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Science Advisory Council

The Future of Gas

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Science Advice for the Benefit of Europe

EASAC

EASAC – the European Academies' Science Advisory Council – is formed by the national science academies of the EU Member States to enable them to collaborate with each other in giving advice to European policy-makers. It thus provides a means for the collective voice of European science to be heard. EASAC was founded in 2001 at the Royal Swedish Academy of Sciences.

Its mission reflects the view of academies that science is central to many aspects of modern life and that an appreciation of the scientific dimension is a pre-requisite to wise policy-making. This view already underpins the work of many academies at national level. With the growing importance of the European Union as an arena for policy, academies recognise that the scope of their advisory functions needs to extend beyond the national to cover also the European level. Here it is often the case that a trans-European grouping can be more effective than a body from a single country. The academies of Europe have therefore formed EASAC so that they can speak with a common voice with the goal of building science into policy at EU level.

Through EASAC, the academies work together to provide independent, expert, evidence-based advice about the scientific aspects of public policy to those who make or influence policy within the European institutions. Drawing on the memberships and networks of the academies, EASAC accesses the best of European science in carrying out its work. Its views are vigorously independent of commercial or political bias, and it is open and transparent in its processes. EASAC aims to deliver advice that is comprehensible, relevant and timely.

EASAC covers all scientific and technical disciplines, and its experts are drawn from all the countries of the European Union, plus Norway, Switzerland and the United Kingdom. It is funded by the member academies. The expert members of EASAC's working groups give their time free of charge. EASAC has no commercial or business sponsors.

EASAC's activities include substantive studies of the scientific aspects of policy issues, reviews and advice about specific policy documents, workshops aimed at identifying current scientific thinking about major policy issues or at briefing policy-makers, and short, timely statements on topical subjects.

The EASAC Council has 30 individual members—highly experienced scientists nominated one each by the national science academies of EU Member States, by the Academia Europaea and by ALLEA. The national science academies of Norway, Switzerland and the United Kingdom are also represented. The Council is supported by a professional Secretariat that is temporarily shared between its member academies and by a Brussels Office at the Royal Academies for Science and the Arts of Belgium. The Council agrees the initiation of projects, appoints members of working groups, reviews drafts and approves reports for publication.

To find out more about EASAC, visit the website – www.easac.eu – or contact the EASAC Secretariat at secretariat@easac.eu

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Foreword

For many years, natural gas has been seen as the cleanest member of the family of fossil fuels, and it has been assumed that a change from burning coal to burning natural gas offers an important reduction in greenhouse gas emissions. However, this report by a group of experts nominated by EASAC's member academies challenges this conventional view.

In particular, the report highlights that natural gas produces not only carbon emissions when it is used to generate electricity and heat, and when it is liquefied for transportation as liquefied natural gas and then re-gasified, but also methane emissions during its extraction and distribution.

Recent reports by the Intergovernmental Panel on Climate Change have emphasised that global warming is likely to overshoot the 1.5 °C target set in the Paris Agreement within the next few years, unless greenhouse gas emissions are quickly reduced. Methane emissions have a lifetime in the atmosphere of only about 10 years, which is an order of magnitude shorter than that of carbon dioxide. However, the short-term (20-year) global warming potential of methane is over 80 times that of carbon dioxide. In the past, experts have used 100-year values of global warming potentials in their analyses, but the urgent need to limit global warming is changing this, notably because the 20-year global warming potential of methane is almost three times the 100-year value.

The urgent need to limit global warming coupled with the high global warming potential of natural gas is forcing other changes to conventional wisdom. For example, natural gas should no longer be considered as a transitional option for replacing coal on the road towards net-zero carbon emissions by 2050. Instead, natural gas must also be replaced.

Without natural gas, oil, or coal, the European Union (EU) will need a massive increase in the supply of renewable or other low-carbon sources of energy, and these energy sources will need to be carried and stored using one or more of the following energy carriers:

- Electricity will become by far the largest energy carrier in the EU, but major investments will be needed in more infrastructure to transport it. Renewable electricity will also require investments in demand response systems, in batteries, pumped hydroelectricity storage, in heat storage systems, and in back-up generators.

- Biofuels can be used to carry and store energy, but in future bio-resources will be limited and prioritised for high-value applications.

- Hydrogen and e-fuels can be used to carry and store energy, but these energy carriers (vectors) will be produced from either renewable electricity or natural gas with carbon capture and storage.

- Fossil fuels will continue to carry and store some energy for use in systems that are connected to carbon capture and storage facilities. However, few such facilities are currently in operation and their costs are still high.

Natural gas has three main uses in the EU today: in gas boilers to heat buildings; in gas turbines to generate electricity; and in industries for process heating and as a chemical feedstock. Alternatives to natural gas with cheaper running costs are already available to meet these needs, but their deployment will require many investment decisions and substantial amounts of investment capital.

For buildings, many EU Member States have already published plans to ban new gas boilers, which can be readily replaced by electric heat pumps or by district heating in urban areas. Such actions should be stimulated throughout Europe. Moreover, to reduce greenhouse gas emissions, heat pumps and district heating must use renewable or other energy supplies with low greenhouse gas emissions. For electricity generation, major increases in wind and solar power are expected, and electrification is expected to be a common option for many industries.

In summary, EASAC's conclusion is that Europe must prepare urgently for a future that will be built largely on renewable electricity and without natural gas. Current electricity demands will continue but more electricity will be needed to replace natural gas for heating buildings and industrial processes, to replace oil for transport, and to replace coal and gas for power generation.

Every possible step must therefore be taken to accelerate permitting for the construction of more renewable electricity generators and grid infrastructure for electricity supplies. At the same time, investments must be made in energy saving and in the electrification of energy-consuming systems in industry, buildings, and transport.

This EASAC project was started in the late autumn of 2021, before the invasion of Ukraine brought energy security and the role of gas to the top of the political agenda. Beyond the suffering of the Ukrainian population, the invasion has created disruptions in energy and pressures on the European economy that weigh on all parts of society, but it has also acted as a catalyst for action. Policy-makers, energy suppliers, energy users, and the finance sector must now work together to secure adequate supplies of clean energy while rapidly phasing out the use of fossil fuels. Simultaneously, they must minimise energy poverty by protecting and supporting vulnerable groups, households, and businesses.

Europe's energy system is on the verge of a massive transformation which will have wide repercussions on its economic, social, and geopolitical position.

Beyond technological questions, preparing for a renewable energy future also offers the unique opportunity to rethink the distribution of revenues and risks, of social value or social harm—both domestically and in our new partnerships with other countries. Although not specifically covered in this report, this will require developing a solid set of ethical criteria.

If managed quickly and correctly, the transition from natural gas and other fossil fuels to an energy economy with low greenhouse gas emissions will not only enable industries and businesses to develop and produce new products and services, and to create new high-quality jobs, but also to put Europe on a path towards a truly sustainable future.

Wim van Saarloos
EASAC President

Executive summary

The extraction, distribution, and burning of natural gas, coal, and oil (fossil fuels) produce greenhouse gas (GHG) emissions (mainly carbon dioxide and methane), which drive global warming and climate change. This is increasing the frequency of extreme weather and having devastating and costly impacts on our homes, communities, businesses, and agriculture. It is also reducing biodiversity by destroying marine and rural environments, notably in forests.

The need to reduce carbon dioxide emissions is now widely accepted, as illustrated in 2021 by the adoption of the European Union (EU) Climate Law to reduce carbon emissions to net zero by 2050. Similarly, acceptance of the need to reduce methane emissions was shown during 2021/22 by 150 countries signing up to the Global Methane Pledge for a reduction of 30% by 2030.

Phasing out the unabated[1] use of natural gas is an urgent priority

In the EU, natural gas is used in three sectors: buildings (for heating), electricity (for power generation), and industry (for process heating and as a feedstock for chemical processes).

Carbon emissions from natural gas accounted for nearly a quarter of carbon dioxide emissions from the EU's energy sector in 2021, and methane emissions from natural gas are substantial, but not adequately monitored. Some carbon emissions from the combustion of natural gas can be abated, namely captured and stored for the long term ('carbon capture and storage', CCS). However, carbon cannot be captured from all uses of natural gas, and few long-term carbon storage systems have yet been built.

Hence, most of the natural gas that will be used in the EU, at least in the short and medium terms, will be unabated, and to phase this out, along with coal and oil, is an urgent priority.

The EU energy transition is delivering secure energy supplies, but with high prices and serious risks of failing to deliver commitments to GHG emission reductions

For the EU to deliver its commitment to net zero by 2050, its energy transition must be accepted by energy suppliers and consumers, and they will require the unabated use of natural gas to be replaced by sustainable energy services without reducing the security and affordability of energy supplies for buildings, electricity generation, industry, and transport.

The war in Ukraine and the continuing recovery from the COVID pandemic have made the transition from natural gas to sustainable energy services riskier and more challenging. Supplies of piped natural gas and liquefied natural gas from Russia to the EU have been substantially reduced and there have been unprecedented rises in global energy prices. The high prices have provided an immediate incentive for energy saving, but basic energy services have become unaffordable for low-income households, vulnerable groups, and many businesses. Policy-makers and governments must therefore step up their actions on energy poverty reduction and business support.

Since early in 2022, EU Member States have implemented emergency measures to replace Russian supplies of natural gas and liquefied natural gas with imports from other sources, and they have also extended the planned lifetimes of some old fossil-fuelled electricity-generating plants. In other words, they have prioritised the provision of secure energy supplies over energy costs and the risks of failing to deliver their commitments to GHG emission reductions. More must now be done to reduce GHG emissions and bring down energy prices.

An integrated approach is called for with energy efficiency and renewable electricity to deliver GHG emission reductions and secure energy supplies at affordable prices

Substantial GHG emission reductions can be achieved by improving energy efficiency, but this cannot replace all the unabated uses of natural gas for energy, or the feedstock used by chemical industries.

To deliver enough low-carbon footprint (renewable or nuclear) electricity for replacing natural gas is by far the biggest challenge for policy-makers. It is a challenge because clean electricity is not only needed for the electrification of systems in buildings and industry that are currently fuelled by natural gas, but it is also needed for the electrification of transport and to produce renewable hydrogen and e-fuels, such as renewable ammonia and renewable methanol.

The already-growing demand and competition for renewable electricity calls for an integrated approach to

[1] Unabated use of natural gas means that the gas is burned without its carbon emissions being captured and stored, for example by using a carbon capture and storage (CCS) system.

energy supply and demand in the buildings, electricity generation, industry, and transport sectors, with the aim of accelerating the deployment and optimising the use of renewable electricity resources. This will help to bring down electricity prices because renewable electricity is already cheaper than electricity produced using fossil fuels. However, it will require long-term commitments and financing from policy-makers and industries, together with the retraining and re-skilling of workers at all levels in the existing workforce.

