgrades, including:

- **Transmission and distribution networks.** Modernisation to accommodate renewable energy flows and enhance inter-connectivity, with investment needs of between EUR 2.2-2.5 trillion by 2050 in both the PES and DES.
- **Digital infrastructure.** Deployment of smart grids to manage decentralised generation, balance supply-demand and optimise energy flows across borders.

Energy storage systems. Both battery and pumped storage capacity are projected to rise to play a key role by 2050 in system operation and reliability. Crucial investments are needed in:

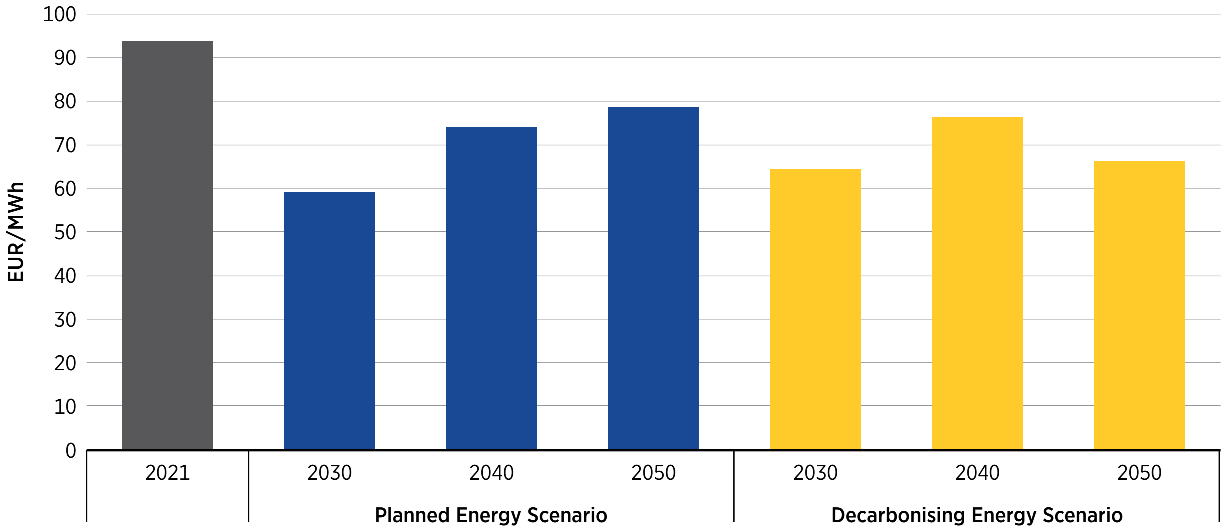
- **Utility-scale batteries.** To ensure system stability and provide peak-shaving capabilities, up to 240 GW of batteries will need to be deployed across the European Union, with cumulative investment needs reaching approximately EUR 224 billion by 2050 in the DES.

Electrification of end-use sectors. The electrification of transport, buildings and industry demands significant upgrades to existing networks and charging infrastructure. Investments must also address rising peak loads through distributed energy resources and demand-side flexibility solutions.

5.12 WHOLESALE ELECTRICITY MARKET IMPACTS

Figure 5.10 shows how wholesale electricity prices in the EU27 evolve under both scenarios considered – the PES and DES – at four milestones: 2021, 2030, 2040 and 2050. The analysis is based on hourly dispatch modelling for each milestone year, broadly aligned with European day-ahead market modelling, ensuring it captures operational constraints such as flexibility needs, fuel costs and system balancing requirements.

Figure 5.9 Annual generation-weighted average of wholesale electricity market pricing



Notes: EUR = Euro; MWh = megawatt hour.

In 2021, prices were exceptionally high, averaging EUR 94 /megawatt hour (MWh), due to tight supply, surging demand and rising carbon costs. By 2030, they drop significantly, reaching EUR 64 /MWh in the DES and EUR 59 /MWh in the PES, as electrification and renewables expand.

From there, trends shift. By 2040, prices climb again – EUR 74 /MWh in the PES, EUR 77 /MWh in the DES – as fossil fuel dependence in the PES keeps costs volatile, while the DES faces challenges in integrating a rapid scaling of electrification with a rising carbon price along the whole horizon. By 2050, the PES prices rise further to EUR 79 /MWh, while the DES stabilises at EUR 66 /MWh, highlighting the long-term cost advantage of a decarbonised system.

These findings align with the priorities outlined in the 2024 Mission Letters issued by European Commission President, Ursula von der Leyen, to the Commissioner. Notably, the emphasis on accelerating the green transition and enhancing energy system resilience is evident in the mandates given to key figures such as the Executive Vice-President for Clean, Just, and Competitive Transition, Teresa Ribera Rodríguez, and the Executive Vice-President for Prosperity and Industrial Strategy, Stéphane Séjourné. The analysis supports the Commission's strategic direction, highlighting the importance of early investments in renewable energy, grid modernisation and system flexibility to achieve a stable and affordable energy future.

The key takeaways are that delaying clean energy investments raises long-term electricity costs. A market built around renewables and flexibility leads to more stable, affordable power in the long term, even as carbon prices rise. High CO_2 costs alone will not guarantee an efficient transition – without grid upgrades, storage and DSM, a vast clean energy expansion can become costly. The modelling, broadly aligned with the European day-ahead market, confirms that system constraints must be addressed early to prevent volatility and ensure a cost-effective transition. Additionally, managing price volatility requires continuous review of market designs to ensure they support flexibility, resilience, and affordability as the energy mix evolves.

5.13 KEY ACTIONS AND PRIORITIES FOR POWER SECTOR DECARBONISATION AND GREEN HYDROGEN

Achieving the transformative energy scenarios envisioned for Europe as described in this analysis requires a co-ordinated effort across policy, market and technology fronts. This section outlines the policies and actions needed to accelerate the shift to a cleaner, more resilient and inter-connected energy system (Table 5.6). Central to this transition are measures to expand renewable energy, modernise infrastructure, improve grid flexibility and phase out carbon-intensive technologies.

Table 5.6 Key actions and priorities in power and green hydrogen

OUTCOMES	CURRENT REGULATIONS, DIRECTIVES OR PROPOSALS	ADDITIONAL MEASURES AND ACTIONS SUGGESTED
Phasing out coal-fired power plants in Europe by 2040	Just Transition Mechanism, EU Coal Phase-Out Strategy	• Providing financial mechanisms for coal plant retirement. • Investing in retraining programmes for coal-dependent workers. • Implementing social equity measures to ensure a just transition. • Enhancing renewable energy deployment in coal-reliant regions.
Developing cross-border electricity markets for increased integration of renewable energy sources	Regulation (EU) 2019/943 on the internal market for electricity, Revised TEN-E Regulation	• Harmonising regulations for cross-border energy exchange. • Expanding inter-connections to meet the 15% inter-connection target by 2030. • Implementing market rules to support flexible energy trading. • Establishing regional energy hubs for co-ordinated planning.
Increasing offshore wind capacity by 2050	Offshore Renewable Energy Strategy, Revised TEN-E Regulation	• Supporting research and development for advanced offshore wind technologies. Aligning offshore wind developments with the TEN-E priority corridors. • Simplifying permitting and licensing procedures for offshore projects. • Establishing mechanisms for public-private partnerships to fund large-scale offshore developments.

Scaling up hydrogen infrastructure to support a decarbonised energy system	Revised TEN-E Regulation (EU/2022/869), EU Hydrogen Strategy	• Providing financial incentives for the deployment of electrolysers and green hydrogen production plants. • Harmonising technical standards for hydrogen infrastructure to ensure compatibility across EU countries. • Supporting hydrogen imports from neighbouring regions through projects of mutual interest.
Ensuring sufficient storage capacity for a highly renewable power sector by 2050	EU Battery Alliance, Hydrogen Strategy, Revised TEN-E Regulation	• Scaling up investments in hydrogen storage infrastructure. • Supporting pumped hydro storage deployment in suitable regions. • Establishing a clear policy framework for energy storage. • Enhancing access to EU funding for modernisation of distribution grids and smart-grid projects.
Support smart and bi-directional charging functionalities for electric vehicles	Auto action plan and communication on corporate fleets	• Set minimum targets for the deployment of bi-directional charging points in public and workplace charging infrastructure, especially for corporate fleets. • Establish a certification scheme for vehicle to grid ready vehicles and chargers to support consumer trust and accelerate market uptake.
Enhancing energy system resilience and reliability to manage variability in renewable generation	EU Strategy for Energy System Integration, European Grid Action Plan	• Promoting the integration of distributed energy resources. • Implementing real-time grid balancing technologies. • Encouraging consumer participation in energy markets through innovative demand-side response programmes. • Improving supply chains for grid infrastructure and harmonising manufacturing requirements.
Achieving carbon neutrality in the power sector by 2050	European Climate Law, Fit for 55 Package, Revised TEN-E Regulation	• Expanding renewable energy capacity through competitive auctions. • Implementing carbon pricing mechanisms to disincentivise fossil fuel usage. • Promoting circularity in renewable energy technologies to reduce life-cycle emissions. • Strengthening policies for net-negative technologies.

6

SOCIO-ECONOMIC IMPACTS OF THE ENERGY TRANSITION

KEY FINDINGS

- **Under the Decarbonising Energy Scenario (DES), the EU27's GDP is expected to improve by an additional 2.1% on average annually over 2023-2050 compared with the Planned Energy Scenario (PES)**. The EU27 economy would be adding approximately EUR 724 billion in 2050 (or around EUR 576 billion per year throughout the 2023-2050 period) under the DES compared with the PES.