Seemingly conflicting priorities can and must be reconciled

Endorsed by its 28 member academies, and exploring the fast-moving (geo)political tensions, debates, and scientific evidence on the future of gas, this report provides messages for policy-makers who are grappling with seemingly conflicting priorities between urgent actions to maintain reliable but affordable energy services and equally urgent actions to reduce GHG emissions. It also recognises that policy-makers must prepare legislative frameworks for the medium and long terms. In summary, this report does the following:

1. Identifies key questions and assesses options for replacing natural gas with renewable electricity or other gaseous fuels, such as biomethane, hydrogen, renewable methanol, and e-fuels[2] for electricity generation, buildings, and industry, as well as impacts related to the simultaneous decarbonisation of transport. It also addresses the replacement of natural gas as a feedstock for the production of chemicals.

2. Considers the future of gas in the context of the EU Climate Law (net zero by 2050) and EU commitments to reduce GHG emissions by 55%[3] (compared with 1990 levels) by 2030.

3. Discusses the challenge of phasing out the unabated use of natural gas in the EU within the agreed timeframe while maintaining overall security of energy supplies and affordability for energy consumers and businesses.

4. Offers independent science-based advice for policy-makers on regulating the use of gaseous fuels in the transition to a decarbonised[4], secure, and affordable EU energy system by 2050.

EASAC's messages are prioritised under three timeframes for action: emergency measures (until 2025), short term (2023–2030), and medium/long terms (2030–2050)

EASAC's messages for EU policy-makers, investors and other stakeholders address three key dimensions of policies for the future of gas: GHG emission reduction, security of energy supplies, and affordability.

A summary of EASAC's messages for policy-makers is given in Tables S1a and S1b. Each message is explained in Chapter 10, and more detail on the science behind the messages can be found in the main body of the report.

Many of EASAC's messages are inter-dependent, but they fall into two broad categories: 'policies' that justify special attention and 'actions' to be taken by the responsible stakeholders.

Proposals for addressing some of the policies highlighted in Tables S1a and S1b have already been put forward by the European Commission so, in these cases, EASAC's messages relate to continuing discussions before adoption by the European Parliament and Council of the EU, and/or to their implementation at EU, national, and local levels.

Six high-priority messages in this report are the following

- **Energy efficiency first:** reduce energy demands in buildings, industry and transport.

- **Build more renewable electricity generators and electricity supply infrastructure** so that unabated natural gas can be phased out, together with coal and oil.

- **Ban installation of new gas boilers** in buildings because these consume 39% of natural gas used in the EU. Switch to heat pumps with renewable electricity or district heating.

- **Produce sustainable technologies in the EU and diversify supplies of critical raw materials and sustainable fuels** to maximise the future security of EU energy supplies.

[2] e-Fuels (e.g. e-methane, e-methanol, or e-ammonia) are produced using renewable hydrogen (produced by electrolysis of water using renewable electricity) and carbon dioxide captured from the air. They can be processed in refineries to produce drop-in fuels, such as e-gasoline, e-diesel, or e-kerosine.
[3] Fifty-seven per cent if the proposed revision of EU Regulation on Land Use, Land-Use Change and Forestry is adopted.
[4] To decarbonise is synonymous with to de-fossilise and to reduce GHG emissions in the context of this report.

- **Support vulnerable households and businesses** to limit energy poverty and bankruptcies caused by high energy bills.
- **Re-skill and expand the EU workforce** for producing and installing sustainable energy technologies and fuels.

This report focuses on the following United Nations Sustainable Development Goals: goal 7 (affordable and clean energy) and on goal 13 (climate action); it also addresses aspects of goals 1 (no poverty), 4 (quality education), 9 (industry, innovation and infrastructure), 11 (sustainable cities and communities) and 12 (responsible consumption and production).

Table S1a Messages for policy-makers on emergency and short-term measures (for details see Chapter 10)

Emergency measures (Until *ca.* spring 2025)	1. Negotiate with diverse suppliers of natural gas and liquefied natural gas to fill gas storage annually for the next two to three winters. 2. Accelerate deployment of renewables (with infrastructure), heat pumps, and gas boiler replacement using policies and funding. 3. Promote energy-saving campaigns with advice on 'no cost' measures, e.g. adjust thermostats; switch off systems not in use. 4. Compensate vulnerable households and businesses for high energy bills to limit energy poverty and bankruptcies. 5. Temporarily extend lifetimes of existing coal, natural gas, oil, and nuclear plants to operate within the EU Emission Trading System, but only until more renewable energy sources are built. 6. Expand education and training courses, starting immediately, to build a stronger EU workforce with sustainable energy skills.		
	1 Greenhouse gas emission reduction	**2 Security of energy supplies**	**3 Affordability**
Short-term measures (2023–2030)	**1a Policy: replace unabated natural gas** 1.1 Ban installation of new natural gas boilers. 1.2 Accelerate EU Emission Trading System 2 to reduce greenhouse gas emissions from buildings and transport. 1.3 Measure, verify and limit methane emissions of imported natural gas and liquefied natural gas. 1.4 Review Taxonomy for natural gas. 1.5 EU Heating and Cooling Strategy: update. 1.6 Hydrogen leaks (high global warming potential): measure and regulate. 1.7 Sustainable fuels: certification scheme. **1b Action: accelerate deployment of renewable energies with energy efficiency** 1.8 'Energy efficiency first': promote it, e.g. switch to heat pumps in buildings. 1.9 Permitting for renewable electricity generators and infrastructure: speed it up. 1.10 EU workforce: re-skill for making and installing low greenhouse gas emission technology. 1.11 Local heat maps: show options to replace gas. 1.12 Financial guarantees and project development assistance for buildings.	**2a Policy: diversify supplies** 2.1 Renewable energy technologies: ramp up EU manufacturing capacity for wind, solar photovoltaics and heat, heat pumps, and geothermal systems. 2.2 Low greenhouse gas emission fuels: negotiate (using the EU Energy Platform) with diverse suppliers. 2.3 Critical raw materials and components: negotiate with diverse suppliers. **2b Action: diversify and reduce demands** 2.4 Buildings: reduce energy demand by renovation, digital controls. Switch to heat pumps, renewables, or district heating. 2.5 Industry: switch from natural gas to renewables or low greenhouse gas emission fuels. 2.6 Transport: switch from fossil fuels to green electricity or hydrogen, sustainable aviation fuels or e-fuels. 2.7 Ammonia-based fertiliser: reduce demand, switch to other fertilisation options. **2c Action: strengthen energy infrastructure** 2.8 Electricity grids: urgently increase capacity. 2.9 Temporary gas grids: build/adapt to import non-Russian natural gas and liquefied natural gas. 2.10 Hydrogen grids: commit to develop, share risks with hydrogen market stakeholders.	**3a Policy: reduce energy poverty** 3.1 Emission Trading System revenues: redistribute through Member State support schemes that target vulnerable groups and businesses. 3.2 EU funding instruments: energy poverty reduction budget for each Member State. 3.3 Energy poverty reports in national energy and climate plans: EU to analyse and publish definitions, criteria, targets, and reductions reported. 3.4 Eurostat: add energy poverty data and maps to EU Statistics on Income and Living Conditions reports. 3.5 Energy poverty maps: publish at national and local levels. **3b Action: protect EU industries** 3.6 Strategically important industries (e.g. renewable generators, heat pumps, sustainable fuels): support for growth of production in the EU. 3.7 Energy-intensive industries: support for switching from fossil fuels.

Table S1b Messages for policy-makers on medium- and long-term measures (for details see Chapter 10)

	1 Greenhouse gas emission reduction	2 Security of energy supplies	3 Affordability
Medium- and long-term measures (2030–2050)	**1c Policy: long-term instruments** 1.13 Emission trading: EU Emission Trading System with clear future trajectory to end by 2050. 1.14 Guarantees: to facilitate financing for long-term investments. 1.15 Targeted (temporary) incentives for innovative technologies: to accelerate market uptake. 1.16 Energy market rules: update to manage competing electricity demands of integrated energy market.	**2d Policy: expand diversity of supplies** 2.11 Renewable (and blue) hydrogen: long-term contracts for EU from global markets. 2.12 Sustainable aviation fuels: increase imports and EU supplies. 2.13 Ammonia and hydrogen derivatives for shipping: increase imports and EU supplies. 2.14 Ammonia-based fertiliser: promote switch to low greenhouse gas emission fertilisation options.	**3c Policy: support energy poverty reduction** 3.8 Energy poverty reduction: prioritise in climate, energy and social care policies. 3.9 Financial guarantees: for investments in sustainable energy projects to help vulnerable groups. 3.10 EU funding for energy poverty reduction: regularly review needs and support options as Emission Trading System revenues fall.
	1d Action: stop unabated fossil fuel use 1.17 Buildings: design/renovate to run without gas, e.g. on renewable electricity and/or district heating. 1.18 Industry: switch processes from natural gas to renewable electricity or hydrogen as appropriate. 1.19 Road transport: switch to renewable electricity and hydrogen where needed (e.g. in long-haul trucks). 1.20 Maritime transport: stop using liquefied natural gas. Switch to low-carbon footprint fuels made using renewable electricity. 1.21 Aviation: make sustainable aviation fuel using sustainable bio-wastes or renewable electricity.	**2e Action: reinforce electricity infrastructure** 2.15 Transmission interconnectors: upgrade. 2.16 Large-scale electricity and heat storage: build more for grid flexibility management. **2f Action: reinforce fuel supply infrastructure** 2.17 Gas transmission networks: adapt to carry imports of hydrogen to demand centres. 2.18 Sustainable aviation fuels and ammonia: build infrastructure for transportation to demand centres.	**3d Policy: foster investor confidence and protect EU industries** 3.11 EU policies and targets: minimise changes, so investors in sustainable energy projects perceive risks to be low. 3.12 EU Emission Trading System and the Carbon Border Adjustment Mechanism: regularly monitor impacts on EU industries and adapt.

THE FUTURE OF GAS

Record gas prices in 2022 contributed to a major **cost of living crisis** and **increasing energy poverty**

Heating buildings is by far the largest use of natural gas

20% of energy consumption in the EU is provided by natural gas

A quarter of EU energy sector emissions in 2021 came from natural gas

729 Mt CO_2 =

65 MILLION
Gas boilers in buildings

20-year **global warming potential of** methane
> 80 times that of CO_2

10% ▶ 1%

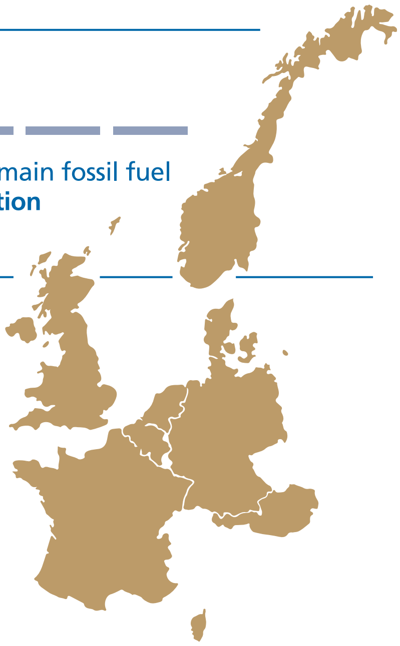
Blending 10% hydrogen in natural gas only delivers 1% in CO_2 reduction

1/5

In 2022, gas was the main fossil fuel for **electricity generation** in the EU

Natural gas is **no longer a transitional option** for replacing coal

Heat pumps and district heating are efficient alternatives



8 countries
have policies in place for **banning new natural gas boilers** or requiring high levels of renewables in buildings

Europe must take action to massively ramp-up:

energy efficiency
renewable heat
renewable electricity

!

1 Introduction

1.1 Overview

When this EASAC project was conceived, it was expected to focus mainly on greenhouse gas (GHG) emission reduction and the future roles of gaseous fuels in the transition to net-zero carbon emissions by 2050 as required by the European Union (EU) Climate Law (EC 2021a) and in line with the United Nations Sustainable Development Goals (UN 2022) and the Paris Agreement to limit global warming to 2 °C while pursuing efforts to limit the increase even further to 1.5 °C (UNFCCC 2015). Broadly in line with the EU Reference Scenario 2020 (EC 2021r), natural gas was expected to initially replace coal for power generation in several of the Eastern European Member States, and then to be phased out for unabated uses and replaced mainly by renewable energy sources in all European countries.

The project had to be adapted to address the impacts of Russia's invasion of Ukraine

The decision by the EU to stop importing natural gas from Russia and the rapid increase in gas prices have changed the perception of natural gas for many consumers. This new perception is expected to reduce the future role of natural gas in the energy transition and to accelerate its phase-out because consumers of natural gas in buildings, industry, and business will switch from natural gas to renewable electricity or low GHG emission fuels earlier than they might have done if the invasion had not taken place.

Policies, legislation, and financing must continue to be updated at an EU level to deliver common goals in timely and cost-effective ways, for example through cross-border collaborations and trade, common regulations, specifications, and market rules (EC 2023g), shared experiences, and economies of scale. In this report, EASAC discusses the challenges associated with this and identifies key messages for EU policy-makers as EU Member States increase their efforts to deliver their commitments to net zero by 2050.

EASAC recognises that each EU Member State must implement the energy transition in ways that fit with its own mix of energy supply and demand, national and international gas and electricity infrastructure (including importing facilities and pipelines), renewable energy resources, and building and industry structures, as well as its own culture and traditions.

1.2 Greenhouse gas emissions from natural gas contribute to global warming

Natural gas is a fossil fuel, which produced an estimated 729 million tonnes (megatonnes, Mt) of carbon dioxide (CO_2) emissions, or 22% of the CO_2 emissions from the EU's energy sector, in 2021 (IEA 2022h). In addition, supplies of natural gas produce fugitive emissions of methane from leakages along their supply chains. GHG emissions (including CO_2 and methane) accelerate the process of climate change, notably global warming, which increases the frequency of extreme weather events, including sea level rises, water shortages, and wildfires that can lead to famine, disease, and increased risks of mass migration and wars.

Methane, which is emitted during the extraction of natural gas (like coal and oil), as well as during its transport and distribution to end-users, is a relatively short-lived but nevertheless powerful GHG, and its emissions vary between natural gas supply chains (IEA 2020a). The EU has been leading efforts to reduce methane emissions through the EU's Methane Strategy (EC 2020b) and by being part of the Global Methane Pledge (GMP 2021) which aims to reduce global methane emissions by at least 30% from 2020 levels by 2030.

Responding to increasing evidence of the destructive outcomes of climate change, the EU has adopted a Green Deal (EC 2019a) and a Climate Law to reduce GHG emissions to net zero by 2050 (EC 2021a). It has also set a target of 55% reduction in GHG emissions by 2030 (compared with 1990 levels), which has effectively been increased to 57% by a revision of the EU Regulation on land use, land-use change and forestry because this changes the limit of carbon removals from the atmosphere (EP 2022b).

To deliver these commitments to GHG emission reductions, the use of all fossil fuels, including unabated natural gas, must be phased out and replaced with renewable electricity and heat, and low-carbon footprint fuels. However, massive infrastructural and industrial assets are still locked into the supply and consumption of fossil fuels and many households and businesses rely on fossil fuels for heating and power. The owners of such assets must therefore look for ways either to continue using their existing equipment with different fuels or to replace them with new technology before the end of their economic life, which might be 20–30 years or even more. To reconcile the continued use of existing equipment with GHG emission reduction targets, there is a demand for fossil-free 'drop-in'[5] fuels or other fossil-free fuels that can be used with only low-cost changes to existing equipment.

[5] 'Drop-in' fuels are fuels that can replace others in existing systems, such as boilers or combustion engines.

1.3 Ramping up supplies of renewable electricity and sustainable gases is crucial for the energy transition to net zero by 2050

The future consumption of natural gas during the EU's transition to a sustainable energy economy will be driven by global energy prices and affected by the deployment of energy efficiency measures that influence demand. However, it will depend mainly on the speeds of electrification and fuel substitution (e.g. by green gases).

The future role of sustainable gases will depend on prices (including carbon prices or sustainability mark-ups) and on their availability at the point of demand, which will require the availability of infrastructure for their transmission, distribution, and storage.

Crucial to the future roles of natural and green gases will be the policies and regulatory frameworks used by the EU to manage the transition to a secure and affordable low-carbon footprint energy future. Also important will be the energy industry's capacity to scale up the deployment of alternatives (renewables) and energy efficiency in response to the targets set in the REPowerEU plan (EC 2022a; 2022g).

In the short and medium terms, the future mix of gaseous fuels and electricity in the EU will depend primarily on policy decisions about future imports of natural gas, and on decisions by individuals and industries to take action and invest in energy demand reduction and electrification. Particularly important in the next 2–3 years will be investments in renewable electricity generation and in terminals and pipelines for importing liquefied natural gas (LNG).

Priority must also be given to investments in facilities for producing and storing biomethane, hydrogen, e-methane, and other low-carbon footprint gaseous fuels that can be used in hard-to-electrify applications in industry and transport (Corbeau 2022; Financial Times 2022). In addition, the transition will require digitally controlled demand response systems and flexible electricity generators using low-carbon footprint fuels to be brought online through energy market mechanisms and regulations to provide back-up for solar and wind generators.

1.4 Future scenarios for the EU energy transition

Growing numbers of scenarios have been developed in recent years and used for modelling possible ways in which the transition to an energy economy with a low-carbon footprint might be implemented, including scenarios published by the European Commission (EC 2018a; 2020c), the International Energy Agency (IEA 2021a; 2022a), and other expert teams (NTNU 2021; SAPEA 2021; Ram *et al.* 2022).

The EU's networks of transmission system operators for gas and electricity (ENTSO-E 2022; ENTSOG 2022a), which have been working together on their 10-year network development plans (ENTSOG 2022b) to deliver the EU's Paris commitment and EU Green Deal goals (EC 2019a), have used two main scenarios to underpin their work. These were 'Distributed Energy' (with a high European autonomy, a renewable and decentralised focus, minimal carbon capture and storage (CCS), and nuclear power) and 'Global Ambition' (with a global economy, centralised low-carbon footprint, options for renewable energy sources, and integration of nuclear and CCS).

Similarly, the impact assessments for the recent European Commission strategies 'Clean Planet for All' (EC 2018a) and the 'Climate Plan' (EC 2020e) with its 'Fit for 55' package of proposals (EC 2021e) have used an evolving series of future scenarios, including the EU Reference Scenario 2020 (EC 2021r), which was expected to provide guidance to policy-makers for several years to come.

However, the invasion of Ukraine created an urgent need for a new scenario in which two-thirds of the imports of Russian gas would be replaced before the end of 2022. This was developed rapidly in 2022 and has underpinned the European Commission communication on REPowerEU in March 2022 (EC 2022a), which was followed in May 2022 by the REPowerEU Plan (EC 2022g). This proposed more ambitious targets for renewable energy supplies than those of the Fit for 55 package, and new emergency measures including the following:

- Delayed phasing out of coal, but still to be done before 2030.
- Slightly earlier phasing out of unabated natural gas, owing primarily to more rapid replacement of natural gas boilers for space and water heating, but also to changes in heating systems for industrial processes.
- Extensions to the operating lifetimes of some nuclear plants, although a mixed approach between Member States will continue, with some Member States constructing new nuclear plants while others continue their decommissioning plans or use none.
- More rapid growth of wind (offshore and onshore plants) and photovoltaic power generation in response to accelerated electrification of industry and transport, and growth in the demand for hydrogen and e-fuels (Ram *et al.* 2022).
- More rapid reinforcement of electricity and gas grids, with particular attention to strengthening interconnections and to cross-border trading (market rules).

- Substantial acceleration of renewable hydrogen production from the 5 Mt foreseen in the Hydrogen Strategy (EC 2020d) to a new level of 10 Mt production in the EU plus 10 Mt of imports from outside the EU by 2030.
- An aim to double the current deployment rate of heat pumps[6], and deliver a cumulative 10 million more units in the EU over the next 5 years.

Taken together, the Clean Planet for All, EU Reference Scenario 2020, Fit for 55, and REPowerEU scenarios illustrate the range of challenges faced by policy-makers as they work to deliver the EU's transition to net zero by 2050. No single scenario should be used for policy-making in isolation, but the most important messages for policy-makers are supported by modelling studies based on scenarios from several independent sources.

1.5 Natural gas loses its role as transition fuel to replace coal for electricity generation

In recent years, until 2022, natural gas has been increasingly used to replace coal for electricity and heat generation because of its lower GHG emissions per unit of electricity generated (and corresponding lower costs for compliance with the EU Emission Trading System). Also driving the replacement of coal with natural gas for power generation have been relatively low natural gas prices and lower local pollutant emissions (e.g. sulfur and particulates). Typically, natural-gas-fired boilers are only slightly more efficient than coal-fired boilers for heating, but combined-cycle gas-turbine power plants are substantially more efficient than coal-fired plants for electricity generation, so natural-gas-fired power plants emit substantially less CO_2 per megawatt-hour of electricity than coal-fired power plants.

The GHG emission savings that result from replacing coal with natural gas depend not only on the differences in combustion emissions but also on those in their supply-chain emissions (including methane). The amounts of methane emitted vary with location and for natural gas; they also depend on how it is transported, so replacing coal with natural gas can lead to less reduction of GHG emissions than expected (Partanen 2020).

However, in Member States where coal is still used for power generation, it may no longer be viable (after the invasion of Ukraine) to convert from coal to natural gas. Instead, it is advisable to move immediately to renewable/low-carbon footprint electricity generation and/or to strengthen interconnections with those countries that can supply renewable or low-carbon footprint electricity.

Most EU countries have either already stopped using coal or have committed in their national energy and climate plans to phasing it out before 2030 (Europe Beyond Coal 2022). Nevertheless, it may be necessary in some cases as an emergency measure to continue using coal for longer than previously planned, until new renewable power generators have been built. For example, the restarting of mothballed coal-fired plants has been observed in various countries including Germany and the Netherlands, but phasing out the use of coal in the EU must still take place before 2030 (EMBER 2022).

1.6 Ensuring adequate supplies of affordable energy is vital for the EU economy and citizens, following the invasion of Ukraine, but GHG emission reductions must not be delayed

The Russian invasion of Ukraine, which took place just before this EASAC project started, has already had, and will continue to have, major impacts on many aspects of the global energy transition, including global natural gas and LNG markets and on the use of natural gas in the EU. In the past, there was a lack of investment in LNG import infrastructure in some EU countries, buyers focused on choosing the supplier with the lowest price, and EU Member States allowed the region to play a role in balancing the market. However, in 2022, steps had to be taken urgently to reduce the risks of the EU becoming over-dependent again on any single energy supplier, without losing the cross-border trading and price-reducing benefits for consumers and businesses of the EU's competitive single energy market.