- **The difference in the GDP is mostly due to investment in the transition's first decade (2023-2030), and then due to investment as well as indirect and induced effects from 2030 onwards.** Trade has a decreasing but positive impact in driving GDP differences throughout the transition period (*i.e.* 2023-2050), but to a lesser extent in comparison with investment and indirect and induced effects.

- **The domestic responses to carbon price shifts, technology prices, power sector capacity, fossil fuel subsidies and investment expenditures are all reflected in the positive effect of induced-aggregate prices.** Price levels are expected to increase as the front-loaded investment in renewables and increased carbon prices drives up electricity prices in the transition's first decade (*i.e.* 2023-2030).
- **Under the DES, employment is expected to be 0.9% higher on average annually than under the PES over 2023-2050.** The employment difference peaks in the transition's first decade (about a 1.6% difference, approximately 4 million additional jobs), and then declines progressively to 1.8 million additional jobs (representing more than 0.7% difference) created in 2050.
- **Compared with the PES, the higher economy-wide employment under the DES is mainly due to the indirect and induced effects throughout the transition period. In the first decade, the positive contributions are mainly driven by consumer expenditures.** Public investment and spending, coupled with private investment, lead to more jobs under the DES compared with the PES. The effects are higher in the years until 2030, due to a higher government contribution to transition-related investments (*e.g.* energy efficiency and end uses, electrification, renewables) in the short term.
- **Employment in the EU energy sector would potentially reach nearly 8 million under the DES, relative to the recent figure of 3.2 million jobs by 2030.** The approximately 2.7 million additional jobs in renewables and other transition-related sectors (energy efficiency, power grids and flexibility, vehicle charging infrastructure and hydrogen) would far exceed job losses (approximately 0.3 million) in the conventional energy sector (fossil and nuclear) under the DES compared with the PES in 2030. By 2050, the number of jobs would fall to 6.8 million under the DES – still 45% higher than the expected figure under the PES.
- **Approximately 92% of energy employment would relate to renewables and other transition-related sectors under the DES in 2030.** The sectoral pattern is expected to persist and increase to 96% in 2050, signalling a substantial shift towards cleaner energy sources. Under the DES, other transition-related sectors would have approximately 4.2 million jobs, representing about 62% of energy sector jobs, consistent with the investment driver. Renewables would represent 34% of energy sector jobs in 2050, amounting to 2.3 million positions.

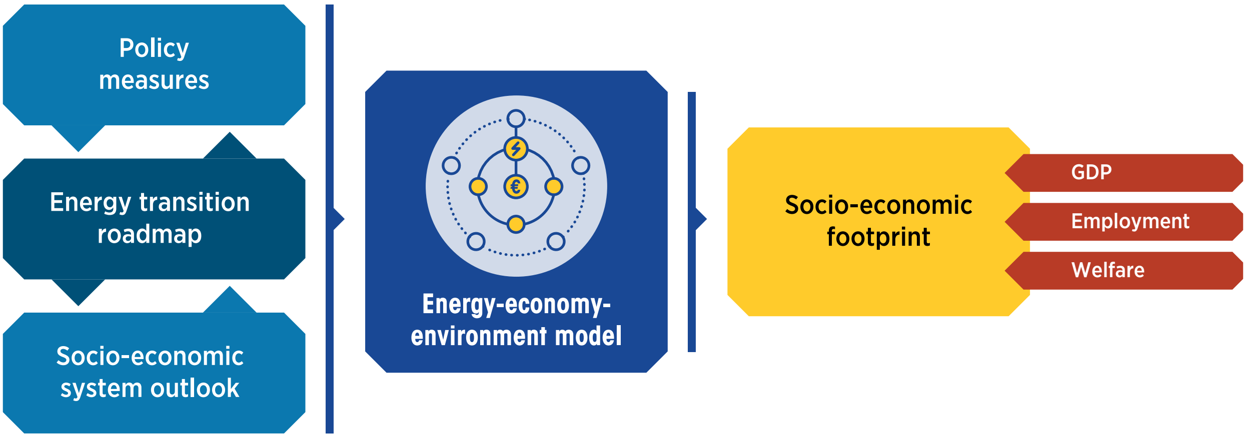
KEY MESSAGES

- **These figures demonstrate the possibility of increasing renewable energy across the EU27 job market, mainly driven by wind and solar development.** Under the DES, wind and solar are expected to dominate the renewable energy job market in the EU27, accounting for over 1.1 million and approximately 1.6 million jobs in 2030 and 2050, respectively. Bioenergy follows with approximately 0.6 million jobs in 2050. Lastly, hydropower and others (tidal/wave and geothermal) contribute with nearly 0.15 million jobs in 2050.
- **Proper planning and policy making require an understanding of the socio-economic consequences of the transition pathways (at different levels of ambition).** Policy makers must be aware of how policy choices will affect people's well-being and overall welfare. To this end, IRENA has developed a Welfare Index covering five dimensions of the energy transition: economic, social, environmental, distributional and energy access. Under the DES, the social, distributional and environmental dimensions drive overall Welfare Index improvements in the EU27.
- **The immediate redirection of capital to low-carbon solutions would avoid locking economies into carbon-intensive systems and minimise stranded assets.** Planning would ensure the countries and individuals most dependent on fossil fuels can benefit from the transition. Involving local communities fosters trust, increases project acceptance and can contribute valuable local knowledge. Efforts towards a just transition must be integrated early, at both micro and macro levels, to create inclusive opportunities.

6.1 OVERVIEW

Based on its analysis of key drivers and impacts, IRENA has offered insights supporting energy transition planning and implementation at the global, regional and national levels since 2016 (IRENA, 2016, 2018b, 2019a, 2019b, 2020b, 2021, 2022, 2023c, 2023d, 2023a). It has stressed the importance of a holistic global policy framework (Figure 6.1) for an effective and broadly beneficial energy transition. A faster transition requires wide sharing of the transition's advantages and mitigation of challenges, and complementarity and support among policy aspects spanning a diversity of technological, social and economic challenges.

Figure 6.1 Socio-economic assessment framework



A socio-economic analysis was conducted using a macro-econometric model (Energy-Environment-Economy Macro-Econometric model, E3ME[11]) that integrates the energy system and global economies into a single quantitative framework. The model sheds light on the trade-offs between economic prosperity and employment, while examining welfare aspects, including the distributional implications of these policy choices. Policy makers need to be aware of how such choices will affect people's well-being and overall welfare. They must also be aware of the potential gaps and hurdles that could affect progress. This chapter aims to provide EU policy makers with valuable insights and recommendations for ensuring that the region's transition to a low-carbon economy is both just and equitable, creating jobs while reducing inequalities.

[11] *The E3ME global macro-econometric model (www.e3me.com) is used for the assessment of socio-economic impacts. Energy mixes and related investment, based on the World Energy Transitions Outlook (IRENA, 2023a), are used as exogenous inputs for each scenario, as well as climate- and transition-related policies.*

This chapter discusses the socio-economic differences between the DES[12] and PES in the EU27 region. The same inputs and assumptions as in the 2023 edition of the *World Energy Transitions Outlook* (IRENA, 2023a) have been used. Under the PES, the EU27 is expected to experience robust economic growth, as envisioned in the baseline assumption for the E3ME model.[13] Under this baseline trend, the region's real GDP would increase at a compound annual growth rate of about 1.5% per year over 2023-2050, in which period the region's population is projected to decrease slightly, reaching approximately 512 million in 2050 (Table 6.1). Economy-wide employment is also expected to rise, by an average of about 0.1% per year, over the same period.

Table 6.1 GDP, labour force and population growth projections under the PES

VARIABLE	2023-2030 (CAGR %)	2031-2040 (CAGR %)	2041-2050 (CAGR %)
Real GDP	2.0	1.6	1.1
Economy-wide employment	1.2	-0.3	-0.2
Total population	0.04	-0.02	-0.09

Notes: CAGR = compound annual growth rate; GDP = gross domestic product.

IRENA's analysis explores the socio-economic footprint of the transition, using assumptions from its climate policy baskets (Box 6.1), which include several measures to support a just and inclusive transition (carbon pricing, international collaboration, subsidies and progressive fiscal regimes to address distributional aspects, investments in public infrastructure and spending on social initiatives) as well as policies encouraging the deployment, integration and promotion of energy transition technologies.

The next sections delve into the macroeconomic findings to analyse the socio-economic impacts of policy baskets on the energy transition in the EU27 until 2050. An analysis of how the transition might affect GDP, job creation and people's welfare is provided.

[12] *The DES in this analysis corresponds to the 1.5°C Scenario in the World Energy Transitions Outlook.*

[13] *Baseline forecasts are constructed using a comprehensive set of international data sources. The main source for population data is the United Nations (World Population Prospects), and for GDP forecasts, the main sources are the International Monetary Fund (for short-term forecasts), European Commission (annual ageing report) and International Energy Agency (World Energy Outlook) (for long-term forecasts). These are applied to historical data from the World Bank, International Monetary Fund and European Commission (AMECO, Eurostat). E3ME is a global, macro-econometric model owned and maintained by Cambridge Analytica: www.e3me.com.*

Box 6.1 IRENA's climate policy baskets

IRENA's socio-economic footprint analysis includes in its modelling a diverse set of policies to enable and support a sustainable energy transition. Holistic planning and synergistic implementation can address the multiple angles of interactions among the energy, economy and social systems more successfully than an approach that relies on a limited number of disconnected interventions.

Importantly, the level of carbon pricing needed to bring about an energy transition roadmap depends on the effective implementation of accompanying policies. Since IRENA's analysis includes a diverse policy basket, the transition targets can be achieved with significantly lower carbon prices than might otherwise be required.

IRENA's socio-economic analysis assesses the following comprehensive set of policies:

- International co-operation, supporting enabling social policies in all countries and addressing the international justice and equity dimensions
- Domestic progressive redistributive policies
- Carbon pricing, evolving over time, with carbon prices differentiated by each country's income level and special treatment of sectors with high direct impacts on people (households and road transport)
- Fossil fuel phaseout mandates for all sectors
- Phaseout of all fossil fuel subsidies
- Regulations and mandates to deploy transition-related technologies and strategies, including renewables, electric vehicles and hydrogen, and system integration through electrification and P2X (Power-to-X)
- Mandates and programmes for energy efficiency deployment across sectors
- Policies for adapting organisational structures to the needs of renewables-based energy systems (such as in the power sector)
- Subsidies for transition-related technologies, including for households and road transport
- Direct public investment and spending to support the transition, with participation in all transition-related investments, but with special focus on enabling infrastructure deployment (*e.g.* electric vehicle charging stations, hydrogen infrastructure, smart meters), energy efficiency deployment and policy expenditure
- Policies to ensure international co-operation supports transition requirements: earmarking of funds to transition-related investments, increasing social spending
- Public involvement in addressing stranded assets, both domestically and internationally
- Policies to ensure government fiscal balances support transition requirements, addressing domestic distributional issues and ensuring deficit spending supports transition requirements

6.2 ECONOMIC IMPACTS

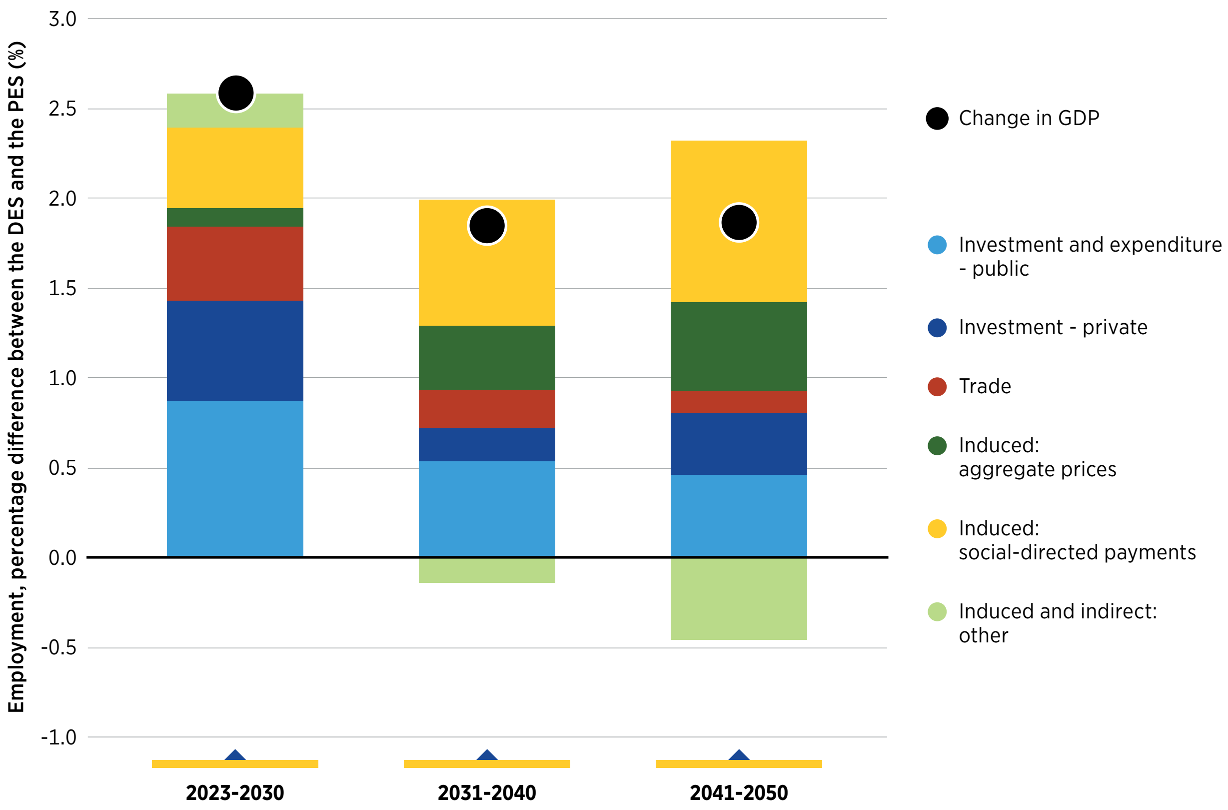
Under the DES, the EU27's GDP is expected to improve by an additional 2.1% on average annually over 2023-2050 compared with the PES. The EU27 economy would be adding approximately EUR 724 billion in 2050 (or around EUR 576 billion per year throughout the 2023-2050 period) under the DES compared with the PES. Investment, and indirect and induced effects, and trade, to a lesser extent, are the main macroeconomic factors that have key impacts on the GDP difference depending on the period analysed. The difference in GDP is mostly due to investment in the transition's first decade (2023-2030), and then due to investment as well as indirect and induced effects from 2030 onwards. Trade has a decreasing but positive impact in driving GDP differences throughout the transition period (*i.e.* 2023-2050), but to a lesser extent in comparison with investment and the indirect and induced effects.

For a better understanding of the structural elements underlying the socio-economic footprint, IRENA's macroeconomic analysis disaggregates outcomes by drivers and sectors (Figure 6.2).

Investment, which is of two types (private investment, and public investment and expenditure), has the most influence on the GDP difference between the two transition scenarios and mainly in the transition's first decade (*i.e.* 2021-2030) (Figure 6.2). Public investment and expenditure contribute positively to the GDP difference between the DES and PES. The average impact on the GDP difference is 0.9% over 2023-2030 and approximately 0.5% from 2031-2050. This is primarily due to front-loaded investment. Under the DES, government social spending will more than double between 2023 and 2050. It will increase by around EUR 24 billion compared with the PES in 2050 (and over EUR 459 billion in cumulative money throughout the transition period). This leads to increased spending on non-defence services predominantly provided by the government, including public administration, health care and education, therefore mainly benefiting public and personal services.

Private investment also has a positive impact on the GDP difference throughout the transition period. Over the transition's first decade, the positive impact is significantly higher under the DES than the PES; the average impact is approximately 0.6% per year over 2021-2030. However, the impact is lower from the second decade. Despite the negative impact of fossil fuel investment in the power sector on other sectors and the loss of investment in fossil fuel supply, transition-related investments from the private sector (in energy efficiency and other end uses, grids and energy flexibility, and mainly renewables) play an important role in offsetting these trends. Investment in the power sector crowds out investment in other sectors, such as construction, metals and engineering. But soon after the first decade, this effect dissipates as the relative impact of the front-loaded investment tapers off.

Figure 6.2 GDP in the EU27, percentage difference between the DES and PES, by driver, 2023-2050



Notes: DES: Decarbonising Energy Scenario; GDP = gross domestic product; PES: Planned Energy Scenario.

Induced and indirect effects have different components (aggregate prices, social-directed payments and others). Together, they form the second-strongest factor in driving GDP differences. The combined effect of aggregate prices and social-directed payments becomes an increasingly significant factor in driving the GDP difference. The average impact is 0.6% over 2023-2030, to 1.4% in the decade 2041-2050. The positive role of social-directed payments highlights how increased social spending stimulates the EU economy, while induced aggregate prices reflect domestic responses to carbon pricing, technology costs, power sector capacity and investment expenditures during the transition. The social-directed payment driver addresses domestic distributional issues, that is, supporting the lower-quintile population. The revenue recycling treatment assumes that households receive lump-sum payments directly under the DES when the government accumulates excess tax revenues after covering transition-related investment and other policy costs. Thus, it has an increasing positive impact throughout the transition period. The domestic responses to shifts in carbon prices, technology prices, power sector capacity, fossil fuel subsidies and investment expenditures are all reflected in the positive role of induced-aggregate prices.

Price levels are expected to increase as the front-loaded investment in renewables and increased carbon prices drive up electricity prices in the transition's first decade (*i.e.* 2023-2030). Electricity costs in the two subsequent decades are lower than in the first decade due to net-zero emissions by 2050, as well as a rapid renewables deployment throughout the transition and significant decline in their costs under the DES. Industries have lower production costs, and households are under less financial strain due to energy expenditure. On the other hand, the impact of other induced and indirect effects is changing from positive in the first decade, mainly due to consumer expenditure, to negative from the second decade, as the EU economy comes under a more pronounced income tax burden over 2041-2050. Differences in revenue and spending between the DES and PES throughout the transition period require increases of income taxes under the DES. The observed higher negative impact is due to a decline in revenues from the carbon tax alongside emissions, which leads to a significant increase in income tax to cover transition-related investments and the loss of value in the fossil fuel supply sector.