Even before the Russian invasion of Ukraine, a global energy crisis had started in 2021, caused in part by the recovery from the COVID pandemic, and in part by reduced supplies of gas from Russia. The return of demand together with tight energy supplies pushed up energy prices across the world and caused energy shortages in those countries that struggled to afford the increased prices, including some countries in the EU. During 2022, the war in Ukraine made matters worse.

This report therefore highlights the need to ensure that adequate energy supplies can be reliably delivered to consumers at affordable prices in the EU despite the disruptions, and at the same time to achieve a fair transition to an energy economy without GHG emissions.

[6] Approximately 2.1 million heat pumps were installed in the EU-27 in 2021 (1.1 million air-to-water or water-to-water, 0.8 million air-to-air, 0.2 million sanitary hot water). The total number of heat pumps in the EU in 2022 was approximately 20 million (EHPA 2022; Rosenow *et al.* 2022).

1.7 Engagement of citizens, businesses, and stakeholders at all levels must be enhanced through education, training and skills development, and independent advice

The EU's transition to a fully decarbonised, secure, and affordable energy system by 2050 must be well explained and communicated to citizens and businesses because it will require the active engagement and participation of all sectors of society. People will be required to behave differently, to invest differently, and to focus more attention on energy solutions that will deliver cleaner air, better health, reduced environmental damage, and improved biodiversity. Such communications cannot all be done at EU level. Information and support must also be provided at local and regional levels and in local languages, for example by using 'one-stop shops' to provide independent advice on locally available energy-saving products and services to householders and businesses.

To educate and train scientists, engineers, experts, technicians, and craftspeople takes years. Therefore, to minimise the risks of delays in the energy transition, a comprehensive skills strategy must be agreed and implemented urgently, especially for new and emerging sectors such as renewable electricity generation and heat pumps. New skill centres and training courses must be set up and existing facilities expanded across the full range of education levels from apprenticeships to post-doctoral experts, and teachers must be trained to run them. Refresher courses for the existing workforce will be needed especially on issues related to the rapidly evolving digital technologies and cyber security.

Curricula in schools must be adapted and student numbers in universities increased for courses on, for example, energy systems analysis and socio-economic studies as well as energy-related materials science, engineering, and digital technologies. Similarly, curricula must be strengthened, and student numbers increased in colleges to train more technicians and craftspeople to build and install millions of heat pumps and solar panels, and thousands of wind turbines and district heating systems. More technicians and craftspeople will be needed to renovate millions of buildings, to reinforce electricity networks, and to build and operate LNG terminals in areas where these have not existed before.

The existing workforce in energy-related sectors will unavoidably have to adapt to the energy transition and many will have to learn new skills. However, studies have shown that the overall result of the energy transition will be a significant increase in the overall numbers of jobs in these sectors and, for many of the people involved, the new green jobs will be of better quality (IEA 2021d).

1.8 The body of this report contains data, evidence, and analyses to support EASAC's conclusions and messages for policy-makers

Following this introduction, the report explores the main sectors of natural gas consumption in Chapter 2, and potential influences on future demands for natural gas in Chapter 3. The available and projected supplies of natural gas are discussed in Chapter 4.

The potential contributions of hydrogen are discussed in Chapter 5, and of other gaseous fuels, including biogas, biomethane, and ammonia, in Chapter 6. The EU's gas and electricity infrastructure and how it will evolve as natural gas is phased out are discussed in Chapter 7, and the challenges related to security of EU energy supplies are discussed in Chapter 8.

Key issues related to the affordability of energy for consumers and businesses, including the challenge of reducing energy poverty, are discussed in Chapter 9, and EASAC's conclusions and key messages for policy-makers are presented in Chapter 10.

Substantial uncertainties have been identified by EASAC during its work on the future of gas, and a shortlist of those that could justify further research is given in Annex 2.

2 Natural gas consumption

How much natural gas is consumed in the European Union, what is it used for, and how could it be replaced?

2.1 Natural gas provides one-fifth of final energy consumption in the EU-27

In recent years, natural gas has contributed approximately 22% of final energy consumption in the EU (Eurostat 2023b). Significant amounts of the natural gas supplied to the EU are put into the EU's gas-storage systems, mainly during the summer months, and removed again mainly during the winter months (section 4.5).

Natural gas consumption in the EU-27 dropped in 2020 but recovered to 418 billion (10^9) cubic metres (bcm) in 2021 (Eurostat 2023b), after falling from a peak in 2010, as shown in Figure 1. A reduction of about 13% is estimated for OECD (Organisation for Economic Co-operation and Development) countries in Europe for 2022, largely as a result of the impacts of the Russian invasion of Ukraine (IEA 2023a; 2023b).

In 2020 and 2021, around 80% of EU natural gas consumption was in seven EU Member States, as shown in Figure 2.

The shares of natural gas consumption between sectors vary among the Member States. However, the main demands for natural gas in the EU, as shown in Figure 3, are for heating buildings (individual and district heating), electricity generation (to supply base loads and peak loads, and to contribute the management of grid flexibility), industry (process heat for industrial processes, chemicals, etc., and carbon for chemicals (e.g. methanol, agricultural chemicals, and olefins used for plastics, detergents and adhesives), fertilisers, CO_2, etc., and the energy sector's own use for regasification, pipeline compression, etc.), and other (transport, etc.) (Li *et al.* 2022; US EIA 2022c). Chemical feedstock uses of hydrocarbons (including natural gas) account for only 5–10% of total hydrocarbon consumption (Levi and Cullen 2018)—the rest is for energy (S&P Global 2022c).

2.2 Largest demand for natural gas in the EU is for heating buildings

2.2.1 Overview

By far the largest demand for natural gas in the EU is for heating buildings (Figure 3), and nearly 40% of residential buildings in the EU were heated by natural gas boilers in 2018 (EASAC 2021). Hence, as the unabated use of natural gas is phased out to reduce the EU's greenhouse gas (GHG) emissions, it will be important to build investor confidence in new heating systems with low-carbon footprints. For this, EU policy-makers need to explain and demonstrate a stable long-term policy framework for the heating sector by updating the EU's Heating and Cooling Strategy (EC 2016).

2.2.2 Cities, housing companies, and individual householders have key roles to play in ending the use of natural gas boilers in buildings and reducing GHG emissions

Building owners, including households, housing associations, housing companies, businesses, and public authorities must be encouraged to switch their heating from natural gas to low GHG emission solutions, including renewables or district heating. Cities and local authorities can provide guidance on fuel switching to building owners in their areas by producing heat maps and publishing local energy plans and strategies to form a solid basis for decision-making.

Figure 1 Natural gas consumption in the EU-27 (estimated for 2022) (Eurostat 2023b).

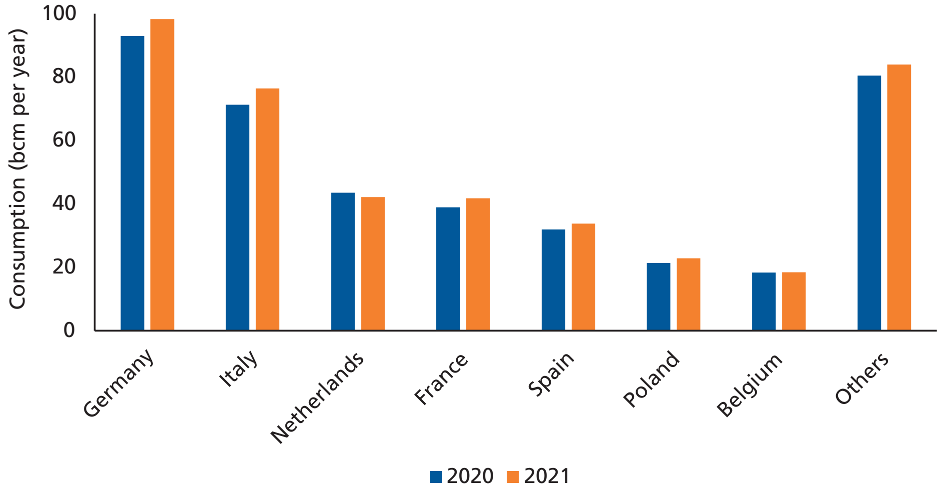


Figure 2 Almost 80% of natural gas consumption was in seven EU Member States in 2020 and 2021 (Eurostat 2023b).

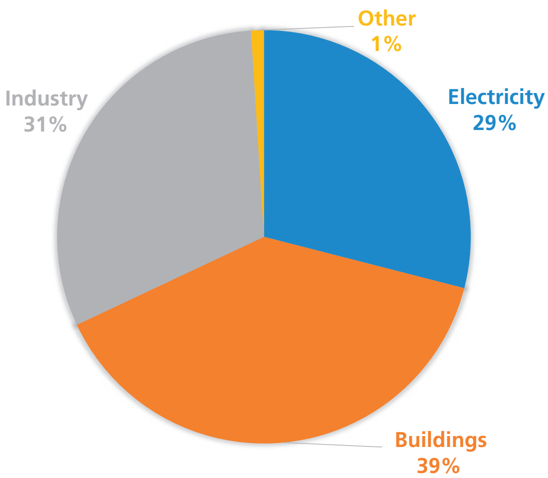


Figure 3 Buildings dominated EU natural gas consumption in 2020 (US EIA 2022c).

For example, a recent study by a group of research institutions, industry representative organisations, and an association of local authorities, as part of the Heat Roadmap Europe project (HRE 2023), has developed many heat maps and used these to explore the potential for using district heating. Their results showed that the use of district heating to supply heat demands across the EU could be increased from today's level of approximately 12% to around half of the heat demand in 2050, with contributions ranging from 20% to 70% depending on the country (Möller *et al.* 2019; EASAC 2021). This study provides a valuable basis for stakeholder discussions and gives confidence that there is substantial scope for increasing the contribution of district heating in the EU's urban areas.

Another important role for cities and public authorities is to secure project development assistance for clusters of buildings, including small businesses, industries, and transport providers in their areas, so that energy saving and GHG-emission-reducing projects can be more easily financed (EC 2022j; EIB 2023).

Modest amounts of funding for project development assistance, for example through the European Investment Bank's European Local ENergy Assistance 'ELENA' funding scheme, have been shown to trigger deep energy-related renovations in groups of buildings by local communities at the neighbourhood scale (EIB 2023). This approach brings economies of scale and allows many small investments to be bundled together such that they can be more easily funded by the major financing institutions. It can also help to overcome hesitation by private building owners, who can be encouraged to see such schemes as a 'now or never' opportunity to improve their own building together with those of their neighbours who are doing the same.

2.2.3 District heating must switch from natural gas to renewables and waste heat

District heating systems offer many benefits for heating buildings, especially in urban areas, but currently most of the heat is still supplied by fossil fuels, including natural gas. In district heating systems, GHG emission reduction, depending on the location and the context, can be achieved by integrating more renewable energy sources, such as heat pumps, geothermal or solar heat, together with waste heat from industry, data centres, shopping malls, and other local sources. In some parts of Europe with adequate local supplies of biomass resources, bioenergy may be used.