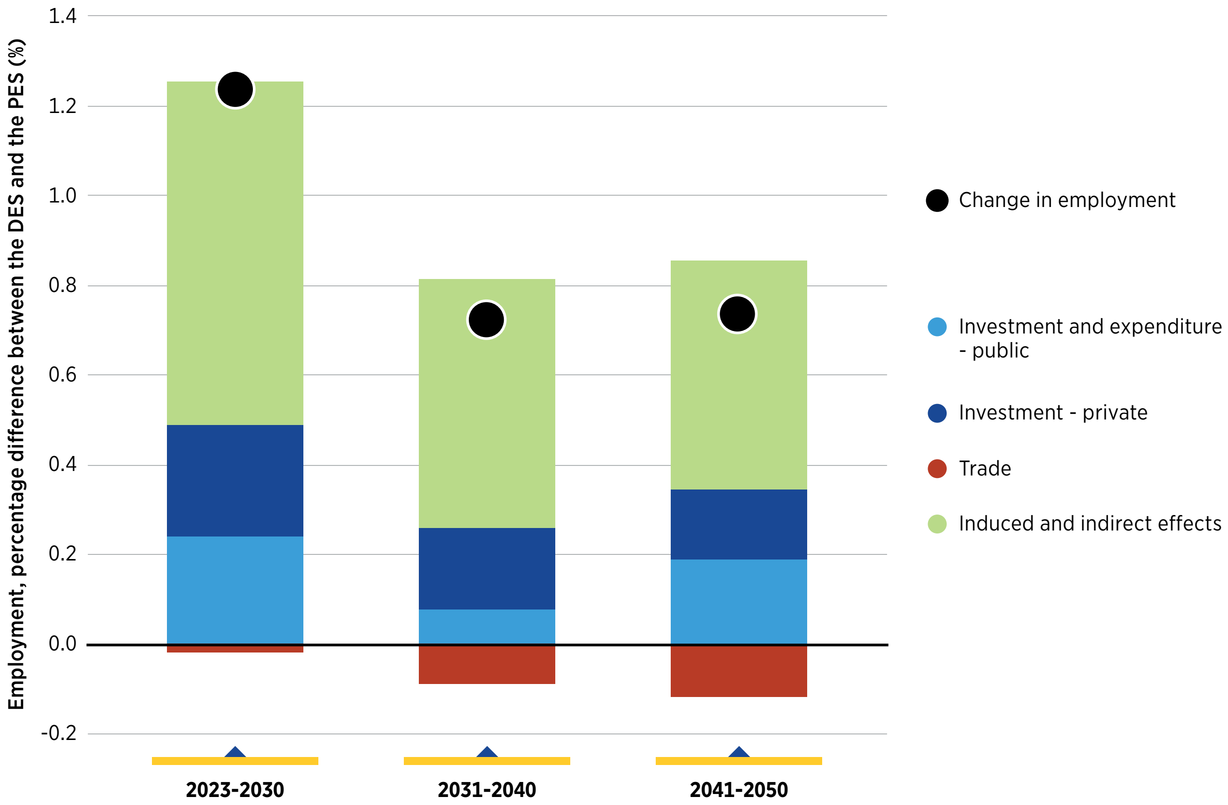
Trade also plays a positive role in the EU27 economy over the transition period, but to a lesser extent than investment and induced and indirect effects. The consumption of all fossil fuels reduces dramatically under the DES. Because the European Union imports fossil fuel products, the trade balance improves and the region is thus under a reduced burden of import dependence. The improvement in the energy trade balance contributes positively to the GDP difference and peaks in the years to 2030, amounting to EUR 413.1 billion over 2023-2030 (equivalent to about 8.3% of the cumulative GDP difference between the DES and PES).

This effect decreases in the subsequent decades as demand for fossil fuel imports declines with renewables' development. Also, the negative impact from changes in other trade diminishes the positive contribution from net trade in fuels. Changes in other trades are negative throughout the last two decades, mainly due to an increase in demand for imports, such as machinery and electronics, critical to transition-supporting infrastructure. This growth in imports demand outweighs the positive impact from the increasing exports of basic non-fuel manufactured products (including metals, wood and paper, and non-metallic minerals) throughout the years to 2050. These increasing exports are attributable to the endogenous investment response, which allows the economy to expand productive capacity and increase participation in the global supply chain to support the development of technology required for the global energy transition.

6.3 ECONOMY-WIDE EMPLOYMENT

Under the DES, economy-wide employment is expected to be 0.9% higher on average annually than under the PES over the period 2023-2050. The employment difference peaks in the transition's first decade (a 1.6% difference, about 4 million additional jobs), and then declines progressively, to 1.8 million additional jobs (a greater than 0.7% difference) created in 2050. This trend is supported by drivers related to induced and indirect effects, and investment, whereas trade has a lesser impact. Figure 6.3 presents the components of the drivers.

Figure 6.3 Economy-wide employment in the EU27, percentage differences between the DES and PES, by driver, 2023-2050



Notes: DES = Decarbonising Energy Scenario; PES = Planned Energy Scenario.

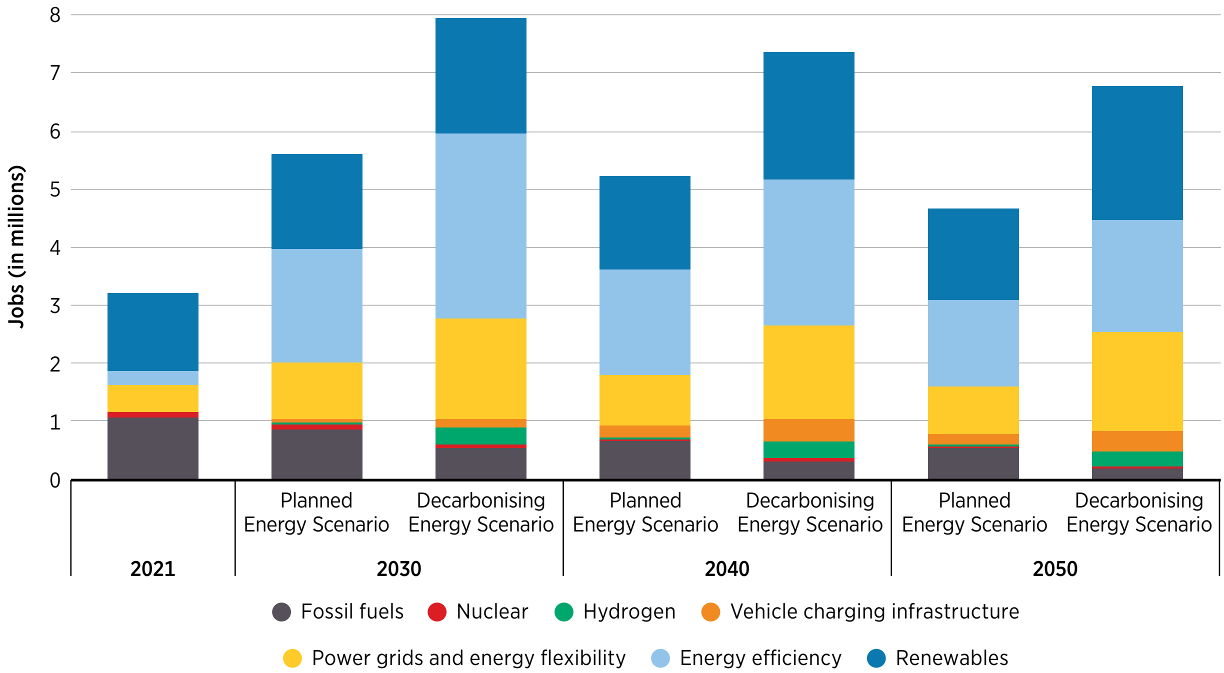
Compared with the PES, higher economy-wide employment rates under the DES are mainly driven by induced and indirect effects throughout the transition period. In the first decade, the positive trend is mainly driven by consumer expenditure. Household consumption has a net positive effect due to lump-sum payments and price effects. Changes in sectors such as food, beverages and tobacco within the basic manufacturing aggregate; machinery and electrical equipment; and public and personal services, which support consumer spending, are a direct result of shifting consumption habits. The indirect effects through supply chain effects are also captured through the substantial increase in intermediate goods, flowing from the substantial increase in consumer expenditure. However the positive effect from consumer expenditure is slightly reduced by the negative impacts from wage effects and lower investment stimulus, mainly in the decade 2041-2050. The negative impact is mainly attributable to the loss in fossil fuel supply and is most visible in the basic manufacturing, engineering and transport equipment, construction, and distribution and retail aggregates. In addition, demand for motor vehicles falls (within the engineering and transport equipment aggregate) due to the accelerated deployment of electric vehicles, whose production requires far less labour than combustion engines.

Public investment and expenditure, coupled with private investment, lead to more employment relative to the PES. The effects are higher in the years to 2030, due to higher government contribution to transition-related investments (*e.g.* energy efficiency and end uses, electrification, renewables) in the short term. More service-oriented sectors receive more public investments, including in the redesign of building spaces, upgrades to energy management systems and retrofits. Also, social spending under the DES remains consistently higher than that under the PES throughout the transition, leading to substantial new employment across the region that benefits from tax receipts. The net effect of private investment on economy-wide employment is lessened from the second decade by a reduction in fossil-fuel-related investments compared with the PES. Most jobs created are related to the power sector. Investment in energy efficiency, the power sector and other low-carbon measures foster investment elsewhere to support the transition. On the other side, the impacts of trade on the economy-wide employment difference become increasingly negative throughout 2023-2050. This is mainly because of changes in net trade in non-energy sectors under the DES. Non-energy trade under the DES is lower because goods imports increase.

6.4 ENERGY SECTOR JOBS

Looking ahead to 2030, jobs in the EU27 energy sector would potentially reach nearly 8 million under the DES, relative to the recent figure of 3.2 million jobs (Figure 6.4). The gain of around 2.7 million jobs in renewables and other transition-related sectors (energy efficiency, power grids and flexibility, vehicle charging infrastructure and hydrogen) would far exceed job losses (approximately 0.3 million) in the conventional energy sector (fossil and nuclear) under the DES compared with the PES in 2030. By 2050, the number of jobs would fall to 6.8 million under the DES – still 45% higher than the expected figure under the PES (approximately 4.7 million).

Figure 6.4 Overview of energy sector jobs in the EU27 by sector

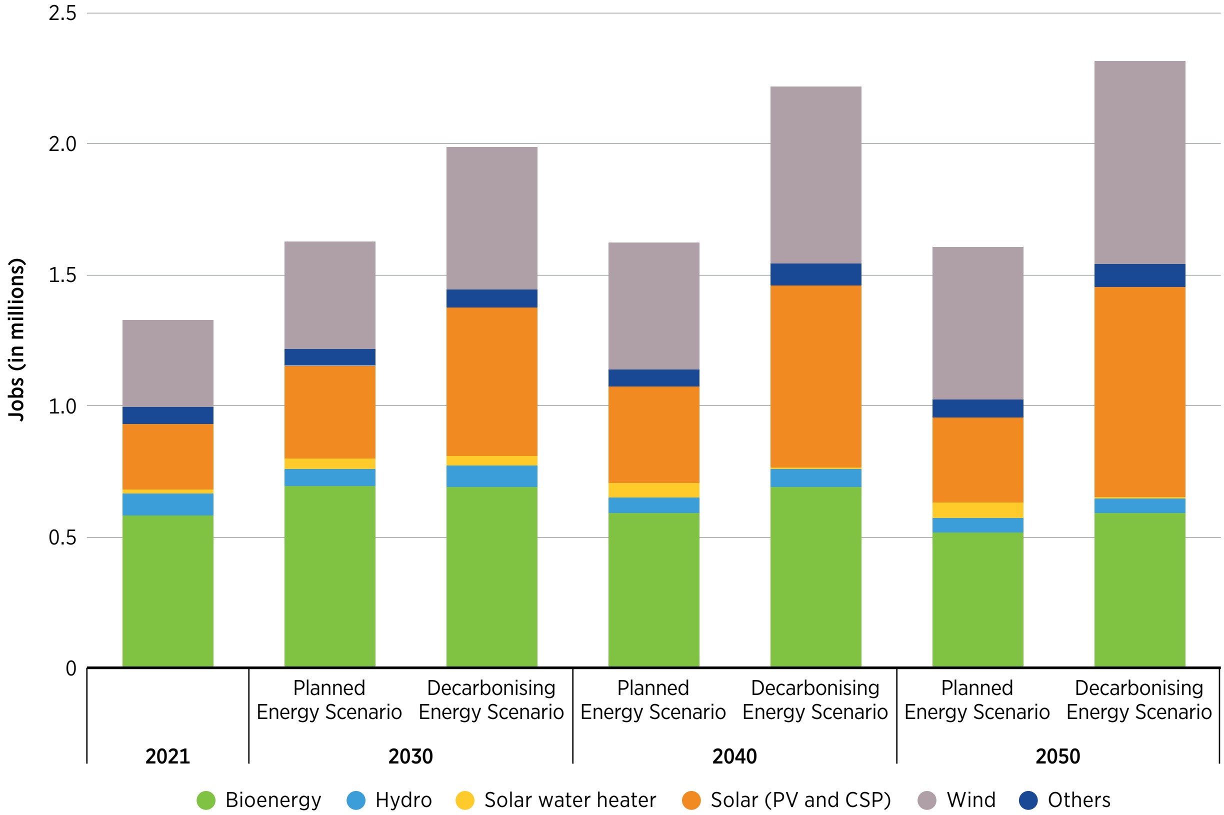


From the sector perspective, approximately 92% of energy employment would relate to renewables and other transition-related sectors under the DES in 2030. The sector's pattern is expected to persist and increase to 96% in 2050, signalling a substantial shift towards cleaner energy sources. Under the DES, other transition-related sectors would have approximately 4.2 million jobs – the highest number – representing about 62% of energy sector jobs, consistent with the investment driver. Renewables would represent 34% of energy sector jobs in 2050, amounting to 2.3 million positions. Compared with the 1.6 million jobs under the PES, this demonstrates a substantial growth in renewable energy job opportunities.

6.5 RENEWABLES JOBS

Job opportunities in renewable energy are projected to increase significantly, from 1.3 million in 2021 to over 1.6 million by 2050 under the PES. The growth is more pronounced under the DES, surging to 2.3 million jobs by 2050. Figure 6.5 illustrates this trend, with an additional 700 000 renewable energy jobs generated relative to the PES.

Figure 6.5 Overview of renewable energy jobs in the EU27



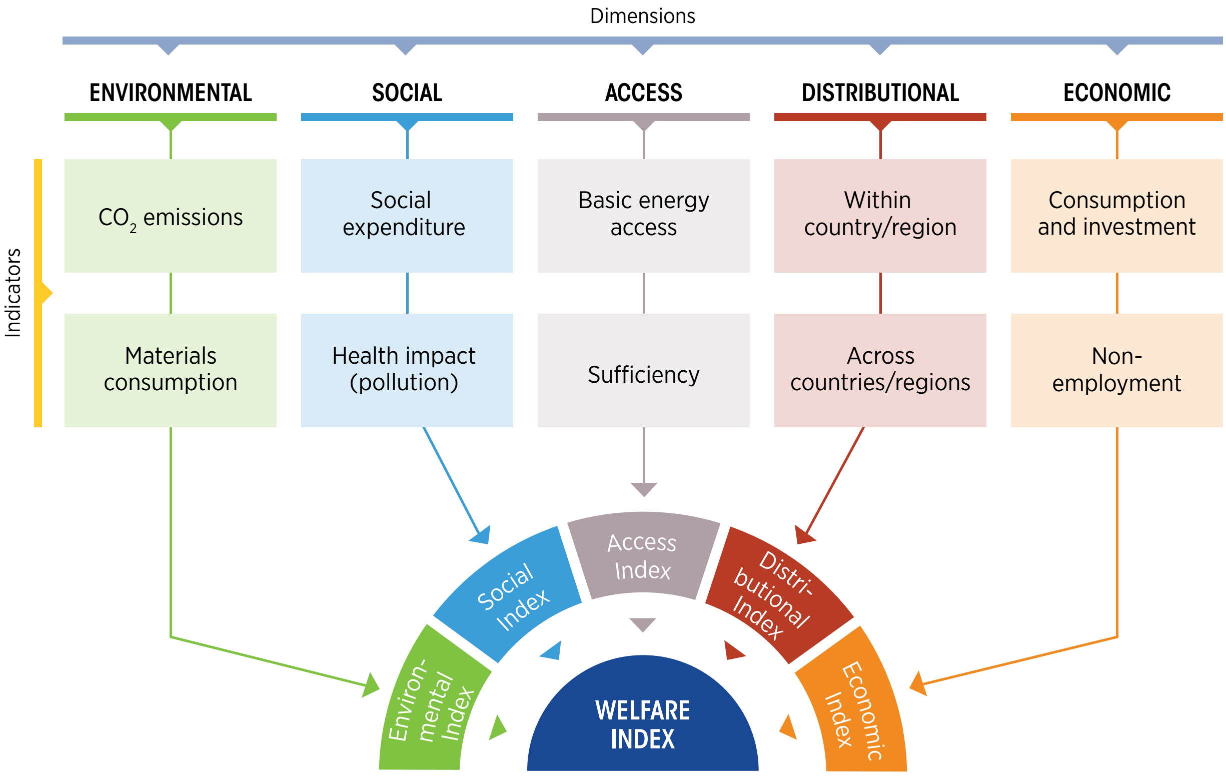
Notes: "Others" includes geothermal and tidal/wave; CSP = concentrated solar power; DES = Decarbonising Energy Scenario; PES = Planned Energy Scenario; PV = photovoltaic.

Under the DES, wind and solar are expected to dominate the renewable energy job market in the EU27. They will account, in total, for over 1.1 million and around 1.6 million jobs in 2030 and 2050, respectively. Bioenergy follows, with about 0.6 million jobs in 2050. Lastly, hydropower and others (tidal/wave and geothermal) contribute with nearly 0.15 million jobs in 2050. Overall, these figures demonstrate a possibility of increasing renewable energy across the EU27 job market, mainly driven by wind and solar energy development.