Europe is a world leader for renewables integration in district heating, with about 25% of its district heating produced from renewable sources. High levels of renewables in district heating can be found in Austria, Denmark, Estonia, Latvia, Lithuania, and Sweden (IEA 2022l).

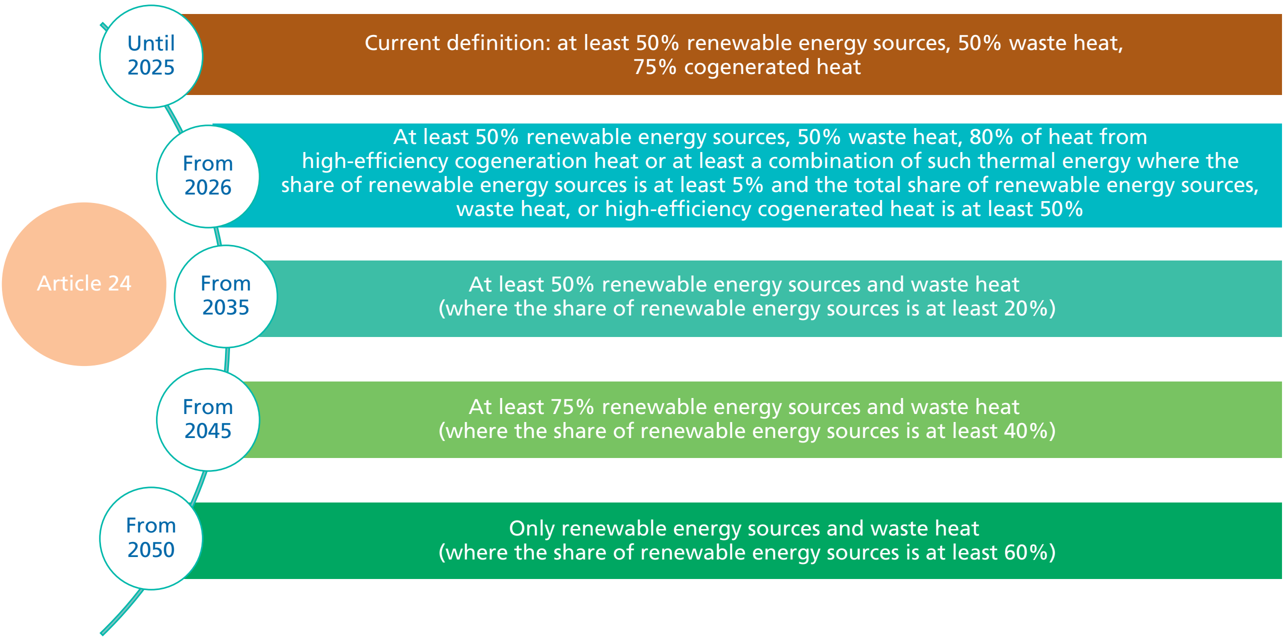


Figure 4 The European Commission has proposed increasingly demanding definitions of efficient district heating and cooling in its recast Energy Efficiency Directive (EC 2021g).

District heating is particularly well suited for use in dense urban contexts, apartment complexes, and where individual solutions are less efficient, for example where they cannot access waste heat or long-term heat storage systems, or because the available fuels cannot be used efficiently in small systems. Figure 4 shows the increasingly demanding future EU definitions for efficient district heating and cooling, which were proposed in the recast Energy Efficiency Directive as part of the Fit for 55 package (EC 2021g).

2.2.4 Natural gas boilers must be replaced

Natural gas boilers are widely used today to provide hot water and space heating in domestic, commercial, and industrial buildings. Natural gas boilers produce 38% of the final energy for space heating in EU residential buildings (EC 2021h) and can produce some gaseous pollutants, such as nitrogen oxides in limited quantities, which may contribute to air quality problems especially in urban areas. To achieve the EU's objectives for GHG emission reduction, natural gas boilers must be replaced, preferably well before 2050, by low-carbon emission alternatives, such as electric heat pumps powered by renewable electricity, solar and/or geothermal heating, or highly efficient district heating systems (EC 2022f).

The REPowerEU proposals encourage Member States to phase out subsidies for fossil-fuelled boilers in buildings, to tighten national requirements for natural gas boiler replacements, and imply an end-date of 2029 for new fossil fuel boilers to be on the market (EC 2022g). They also encourage Member States to introduce national bans for new boilers using fossil fuels in existing and new buildings, although no EU legislation is yet in place to require such bans. Eight European countries already have policies in place either for directly banning natural gas boilers in buildings or with requirements for high levels of heating by renewables, which will effectively prohibit the use of natural gas boilers (e.g. in Germany) (Figure 5).

To replace all existing domestic natural gas boilers will not be easy or quick because of the large numbers of systems involved. The Joint Research Centre of the European Commission estimated that there were around 65 million natural gas boilers in residential buildings in the EU in 2019 (EC 2021h), and many owners do not have the money needed to pay for the replacement. Boiler replacements in rented properties, like many other energy efficiency measures, can be complicated by the owner–tenant relationship and the resulting 'split incentive' whereby the owner pays for the boiler replacement but the tenant benefits from lower heating costs.

Where investment funding can be made available, for example in social housing, it makes sense to reduce the heating demand by renovating the building fabric at the same time as replacing the heating system, although it will typically take longer to renovate the building envelope than to replace the heating system (EC 2021h). Specific policies and measures, including re-skilling and expanding the building workforce, would help to accelerate this process (EASAC 2021).

Today, the natural gas used in domestic boilers is not covered by the Emission Trading System (ETS) because

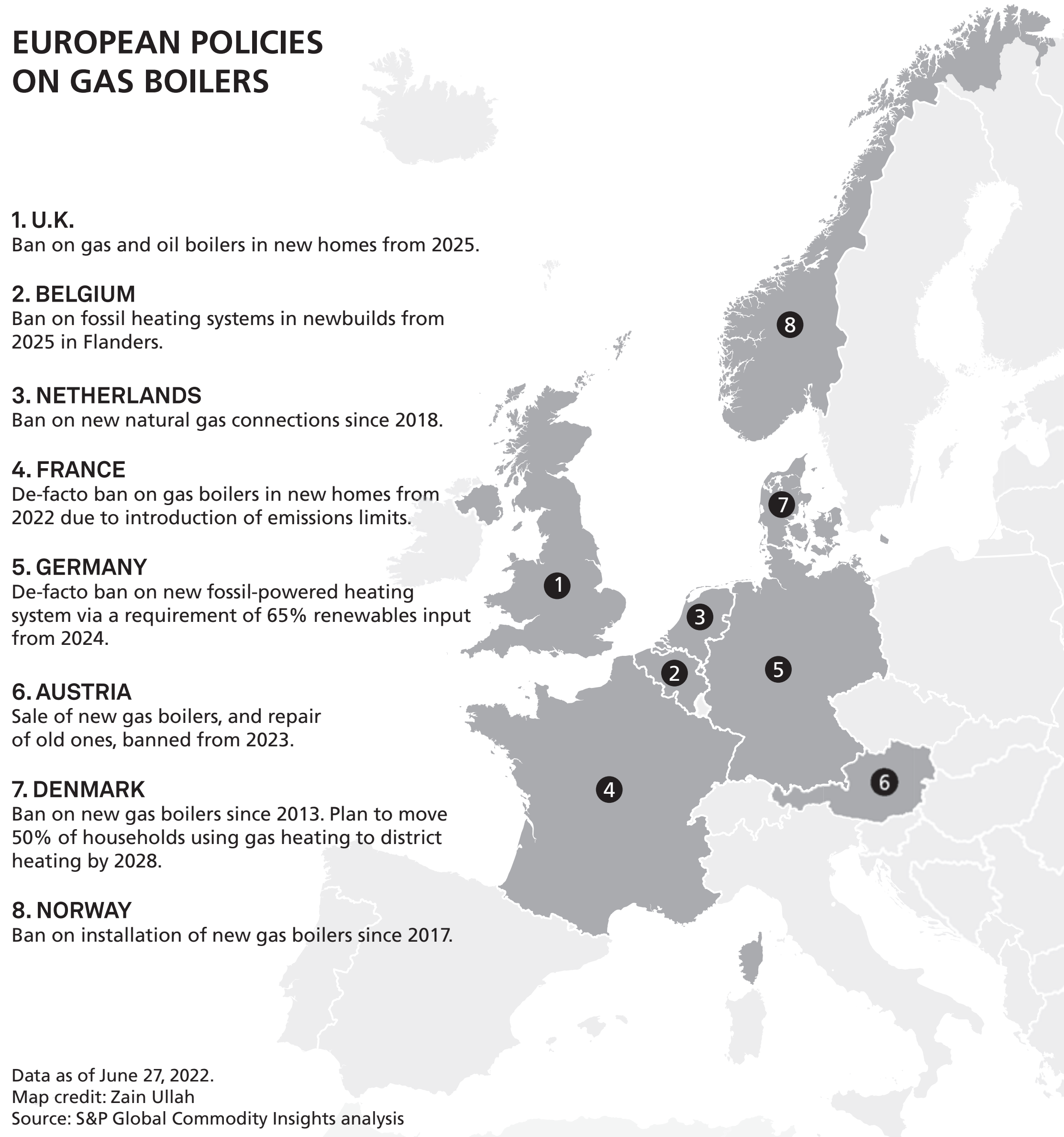


Figure 5 Eight European countries already have policies in place for banning new natural gas boilers (S&P Global 2022b; copyright 2022 by S&P Global Inc.; all rights reserved).

the boilers are too small. This typically makes the running costs of natural gas heating seem cheaper than electric heating in many countries, despite different national energy tax levels between natural gas and electricity in some countries. This is because heat and electricity produced by fossil fuels (including natural gas) in larger installations is always subject to ETS costs while natural gas used in small boilers for heating is not. To encourage the replacement of natural gas boilers, this anomaly must be removed and a level playing field established for heating by natural gas and electricity.

As part of its Fit for 55 package in July 2021, the Commission proposed to do this by extending the ETS directive (ETS 2) to include fossil fuels used in buildings and to put obligations on fuel suppliers (EC 2021f).

This proposal was provisionally agreed (with revisions) in December 2022 (European Council 2022c). The proposal to include all fuel suppliers to buildings in the new ETS 2 system will effectively add a carbon price to their fossil fuels and therefore increase the prices paid by consumers for any fossil fuels that they buy for heating. However, the new ETS 2 system will be phased in over several years, so it is unlikely to discourage the installation of new natural gas boilers in the short term.