6.6 WELFARE

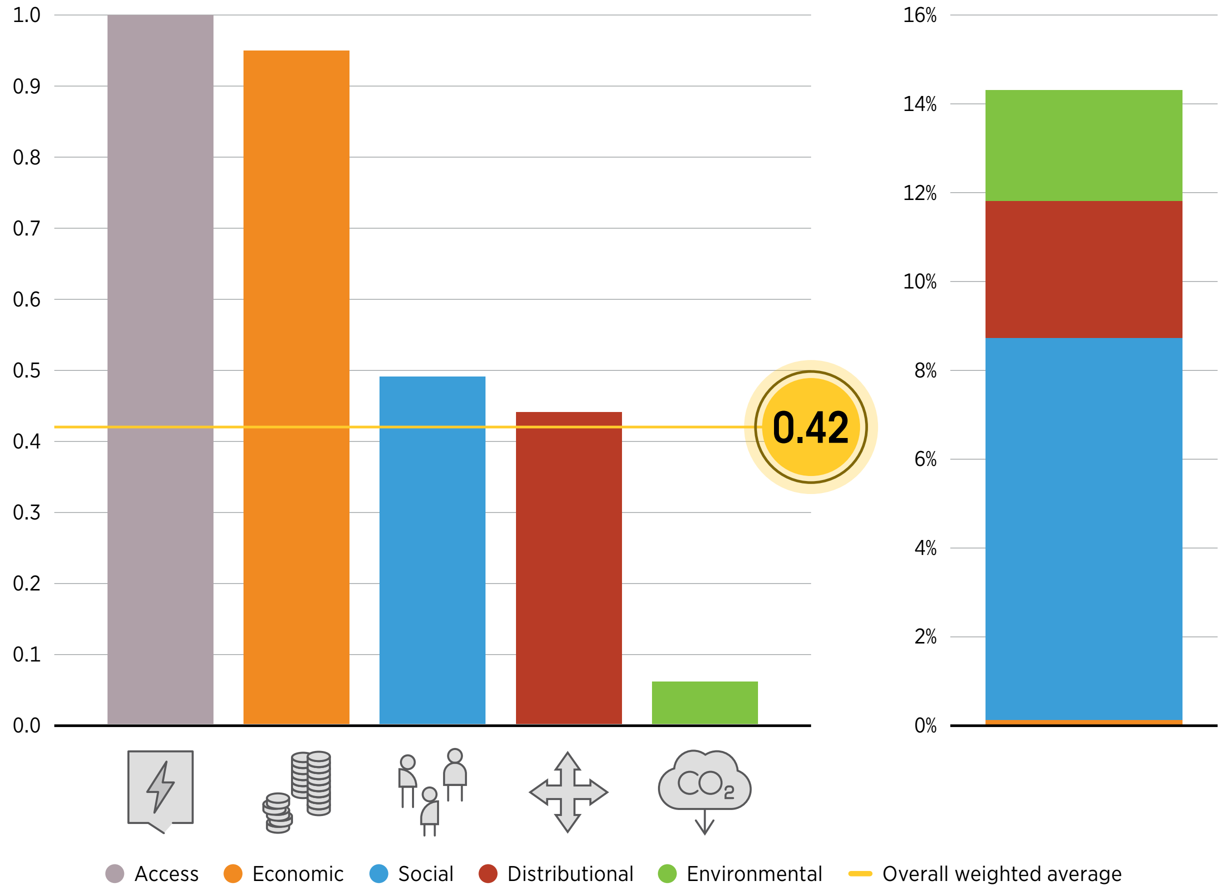
GDP is the standard measure of economic output. The concerns of citizens, however, go beyond GDP, which does not include or value factors that are not priced into the market, such as human health, fulfilling jobs and environmental quality. And while climate change will likely have negative impacts on future GDP, it will also have significant impacts on societies, nature and economies that no measure of GDP captures. Conventional indicators such as GDP are thus incomplete and potentially misleading since they do not consider future constraints of natural resources and climate. To incorporate some aspects of social well-being, IRENA has developed and upgraded a Welfare Index (IRENA, 2016, 2019a, 2020b, 2020c, 2021) for use in its benefits analyses. The index has five dimensions relating to the energy transition: economic, social, environmental, distributional and energy access. Each dimension is composed of two indicators (Figure 6.6).

Figure 6.6 IRENA's Energy Transition Welfare Index



The Welfare Index and its dimensional indicators provide a comprehensive indication of policy development for welfare improvement in the European Union. While the IRENA Energy Transition Welfare Index allows simple, direct comparisons across scenarios and regions, it does not offer insights into the factors behind results, or into which policy actions would bring further improvements. A separate index, for each of the five dimensions, helps to clarify this. To represent this graphically, IRENA presents the overall Welfare Index (shown at the centre of a flower-shaped illustration) along with the five-dimensional indices (shown as "petals") for the European Union for the DES in 2050 (left panel of Figure 6.7). The Welfare Index and its five dimensions are structured on a scale from 0 (low performance) to 1 (high performance). Under the DES, the overall Welfare Index is projected to be 0.42. In the EU27, improvements are driven by the social, distributional and environmental dimensions (reflecting the already high access and economic indices under the PES). Welfare improvement under the DES over the PES reaches 14.3% by 2050 (right panel of Figure 6.7). Although this indicates some benefits of the energy transition for the EU27, there is still significant potential for additional policies to deliver further improvements in welfare. The rest of this section will delve into each of the dimensions.

Figure 6.7 Welfare Index by dimension for the DES (left) and difference in welfare between the DES and PES (right), 2050



The **social dimension**, the largest driver of welfare improvement under the DES is informed by two indicators: social expenditure per capita and health costs per person linked to air pollution attributable to the energy system. This dimension is boosted vastly under the DES due to significant public health improvements from reduced air pollution and lower heat stress. Social expenditure, however, slightly increases between the PES and the DES. Under the PES, the reliance on fossil fuels (oil and natural gas) is expected to entail large adverse health impacts in the European Union. The level attained in the social dimension under the DES (0.49 by 2050 on a scale from 0 to 1) (left panel of Figure 6.7) is due to low levels of improvement in social expenditure, indicating potential for further measures to provide additional improvements on this dimension.

The **distributional dimension** is the second-largest driver of welfare improvement under the DES in the EU27 (right panel of Figure 6.7). This dimension measures income and wealth inequality within and across EU countries. Income distribution improves under the DES compared with the PES, but slightly, because the available fiscal space is limited. While tax receipts increase, carbon tax revenues decline with a diminishing reliance on fossil fuels, a loss of value in the oil and gas sector (lower global oil prices and lower extraction volumes), and an increase of public expenditure (subsidies to support the transition, transition-related public investment). The absolute distributional index reaches 0.44 under the DES by 2050 in the EU27 (left panel of Figure 6.7), compared with 0.36 under the PES. This is higher than the global index of 0.34 in the DES, although it indicates significant room for improvement. Additional efforts are necessary to incorporate measures for reducing distributional inequalities into the climate policy agenda.

The third driver of welfare improvement in the DES is the **environmental dimension**, which addresses the sustainability of socio-economic activity within planetary boundaries. It consists of two indicators: cumulative carbon dioxide (CO_2) emissions and per capita material consumption.[14] Most of the improvement is due to much-reduced CO_2 emissions. By contrast, material consumption in the European Union under both the PES and DES continues to increase, dragging down the absolute environmental dimension, with the lowest index value of 0.06 (left panel of Figure 6.7). To address these environmental challenges, the EU countries should strategically reduce resource dependence, ensure much higher policy commitment to the regional material footprint and focus on developing sustainable consumption – promoting responsible consumption, which prioritises a non-resource-intensive economy.

The **access dimension** of the IRENA Energy Transition Welfare Index is informed by two indicators: access to basic energy and progression along the energy sufficiency level[15] (assumed at 20 kilowatt hours [kWh]/capita/day, in line with the literature; Millward-Hopkins *et al.*, 2020).[16] The European Union has already reached universal energy access; thus, the basic energy access indicator is at the maximum, of 1, under the PES and DES. Under both scenarios, EU's sufficiency level would exceed the sufficiency level throughout the transition period, providing the maximum index value of 1. Therefore, there is no improvement in this dimension under the DES relative to the PES.

The **economic dimension** is composed of an indicator that measures consumption and investment per capita and another that measures non-employment as the ratio of the shares of the working-age population (age group from 15 to 64 years) that is neither employed nor in an educational institution while belonging to the 14-24 age group.[17] Under the DES, there is no improvement in the consumption and investment indicator relative to the PES, and it goes negligibly negative. However, by 2050, the non-employment indicator for the European Union would slightly improve under the DES. Overall, the dimension does not improve under the DES relative to the PES.

In conclusion, Figure 6.7 (left panel) shows where to focus policy action to improve welfare in the European Union. The greatest room for improvement is in the environmental dimension, which could be improved by focusing mainly on the reduction of material consumption. There is also room for improvement in the distributional and social dimensions, which could be improved by focusing on better wealth distribution and providing additional fiscal space, both of which make better income distribution possible, and on the implementation of policies enabling higher social spending. Finally, additional policy efforts supporting higher social spending are needed for additional improvement in the social dimension.

[14] *Currently evaluated as domestic material consumption.*

[15] *This indicator has been defined as the required level of energy consumption for decent living, but no more.*

[16] *The authors estimated a sufficiency level of 11.6-30.4 kWh/capita/day across all 119 countries of the Global Trade Analysis Project: www.gtap.agecon.purdue.edu/databases/regions.aspx?version=9.211.*

[17] *Non-employment is used instead of unemployment or employment metrics because of its more comprehensive gauging of the social implications of paid work, which is the main goal of a Welfare Index.*

REFERENCES

ACEA (2024), "Charging ahead: accelerating the roll-out of EU electric vehicle charging infrastructure", www.acea.auto/publication/automotive-insights-charging-ahead-accelerating-the-rollout-of-eu-electric-vehicle-charging-infrastructure/

Agora Energiewende and Wuppertal Institute (2020), "Breakthrough Strategies for Climate- Neutral Industry in Europe: Policy and Technology Pathways for Raising EU Climate Ambition", www.agora-industry.org/fileadmin/Projekte/2020/2020_10_Clean_Industry_Package/A-EW_197_Strategies-Climate-Neutral-Industry-EU_Summary_WEB.pdf

Ajanovic, A. (2023), "Electricity vs hydrogen in the transition towards sustainable mobility", *Oxford Open Energy*, vol. 2, https://doi.org/10.1093/ooenergy/oiad013

Association of the European Heating Industry (2021), "Heating Market Report 2021", https://ehi.eu/wp-content/uploads/2022/09/EHI-2021-Heating-Market-Report.pdf

Basma, H., and Rodríguez, F. (2023), *A total cost of ownership comparison of truck decarbonization pathways in Europe*, No. Working Paper 2023-28, International Council on Clean Transportation, https://theicct.org/publication/total-cost-ownership-trucks-europe-nov23/

BNEF (2024), "Electric Vehicle Outlook 2024", Bloomberg New Energy Finance, https://about.bnef.com/electric-vehicle-outlook/

Broadbent, C. (2016), "Steel's recyclability: Demonstrating the benefits of recycling steel to achieve a circular economy", *The International Journal of Life Cycle Assessment*, vol. 21/11, https://link.springer.com/article/10.1007/s11367-016-1081-1

Dittmann, F., *et al.* (2016), "Heat Roadmap Europe: Space Cooling Technology in Europe; Technology Data and Demand Modelling", *Heat Roadmap Europe 4* (HRE4), https://heatroadmap.eu/wp-content/uploads/2018/11/HRE4_D3.2.pdf

Draghi, M. (2024), "The future of European competitiveness", Energy Commission, https://commission.europa.eu/document/download/97e481fd-2dc3-412d-be4c-f152a8232961_en?filename=The%20future%20of%20European%20competitiveness%20_%20A%20competitiveness%20strategy%20for%20Europe.pdf

EEA (2024), "New registrations of electric vehicles in Europe", European Environment Agency, https://www.eea.europa.eu/en/analysis/indicators/new-registrations-of-electric-vehicles

ENTSOE and ENTSOG (2024), *Ten-year Network Development Plan 2024*, European Network of Transmission System Operators for Electricity and European Network of Transmission System Operators for Gas, https://2024.entsos-tyndp-scenarios.eu/

Euroelectric (2021), "Connecting the dots: Distribution grid investment to power the energy transition", www.eurelectric.org/publications/connecting-the-dots/

European Biogas Association (2024), *EBA Statistical Report 2024*, www.europeanbiogas.eu/shop-statistical-report-2024/

European Biogas Association (2025), *The Clean Industrial Deal*, EBA Position Paper, www.europeanbiogas.eu/wp-content/uploads/2025/02/EBA-CID-Position-Paper_Feb-2025.pdf

European Commission (2003), "Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a M9 system for greenhouse gas emission allowance trading within the M9 Union and amending Council Directive 96/61/E", https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02003L0087-20240301

European Commission (2012), "Treaty on the Functioning of the European Union", https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:12012E/TXT:en:PDF

European Commission (2016), "Share of renewables in energy consumption in the EU rose further to 16% in 2014", https://ec.europa.eu/eurostat/documents/2995521/7155577/8-10022016-AP-EN.pdf/38bf822f-8adf-4e54-b9c6-87b342ead339?t=1455032643000

European Commission (2019a), "Directive on common rules for the internal market for electricity (EU 2019/944)", https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019L0944

European Commission (2019b), *Clean Energy for All Europeans Package: A legislative package aiming to achieve a clean, secure, and efficient energy transition by 2030*, https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en

European Commission (2020a), "Sustainable and smart mobility strategy", https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789

European Commission (2020b), "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions; A new Circular Economy Action Plan for a cleaner and more competitive Europe", https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF

European Commission (2020c), "EU Strategy for Energy System Integration", https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0299

European Commission (2020d), "A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives", https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0662

European Commission (2020e), *A hydrogen strategy for a climate-neutral Europe*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

European Commission (2020f), *EU Offshore Renewable Energy Strategy: Plans to achieve 300 GW of offshore wind and 40 GW of ocean energy by 2050*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:741:FIN&qid=1605792629666

European Commission (2020g), *EU Reference Scenario 2020*, https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en

European Commission (2021), "Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')", https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119

European Commission (2022a), *Emissions Database for Global Atmospheric Research (EDGAR) Report 2022*, European Commission, Joint Research Centre, https://edgar.jrc.ec.europa.eu/report_2022

European Commission (2022b), "Launch of the Route 35 platform: Our priorities for achieving our electrification goals; Speech by Commissioner Thierry Breton", https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_22_7785

European Commission (2022c), *EU Solar Strategy: Targeting 600 GW of installed solar capacity by 2030, emphasising rooftop installations and integration*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN&qid=1653034500503

European Commission (2022d), *REPowerEU Plan: Accelerating the transition to renewable energy and reducing dependency on fossil fuels, especially imports from Russia*, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

European Commission (2023a), "Directive (EU) 2023/1791 of the European Parliament and of the Council, on energy efficiency and amending Regulation (EU) 2023/955 (recast)", https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023L1791

European Commission (2023b), "Regulation (EU) 2023/851 of the European Parliament and of the Council of 19 April 2023 amending Regulation (EU) 2019/631 as regards strengthening the CO_2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambition", https://eur-lex.europa.eu/eli/reg/2023/851

European Commission (2023c), "Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU", https://eur-lex.europa.eu/eli/reg/2023/1804/oj

European Commission (2023d), " Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC", https://eur-lex.europa.eu/eli/reg/2023/1805/oj

European Commission (2023e), "Directive (EU) 2023/2413 of the European Parliament and of the Council amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652", https://eur-lex.europa.eu/eli/dir/2023/2413/oj

European Commission (2023f), "Regulation (Eu) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation)", https://eur-lex.europa.eu/eli/reg/2023/2405/oj

European Commission (2023g), "Proposal for a Regulation of the European Parliament and of the Council on the use of railway infrastructure capacity in the single European railway area, amending Directive 2012/34/EU and repealing Regulation (EU) No 913/2010", https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0443

European Commission (2023h), "Proposal for a Directive of the European Parliament and of the Council amending Council Directive 92/106/EEC as regards a support framework for intermodal transport of goods and Regulation (EU) 2020/1056 of the European Parliament and the Council as regards calculation of external costs savings and generation of aggregated data", https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0702

European Commission (2023i), "Directive (Eu) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading system", https://eur-lex.europa.eu/eli/dir/2023/959/oj

European Commission (2023j), "Net Zero Industry Act Proposal", https://single-market-economy.ec.europa.eu/publications/net-zero-industry-act_en

European Commission (2023k), "Commission adopts new proposal on combining transport modes for more sustainable freight", https://ec.europa.eu/commission/presscorner/detail/en/ip_23_5587

European Commission (2023l), "Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions; A Green Deal Industrial Plan for the Net-Zero Age", https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52023DC0062

European Commission (2023m), "Commission welcomes completion of key 'Fit for 55' legislation, putting EU on track to exceed 2030 targets", https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_23_4754/IP_23_4754_EN.pdf

European Commission (2023n), "RMIS - Raw Materials Information System", https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials

European Commission (2023o), "Establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020", https://eur-lex.europa.eu/resource.html?uri=cellar:903d35cc-c4a2-11ed-a05c-01aa75ed71a1.0001.02/DOC_1&format=PDF

European Commission (2023p), "Key facts on energy and EU buildings", https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

European Commission (2023q), "Directive (EU) 2023/2413 as regards to the promotion of energy from renewable sources (RED III)", https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202302413

European Commission (2023r), "Energy Efficiency Directive (EU/2023/1791)", https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32023L1791

European Commission (2023s), "Energy Taxation Directive (2003/96/EC)", https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32003L0096

European Commission (2023t), "Biomethane", https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/biomethane_en

European Commission (2023u), *Delivering on the EU offshore renewable energy ambitions*, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52023DC0668

European Commission (2024a), "Mission Letter for Executive Vice-President-designate for a Clean, Just and Competitive Transition", https://commission.europa.eu/document/download/5b1aaee5-681f-470b-9fd5-aee14e106196_en?filename=Mission%20letter%20-%20RIBERA.pdf

European Commission (2024b), *European Commission Priorities 2024-2029*, https://european-union.europa.eu/priorities-and-actions/eu-priorities/european-union-priorities-2024-2029_en

European Commission (2024c), "Mission Letter for Commissioner-designate for Energy and Housing", https://commission.europa.eu/document/download/1c203799-0137-482e-bd18-4f6813535986_en?filename=Mission%20letter%20-%20JORGENSEN.pdf

European Commission (2024d), *Mission Letter for Commissioner-designate for Startups, Research and Innovation*, https://commission.europa.eu/document/download/833e082a-0c39-4bc6-a119-e0760ebc7360_en?filename=mission-letter-zaharieva.pdf