2.2.5 Low-carbon footprint gases will not be widely used in gas boilers

Neither biomethane nor hydrogen will be widely used to replace natural gas for heating because they will be more highly valued for applications in industry or

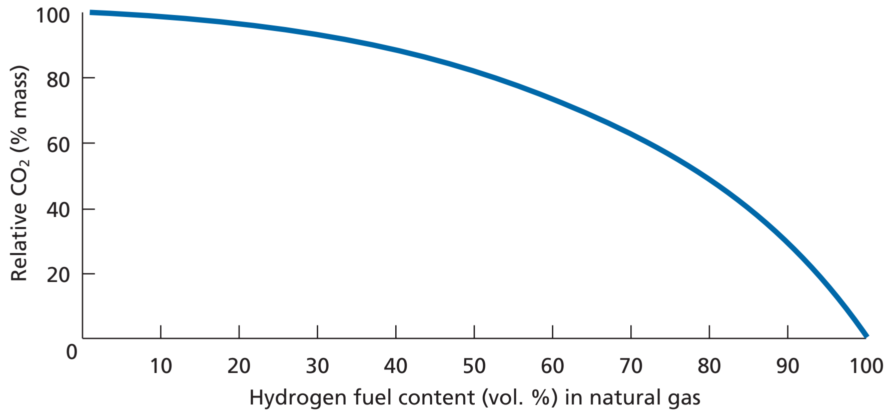


Figure 6 Blends with about 10% by volume of hydrogen in natural gas produce negligible (ca. 1%) reduction in carbon dioxide (CO_2) emissions from combustion (Siemens 2021).

transport that are 'hard to electrify'. Moreover, to supply these gases for heating would risk locking users into inefficient solutions that will become economically unattractive in the future.

1. Biomethane—has the attraction that it performs in the same way as natural gas in networks and boilers, and it could be used to delay capital expenditure on replacing natural gas boilers. However, its availability will be constrained in the future by the limited availability of biomass resources, which will not be sufficient to satisfy much of the demand for heating buildings. Limited amounts of biomethane may be used for heating in locations where it can be produced and used nearby, such as on farms or near to food processing plants, where agricultural or food wastes are digested. It may also be distributed by local gas networks and used as a transitional fuel in some areas until sufficient renewable electricity generation (for heat pumps) has been constructed.

2. Hydrogen—could be transported in dedicated sections of existing natural gas networks, but it cannot be used in most existing boilers. Prototypes of hydrogen-fuelled boilers are under development and might be supplied to niche markets at prices that are lower than those of heat pumps in areas where hydrogen is being produced for industry, for example in hydrogen valleys (Chapter 6). However, it will always be more efficient to use renewable electricity to heat buildings with a heat pump than to use renewable electricity to produce renewable (green) hydrogen for use in a boiler (Chapter 6). Blue hydrogen (produced from natural gas with carbon capture and storage (CCS)) may, depending on market forces and carbon pricing, be cheaper than green hydrogen in some areas, but all low-carbon footprint hydrogen (produced in the EU or imported) will be more highly valued for 'hard-to-electrify' industrial or transport applications than for heating. Hence, the widespread use of hydrogen for low-temperature heating (i.e. in buildings) should not be prioritised in the EU (Chapter 5).

2.2.6 Blends of natural gas and hydrogen will not be widely distributed in EU gas networks

Blends with about 10% (by volume) of hydrogen in natural gas could be used in some existing boilers. However, although it may be feasible to distribute blends of hydrogen with natural gas through small private networks (e.g. in industrial clusters), their widespread distribution by the EU's main gas networks is not expected, for the following reasons:

1. Unacceptably high blends of hydrogen are needed to achieve significant reductions in GHG emissions from combustion: for example, a blend of 10% hydrogen (by volume) in natural gas would produce negligible (*ca*. 1%) CO_2 emission savings, and more than 80% hydrogen (by volume) would reduce CO_2 emissions by only 50% (Figure 6). A demonstration project in a private UK network has shown that a blend with 20% hydrogen can be operated successfully (Hydeploy 2021), but most EU gas networks limit the levels of hydrogen to less than about 10%. To maintain the inter-operability of the EU's gas network, as natural gas is phased out, the European Commission has proposed a regulation (EC 2021s), which would oblige system operators to accept hydrogen blending, but subject to a hydrogen cap of up to 5% at cross-border points from 1 October 2025.

2. It is difficult to justify major investments in adapting gas infrastructure and natural-gas-fuelled systems to accommodate blends of hydrogen with natural gas, when the unabated use of natural gas is scheduled to be phased out. Moreover, EU gas networks

supply not only natural gas boilers but also other systems, such as gas turbines, industrial processes, and natural gas vehicles, which would impose different constraints on hydrogen blends.

3. It is difficult to maintain a homogeneous blend of hydrogen and methane molecules, which have different characteristics, throughout a gas network. Blends pose challenges for the storage and injection of the two gases into the network, for monitoring the quality of the blend across the network, and for managing small leaks (section 5.8). Pockets of pure hydrogen would need to be avoided because parts of the network and of its users' systems might not tolerate pure hydrogen.

2.2.7 Most natural gas boilers will be replaced by heat pumps and/or district heating

Heat pumps powered by renewable electricity offer a climate-friendly option for heating and cooling buildings. They can replace natural gas boilers for heating buildings, either using individual units or through district heating. In the short and medium term, growth in the use of heat pumps will create the need for increased renewable electricity production and grid infrastructure, and for a rapid increase in the production of heat pumps together with the training of heat-pump installers (IEA 2022i). However, provided renewable electricity generation is increased sufficiently, heat pumps will immediately begin to reduce carbon emissions and EU dependency on natural gas.

An important consideration when planning to increase the manufacture of heat pumps is the choice of refrigerant fluid used, because these typically have high global warming potentials. The EU has therefore proposed a revision to the existing F-Gas regulation, which would tighten the requirements for the use of fluorinated GHGs, including their use in heat pumps (EC 2022d). The global warming potential of the refrigerant fluid plays an important role in life-cycle assessments of heat pumps, because even small leaks during the manufacture or end of life processing of heat pumps can produce significant climate impacts. Comparative life-cycle assessments of heat pumps and gas boilers show that the carbon intensity of the electricity used to power heat pumps is also important, which confirms the urgent need to increase the generation of renewable electricity together with the deployment of heat pumps (Naumann *et al*. 2022).

The Commission's REPowerEU Plan (EC 2022g) proposes to roll out 10 million more domestic heat pumps by 2027, which would serve EU targets for energy efficiency. However, heat pumps (especially ground-coupled heat pumps) still have capital costs that are unaffordable for a large part of the population, who would therefore need subsidies, despite the fact that prices of heat pumps are falling owing to economies of scale.

From an energy perspective, it is much more efficient to use renewable electricity with heat pumps than to use natural gas boilers because air-source heat pumps used in residential buildings in the EU typically show a seasonal performance factor (the heat energy output divided by the electrical energy input) of 2.4–3.4, and the seasonal performance factors of ground-coupled heat pumps used in residential buildings in the EU typically lie between 3 and 4.6 (Nouvel *et al.* 2015).

An important challenge for the use of air-source heat pumps, which is still being addressed by research and development, is to improve their performance in very cold climates, firstly by delivering the required heating with less electrical power, and secondly by reducing or completely avoiding the need to defrost the external heat exchanger. Put together, these two improvements would reduce the peak electricity demand of the heat pump in winter, which would be particularly valuable where heat pumps are powered predominantly by wind and solar electricity (IEA 2022i).

Recent data on heat-pump markets in the EU show that they have been growing in the cold Nordic countries, which have traditionally used electric resistance heating. Policies and support schemes have been put in place to encourage the use of heat pumps in these countries (Rosenow *et al.* 2022). However, the Nordic countries typically have large hydro-electricity resources, which are sufficient to allow air-source heat pumps to use electric defrosting of their external heat exchangers.

Ground-coupled heat pumps are a more energy-efficient option for use with solar and wind-generated electricity in cold climates because they avoid (or minimise) the need for a defrosting cycle and the additional peak electricity demand that this causes. Nordic countries have therefore put in place support schemes that can be used to make ground-coupled heat pumps more affordable. However, only about 6% of heat pumps installed in the EU have been ground coupled in recent years (Rosenow *et al.* 2022).

It has been misleadingly suggested that, when the unabated use of natural gas will be phased out, domestic gas boilers fuelled by biomethane and/or hydrogen might be used to provide local back-up heating for electric heat pumps during periods when electricity networks (even with storage and peak generating systems) are unable to supply sufficient (peak) power, for example during very cold weather or when wind speeds are low in winter. However, heat pumps combined with low-carbon footprint gas boilers for domestic back-up heating should not be supported and are unlikely to be widely adopted for several reasons:

1. The operating costs of maintaining gas distribution grids to supply millions of domestic boilers with biomethane or hydrogen for only a few days or weeks per year, together with the costs of storing sufficient quantities of these gases to meet peak winter demands and of controlling their leakage, would be high.

2. Supplies of biomethane and renewable hydrogen will be limited and priority should be given to their use in 'hard-to-electrify' applications in industry and transport, for example through dedicated supply grids with public support where justified.

3. The risks of failure of such hybrid domestic heating systems would be high because domestic boilers are unlikely to be properly maintained if they are used for only a few days or weeks per year.

A much lower cost solution for reducing the peak electricity demands of heat pumps is to use the heat pump together with low-temperature heat storage, for example by using heat exchangers buried in the ground (ground-coupled heat pump) or by using heat stored in a large tank of hot water (water source heat pump). Coupling a heat pump with heat storage can also extend the lifetime of heat-pump components because it reduces short cycling of the heat pump (on and off).

For applications where low-temperature heat storage is not practicable, it is expected that local storage of electricity in batteries will be used to cover peak electricity demands and periods with reduced renewable electricity supplies caused by low wind speeds (IEA 2022i). Local electricity storage will become increasingly competitive as battery prices fall.

2.2.8 Fuel cells will not replace many natural gas boilers in the short to medium term

Solid oxide and other fuel cells that can operate using natural gas or hydrogen are being developed with the aim of generating both electricity and heat that can be fed into district heating systems for buildings (IEA 2019c). However, although the overall energy efficiency of fuel cells might approach 85% (the electricity plus heat produced divided by the energy content of the hydrogen used), their main added value in the short to medium terms will be to contribute to the security of energy supplies. This is because renewable electricity will always deliver more heat when supplied to a heat pump than when used to produce hydrogen for consumption in a fuel cell. It is too early to predict what may influence long-term markets for fuel cells, as their costs come down. For example, they may find their place in new markets in and/or near to hydrogen valleys, as global markets for hydrogen become more competitive.

2.2.9 Summary of sustainable options to replace natural gas for heating buildings

Most buildings in the EU are currently heated using natural gas boilers but these must be phased out and replaced by sustainable sources of heating. Efficient district heating is likely to be the preferred option in urban areas. For many existing buildings, individual heat pumps (ground-coupled where possible to minimise peak electricity demands) powered by renewable electricity are likely to be the most efficient and cost-competitive heating option as soon as sufficient renewable electricity generation has been constructed (Weidner and Guillén-Gosálbezet 2023). However, geothermal heating may be preferred where there are accessible local resources, or solar heating, for example in sunny mountain regions. Sustainable biomass (e.g. pellet) boilers may offer an alternative where there are adequate supplies of agricultural or forestry wastes with short carbon payback periods (section 3.5.2), provided their particulate emissions are limited to minimise health problems (Orru *et al.* 2022).