European Commission (2024e), "Regulation (EU) 2024/1610 of the European Parliament and of the Council of 14 May 2024 amending Regulation (EU) 2019/1242 as regards strengthening the CO_2 emission performance standards for new heavy-duty vehicles and integrating reporting obligations, amending Regulation (EU) 2018/858 and repealing Regulation (EU) 2018/956", https://eur-lex.europa.eu/eli/reg/2024/1610/oj

European Commission (2024f), "Regulation (EU) 2024/1679 of the European Parliament and of the Council of 13 June 2024 on Union guidelines for the development of the trans-European transport network, amending Regulations (EU) 2021/1153 and (EU) No 913/2010 and repealing Regulation (EU) No 1315/2013", https://eur-lex.europa.eu/eli/reg/2024/1679/oj

European Commission (2024g), "National energy and climate plans (NECPs)", https://energy.ec.europa.eu/topics/energy-strategy/national-energy-and-climate-plans-necps_en

European Commission (2024h), "Mission Letter for the Commissioner-designate for Sustainable Transport and Tourism", https://commission.europa.eu/document/download/de676935-f28c-41c1-bbd2-e54646c82941_en?filename=Mission%20letter%20-%20TZITZIKOSTAS.pdf

European Commission (2024i), "Impact Assessment Report Part 3 accompanying the Document Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions", https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52024SC0063

European Commission (2024j), "CEF Transport Alternative Fuels Infrastructure Facility (AFIF) call for proposal", https://cinea.ec.europa.eu/funding-opportunities/calls-proposals/cef-transport-alternative-fuels-infrastructure-facility-afif-call-proposal_en

European Commission (2024k), "Regulation (EU) 2024/1735 of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724", https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401735

European Commission (2024l), "Energy Performance of Buildings Directive (EU/2024/1275)", https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401275

European Commission (2024m), "Eco-design for Sustainable Products Regulation (EU 2024/1781)", https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401781

European Commission (2024n), "EU National Energy and Climate Plans (NECPs)", https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en

European Commission (2024o), *Europe's 2040 climate target and path to climate neutrality by 2050; Impact Assessment Report Part 3*, https://eur-lex.europa.eu/resource.html?uri=cellar:6c154426-c5a6-11ee-95d9-01aa75ed71a1.0001.02/DOC_3&format=PDF

European Commission (2024p), "Fit for 55 - The EU's plan for a green transition", www.consilium.europa.eu/en/policies/fit-for-55/

European Commission (2024q), *Electricity Market Design Directive (2024) (Directive EU/2024/1711)*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401747

European Commission (2024r), *Recommendation on Energy Storage: Enhancing Deployment within the EU Energy Market*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=oj:JOC_2023_103_R_0001

European Commission (2024s), *Electricity Market Stability Regulation (2024) (Regulation EU/2024/1747)*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401711

European Commission (2025a), "Global Climate Highlights 2024", https://climate.copernicus.eu/global-climate-highlights-2024

European Commission (2025b), "A Competitiveness Compass for the EU", https://commission.europa.eu/document/download/10017eb1-4722-4333-add2-e0ed18105a34_en

European Commission (2025c), *Affordable Energy Action Plan: Addressing Energy Price Volatility and Consumer Protections*, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52025DC0079&qid=1741780110418

European Commission, *et al.* (2024), "Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels: final report", In Georgiadou, M., Goumas, T. and Chiaramonti, D., (eds.), Publications Office, LU, https://data.europa.eu/doi/10.2777/679307 (accessed 10 December 2024).

European Heat Pump Association (2024), *European Heat Pumps Market and Statistics* 2022, www.ehpa.org

European Parliament (2024), "Legislative proposal on multimodal digital mobility services", www.europarl.europa.eu/legislative-train/spotlight-JD%2023-24/file-multimodal-digital-mobility-services

Eurostat (2024), "Greenhouse gas emissions by source sector", https://ec.europa.eu/eurostat/databrowser/view/env_air_gge__custom_1879636/default/table (accessed 6 December 2024).

Goldman Sachs (2024), "Electric vehicle battery prices are expected to fall almost 50% by 2026", www.goldmansachs.com/insights/articles/electric-vehicle-battery-prices-are-expected-to-fall-almost-50-percent-by-2025 (accessed 10 December 2024).

Hermelink, A., *et al.* (2019), "Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU", https://energy.ec.europa.eu/document/download/2b58c118-89c1-46b5-a450-0f2d5d215e2c_en?filename=1.final_report.pdf

ICAO, *et al.* (2023), "ICAO's 2050 net-zero CO_2 goal for international aviation" https://theicct.org/wp-content/uploads/2022/12/global-aviation-ICAO-net-zero-goal-jan23.pdf

International Energy Agency (2018), "The Future of Cooling: Opportunities for energy-efficient air conditioning", https://iea.blob.core.windows.net/assets/0bb45525-277f-4c9c-8d0c-9c0cb5e7d525/The_Future_of_Cooling.pdf

IRENA (2016), *Renewable energy benefits: Decentralised solutions in the agri-food chain*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2016/Sep/Renewable-Energy-Benefits-Decentralised-solutions-in-agri-food-chain

IRENA (2018a), *Renewable energy prospects for the European Union*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2018/Feb/Renewable-energy-prospects-for-the-EU

IRENA (2018b), *Global transformation: A roadmap to 2050*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2018/Apr/Global-Energy-Transition-A-Roadmap-to-2050

IRENA (2019a), *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition

IRENA (2019b), *Renewable energy: A gender perspective*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2019/Jan/Renewable-Energy-A-Gender-Perspective

IRENA (2020a), *Renewable energy prospects for Central and Southeastern Europe Energy Connectivity (CESEC)*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2020/Oct/Renewable-Energy-Prospects-for-Central-and-South-Eastern-Europe-Energy-Connectivity-CESEC

IRENA (2020b), *Global renewables outlook: Energy transformation 2050*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020

IRENA (2020c), *Measuring the socio-economics of transition: Focus on jobs*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2020/Feb/Measuring-the-socioeconomics-of-transition-Focus-on-jobs

IRENA (2021), *World energy transitions outlook: 1.5°C pathway*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook

IRENA (2022), *Socio-economic footprint of the energy transition: Japan*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2022/Sep/Socio-economic-Footprint-of-the-Energy-Transition-Japan

IRENA (2023a), *World energy transitions outlook 2023: 1.5°C pathway*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023

IRENA (2023b), *Planning and prospects for renewable power: North Africa*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Jan/Planning-and-prospects-for-renewable-power-North-Africa

IRENA (2023c), *Socio-economic footprint of the energy transition: Indonesia*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Jan/Socio-economics-of-the-energy-transition-Indonesia

IRENA (2023d), *Socio-economic footprint of the energy transition: Southeast Asia*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Jul/Socio-economic-footprint-of-the-energy-transition-Southeast-Asia

IRENA (2024), *World energy transitions outlook 2024: 1.5°C pathway*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2024/Nov/World-Energy-Transitions-Outlook-2024

Joint Research Centre Data Catalogue (2015), "The JRC Integrated Database of the European Energy System", https://data.jrc.ec.europa.eu/dataset/jrc-10110-10001

Knobloch, F. (2017), "A technical analysis of FTT: Heat - A simulation model for technological change in the residential heating sector", www.researchgate.net/publication/350707809_FTTHeat_-_A_

von der Leyen, U. (2024), *Political Guidelines for the Next European Commission 2024–2029*, European Commission, https://ec.europa.eu/info/publications/political-guidelines-next-european-commission-2024-2029_en

Lyu, C., *et al.* (2024), "Volatility spillovers and carbon price in the Nordic wholesale electricity markets", *Energy Economics*, vol. 134, pp. 107559, https://doi.org/10.1016/j.eneco.2024.107559

Marchetti, R. (2019), *Deliverable 2.2: Building vs Heating Stock (Space and Water) Matrix, EU and Country Level.*, https://heating-retrofit.eu/wp-content/uploads/2020/02/20191107_HARP_D2.2_Building-vs-heating-stock-matrix.pdf

Millward-Hopkins, J (2020), "Providing decent living with minimum energy: A global scenario", *Global Environmental Change*, vol. 65/102168, www.sciencedirect.com/science/article/pii/S0959378020307512?utm_source=chatgpt.com

Nijs, W., *et al.* (2021), "EU challenges of reducing fossil fuel use in buildings", https://op.europa.eu/en/publication-detail/-/publication/95fac4d8-5d57-11ec-9c6c-01aa75ed71a1/language-en

ODYSEE-MURE (2024), "Country profiles: Main energy efficiency trends and policies by country", www.odyssee-mure.eu/publications/efficiency-trends-policies-profiles/

POLITICO (2024), "The EU wants new power lines to save the economy; first it needs cash and local support", www.politico.eu/article/energy-eu-france-power-grids-climate-economy-cash-local-support/ (accessed 6 February 2025).

Pothen, F., and Hundt, C. (2024), "European post-consumer steel scrap in 2050: A review of estimates and modeling assumptions", *Econ Stor*, www.econstor.eu/bitstream/10419/283005/1/188041998X.pdf

The Greens/EFA (2025), "The EU Clean Industrial Deal: The need to serve people and planet", The Greens/EFA, https://extranet.greens-efa-service.eu/public/media/file/1/8966

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