The three main ways of using renewable electricity for heating are illustrated in Figure 7, which shows that renewable electricity with heat pumps is the most efficient option because these can typically deliver up to about three times (300%) as much heating energy as is supplied in the form of electrical energy. In contrast, it is much less efficient (typically 55%) to use renewable electricity to produce renewable hydrogen and burn that for heating because of losses in the supply chain, including in the electrolysers and in the combustion system. It is even less efficient (typically 35%) to produce synthetic fuels, such as synthetic methane, from renewable hydrogen and to burn those for heating.

EU markets for heating and cooling have been a challenge for policy-makers for many years, so it would be timely to update the EU's Heating and Cooling Strategy (EC 2016) to guide Member States, cities, and local authorities, and other stakeholders as they tackle the new challenges posed by the phasing out of natural gas.

2.3 Natural gas for electricity generation

2.3.1 Overview of natural gas replacement options for electricity generation

About 29% of EU natural gas consumption was for electricity generation in 2020 (Figure 3), and 19.6% of EU electricity was generated using natural gas in 2022 (European Council 2023). There are several low GHG emission options for replacing this. When choosing between the replacement options, it is important to consider the total GHG emissions produced by fuel extraction, fuel supply chains, and related storage, distribution, and conversion infrastructure per megawatt-hour of final energy (electricity plus useful heat) delivered. In addition, options that produce most

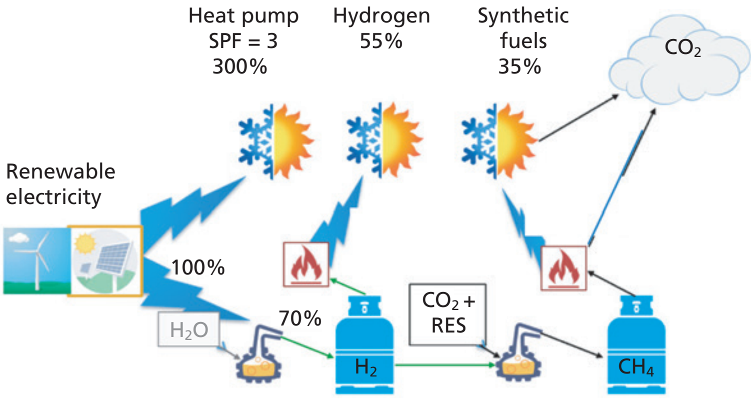


Figure 7 For heating, renewable electricity is most efficiently used by heat pumps (300%) (with a seasonal performance factor (SPF) = 3), and much less efficiently used when converted to renewable hydrogen (55%) or synthetic fuels (35%). Abbreviation: RES, renewable energy sources.

of their life-cycle carbon emissions in the short term should be avoided because they could put the 1.5 °C limit for global warming at risk (UNFCCC 2015).

The life-cycle emissions of the different electricity generation options have been estimated by the UN Intergovernmental Panel on Climate Change and updated in 2021 by the US National Renewable Energy Laboratory (NREL 2021), with ranges to allow for the many different contexts in which fuels are extracted and used (Annex 1). Given the size of these ranges and the need for the emissions of specific energy sources sold in EU markets to be correctly reflected in their market prices (carbon pricing), the carbon footprints of whole supply chains must be monitored and certified (Egerer *et al.* 2022b).

For example, the supply-chain emissions of liquefied natural gas (LNG) should be monitored and certified so that they can be reflected in market prices, because LNG must be liquefied for transportation and then re-gasified before distribution in gas networks. Similarly, the supply-chain emissions of shale gas should be monitored and certified because it typically has high leakage levels and fugitive emissions during extraction (Howarth 2019).

2.3.2 Replacing natural gas for managing flexibility on electricity grids

Variations in renewable electricity supplies must be balanced against electricity demands minute by minute during the day, and over days and weeks to accommodate inter-seasonal variations. Flexibility services are needed for balancing, but also to supply back-up generation for periods of several days (up to weeks) when solar radiation and wind speeds are low over large geographical areas. Flexibility services are also needed to absorb/store electricity during periods with high wind speeds and/or high levels of solar radiation to avoid curtailing renewable generation.

Gas turbines for electricity generation have the important advantages that they are flexible, dispatchable, and are already widely used for grid stability (frequency) management and balancing. However, once the unabated use of natural gas has been phased out, there will be only a very limited long-term role for natural-gas-fired generators on EU electricity grids unless they are sited near CCS facilities and can be connected to those. Instead, gas turbines for back-up electricity generation and grid stability management may be fuelled by low-carbon footprint gaseous fuels such as biomethane (Öberg *et al.* 2022).

In future, flexibility services will be managed using smart (digital) management systems with high levels of cyber security to optimise a combination of flexible dispatchable back-up generators (such as gas turbines or hydropower), electricity storage (e.g. pumped hydropower or batteries), heat storage, demand response (e.g. of electrolysers for hydrogen production: see section 5.3.5), and interconnectors with sufficient capacity to minimise congestion and allow the EU to benefit from the geographical diversity of its renewable energy resources (EASAC 2017).

Technologies for using natural gas or hydrogen or mixtures of the two in large gas turbines are currently under development, and some can already deliver an electric power output exceeding 500 megawatts (MW, 10^6 watts) in a single cycle, and exceeding 1.5 gigawatts (GW, 10^9 watts) with two turbines in a combined cycle (ETN 2020). When these technologies become commercially available, new and retrofitted gas turbines are expected to operate with 100% hydrogen without loss of performance, but with changes to local gas storage and handling equipment.

As an alternative to an all-electric approach, there are potential benefits from using a mix of electricity and molecules (gaseous and liquid fuels) with adequate redundancy and reserves to ensure a good security of energy supplies. Proven ways of meeting these needs may become more widely used, notably converting electricity into low-temperature heat (e.g. in hot water tanks in or near to buildings), and possibly producing additional renewable hydrogen (increased use of electrolysers) and the production of e-fuels, such as e-methanol or e-ammonia depending on costs and markets (Ram *et al.* 2022).

2.3.3 Limited potential for nuclear to replace natural gas for power generation

There are currently 103 nuclear power plants operating in the EU-27, 2 under construction, 7 planned, and 25 proposed (World Nuclear Association 2023).

The time needed to build new nuclear plants will limit their contributions until after 2035. Some Member States are planning to extend the operating lives of their existing nuclear power generation plants and in some cases to build new ones. Life extensions for nuclear plants may offer a short-term solution, although Europe's ageing nuclear fleet is vulnerable to declining availability (Egerer *et al.* 2022a; IAEA 2022b).

Factors that may limit investments in new nuclear power plants in some EU countries include the comparatively high costs of new nuclear plants (higher physical wear and costs in case of operational flexibility), the challenges faced during the summer by nuclear plants that rely on river water for cooling, and risks and uncertainties[7] about disposal of high-level nuclear waste.

There remains a strong split between Member States about the future role of nuclear power, which has resulted in the responsibility for decisions on whether to build more nuclear plants remaining with each sovereign Member State. This split is reflected in EU policies on the future of nuclear power: for example, the proposed Net-Zero Industry Act includes nuclear power in its definition of (eight) net-zero technologies, but nuclear power does not appear in the annex to the regulation, which defines Strategic Net-Zero Technologies that will receive both financial support and help by a dedicated platform with streamlining of administrative procedures and permit-granting processes (EC 2023f). Hence, it remains likely that some Member States will and some will not invest in new nuclear plants.

For more than a decade, research and development has been continuing across the world on small modular reactors, which could potentially offer benefits including economies of scale, closely controlled fabrication in a factory environment, underground installation with lower risk of terrorist attack and lower demands for cooling water, and off-site decommissioning at the end of life (World Nuclear Association 2022). However, despite research and development being largely funded by private companies with support from government programmes, only five small modular reactors are currently reported to be operating (three in Russia, one in India, and one in China). More small modular reactors are under development, but it seems unlikely that such reactors will be commercially available for use in the EU before 2035, and perhaps not before 2040.

Research and development is also continuing on nuclear fusion, notably through the ITER programme, which is building the world's largest international facility in France, but also by private companies. However, grid-connected electricity generation by nuclear fusion reactors is not expected before 2050 (IAEA 2022a).

2.3.4 Cooperation between Member States could reduce electricity generation by natural gas

More cooperation between Member States has been suggested as an emergency and possibly also a short-term measure to reduce the consumption of natural gas for power generation in the EU. For example, if countries with potential excess capacity of nuclear or coal-fired generation could be encouraged to sell more electricity to those that normally generate using natural gas, then it could reduce their natural gas consumption. However, gas-fired generation increased in 2022 owing to low levels of nuclear and hydropower production (Corbeau *et al.* 2023).

Some cooperation occurs naturally through the EU's internal energy market, but this could be expanded by strengthening interconnectors and tackling specific market barriers. However, the growing demand for power generation, coupled with the impacts of droughts caused by climate change on hydro-electricity production, and on the cooling of nuclear power generators, could limit such cooperation, even for the short-term.

2.4 Natural gas for heat production in industry

Natural gas is used as a fuel for process heating in energy-intensive industries, in a range of chemical processes, and in combined heat and power systems. To replace the use of natural gas in these industries will be one of the biggest challenges for industry and for EU policy-makers, and the scale of the challenge will be greater in some EU Member States than in others.

In the EU, the consumption of natural gas fell by 13% year on year in 2022 compared with 2021, largely

[7] An uncertainty imposed by physics is the extremely long persistence of radiation from some radionuclides, which can be up to thousands of years.

because of the curtailment of industrial production (IEA 2022e; 2023b), and in some countries by much more: for example, in the Netherlands it fell by 25% in 2022 compared with 2021 (CBS 2022).

Natural gas is likely to be replaced by electrification for process heating where this is feasible. Alternatively, where they are available, biomethane or biogas (after appropriate purification) can be used to replace natural gas, so the EU is planning to increase the production of biomethane (section 6.3).

In the sunny parts of southern Europe, high-temperature solar heating may become more economically attractive for some industries when the unabated use of natural gas is phased out, so solar heating could be phased in as part of the energy transition. A good example is the use of a parabolic trough solar collector with concrete thermal storage installed in a soft drinks factory in Limassol, Cyprus, where it produces steam at 180 °C and 9.1 bar and has a payback time of 2.5 years (Ktistis *et al.* 2022).

2.5 Natural gas as an industrial feedstock

Natural gas is used as a carbon feedstock for chemical processes, such as to produce grey hydrogen, ammonia, and urea for fertilisers, methanol, monomers, plastics, and many other applications (Figures 8 and 9). It is also used to produce CO_2 for food conservation, beverage production, metal fabrication, cooling, fire suppression, and in greenhouses to stimulate plant growth. However,

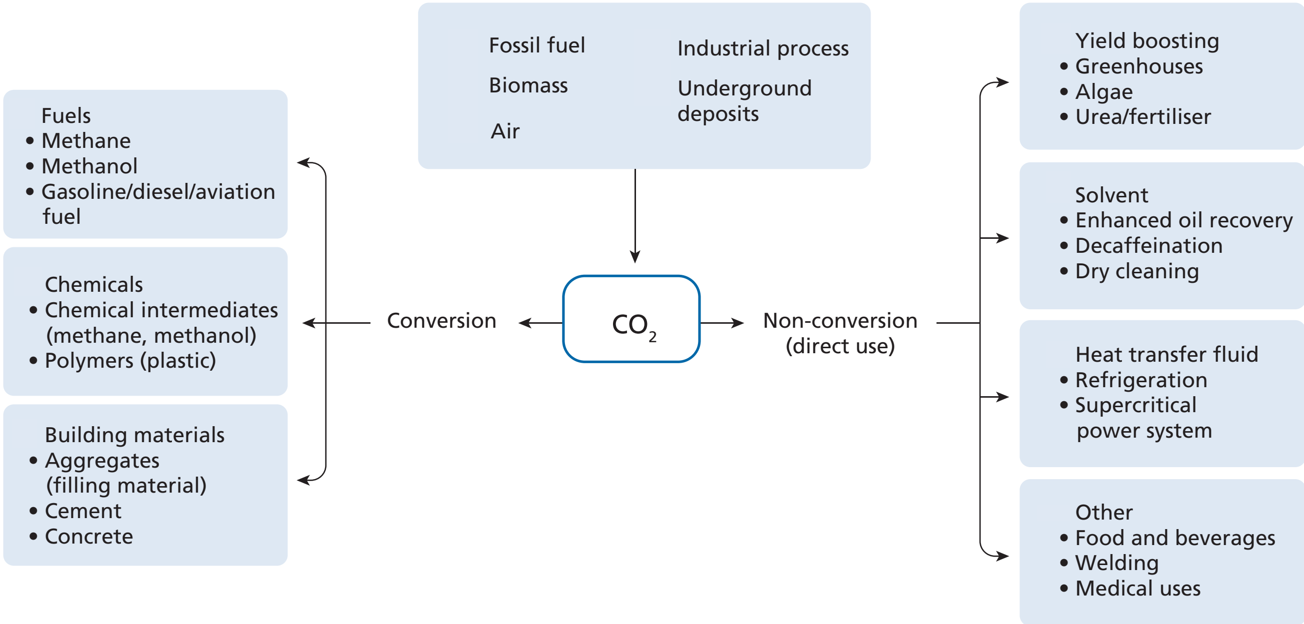


Figure 8 Natural gas is an important feedstock for producing carbon dioxide (CO_2), which is used for many different applications (IEA 2019b; made available under a Creative Commons Attribution 4.0 licence (CC BY 4.0)).

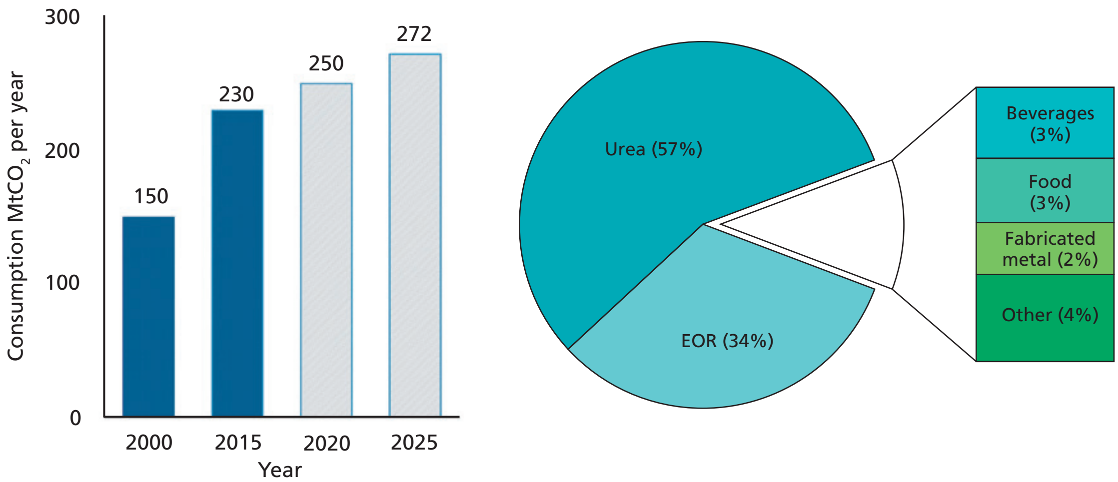


Figure 9 In 2015, carbon dioxide (CO_2) was mainly used to produce urea for fertilisers and for enhanced oil recovery (EOR). CO_2 consumption is expected to grow, largely for new uses (IEA 2019b; made available under a Creative Commons Attribution 4.0 licence (CC BY 4.0)).

compared with the amounts used for energy, the quantities of natural gas used as industrial feedstocks are small, being less than 10% of the natural gas used (S&P Global 2022c).

The feedstock uses of natural gas typically have higher economic value than heat or electricity, so some are likely to continue in the future until alternative production/supply chains can be found. In the case of ammonia-based fertilisers, which are crucial for global food production, the global market went through some turmoil in 2022, but has begun to establish a new mix of supplies with reduced volumes of fertiliser produced using Russian gas (IFPRI 2023).

Producers of bio-fertilisers and insect-based fertilisers are attempting to increase their market share, and farmers are working to introduce regenerative agriculture and thereby reduce their overall demand for chemical fertilisers (EASAC 2022b; 2023). Mineral fertilisers can also be made using renewable ammonia, produced using renewable hydrogen, but it is too early to predict how these options will evolve in the years to come.

Where new carbon sources are required for products that are currently derived from natural gas and other petrochemical feedstock, large biogenic point sources are likely to be the cheapest. For example, municipal or food industry wastes or woody biomass from agricultural or forestry wastes can provide sustainable carbon in the form of synthesis gas, although wastes typically contain other elements that must be removed, thereby adding to processing costs. Industries should always use circular processes for producing chemicals, with built-in recycling to reduce the need for virgin gases (Zimmerman *et al.* 2020).

In future, sustainable carbon may also be obtained from the atmosphere using direct air capture, but further technology development will be needed before that is ready for large-scale commercial deployment.

2.6 Natural gas for transport

2.6.1 Limited potential for replacing natural gas in road transport, but a big demand for renewable electricity

Very little natural gas has been used for road transport in the EU in recent years (Figure 3). Until the Russian invasion of Ukraine, however, the use of natural gas as a short-term transition option for the transport sector was under discussion, because it can be burned in the internal combustion engines of existing fleets, and it offers potential emission savings of 15–20% per vehicle, provided its upstream 'fugitive' methane leakages have been limited to less than about 1% (section 4.6).

With much higher natural gas prices than before the war in Ukraine and stronger EU commitments to phase out its unabated use, significant additional use of natural gas for road transport in the EU is now unlikely. Instead, cars and light-duty vehicles are being electrified because this offers low GHG and air pollutant emissions and can be delivered quickly (EASAC 2019a). Electrification of heavy-duty road vehicles and buses is more difficult, so hydrogen and fuel cells are starting to be used for these (Chapter 5).

The demand for renewable electricity and hydrogen for transport will create competition with the buildings and industry sectors, which need to switch from natural gas to these renewable energy sources. Emission reductions in the buildings and industry sectors are therefore closely linked to those in the transport sector, and they will all rely heavily on increased production of renewable electricity.

2.6.2 Green ammonia and e-fuels are the main options to replace liquefied natural gas for shipping

Stricter regulations for sulfur emissions have been introduced for shipping in recent years by the International Maritime Organization so LNG, with its cleaner combustion emissions, has become an attractive replacement for the commonly used heavy fuel oils. LNG carries a low risk of explosion, and the number of LNG-fuelled vessels is increasing, especially in Europe (DNV 2022).

However, the use of LNG for shipping will have to decrease again as the unabated use of fossil fuels is phased out in line with the European Commission proposal FuelEU Maritime (EC 2021b), and it has also been discouraged by the World Bank (World Bank 2021).

Advanced biofuels offer a more sustainable option, but they are unlikely to be widely used for shipping because of the limited availability of bio-resources and their prioritisation for aviation (Chapter 6). Investments in the next generation of long-haul ships with a low-carbon footprint are therefore likely to prioritise the use of green ammonia, e-fuels (e-diesel, e-methane, e-methanol, or e-ammonia), or possibly biomethane.

2.6.3 Natural gas and liquefied natural gas are unlikely to be used as aviation fuels

The REFuelEU Aviation initiative (EC 2021d), which was included in the Fit for 55 package by the European Commission, proposes that kerosene should be blended with increasing percentages of sustainable aviation fuel in the coming years. Discussions are continuing on which feedstocks and fuels should be counted as sustainable aviation fuel. It seems likely that several different biofuels, synthetic fuels, hydrogen, and renewable electricity will be included but not natural gas or LNG (EPRS 2022b).

3 Impacts on future natural gas consumption

Which policy, market, and technology developments will affect the future use of natural gas?

3.1 Introduction

The use of natural gas during the EU's transition to a decarbonised and secure energy system will be influenced by many factors, which are discussed in this chapter.

Reductions in natural gas consumption are already being driven largely by prices, which may remain volatile for several years, and by the behaviour of consumers who are deploying energy efficiency measures and switching fuels and technologies in buildings and industries.

In the short to medium term, natural gas consumption will also be influenced by increases in the availability of renewable electricity, renewable heat, fossil-free 'drop-in' fuels that can be used to replace natural gas in existing systems, and renewable fuels of non-biological origin (Chapter 5), together with investments in electrification and systems that use fuels with a low-carbon footprint in buildings and industry.

Policies, legislation, financing, and guidance for investors will all have important impacts on the future of natural gas.

3.2 Energy efficiency should come 'first'

A key component of all policies for delivering greenhouse gas (GHG) emission reduction and securing energy supplies must be to reduce the demand for fossil fuels, including natural gas, through energy efficiency measures and changes in consumer behaviour (EC 2021g).

Energy efficiency is equally important when using renewable energy sources, because there will be competing demands throughout the energy transition, not only for renewable electricity and renewable heat, but also for raw materials to build renewable energy generators, capacity on electricity grids, and in some cases also for land use.

Many European countries have been slow with the implementation of energy efficiency measures for years, so this trend must change (Löschel *et al.* 2018; Odyssee-Mure 2021b).

One of the emergency responses of the EU to the cuts in natural gas supplies from Russia in 2022 was to encourage consumers to implement 'no cost' and 'low-cost' energy efficiency measures, such as sealing buildings to reduce draughts and temporarily reducing the temperature settings of heating systems (IEA 2022a). Encouragement of such energy-saving behaviour is best provided by nationally or regionally coordinated campaigns, and by using local 'one-stop shops' to provide independent advice on locally available energy-saving products and services to householders and businesses.

As well as making savings in overall energy consumption, it is important to make reductions in peak demands, especially for electricity, because these determine to a large extent the required electricity-generating capacity and therefore the size of the investments needed in wind turbines and photovoltaic generators. Peak electricity demands can be reduced by using digital controls on electricity consuming appliances, and by using appliances and systems with high energy efficiencies. The timing of the peak demands of individual consumers can be managed by grid operators to avoid creating excessive peaks demands on the grid by using demand response agreements and digital controls linked to smart meters.

The demand for natural gas in the EU will be reduced by electrification, but the result will be an increase in electricity consumption, despite the widespread deployment of energy efficiency measures in the building, industry, and transport sectors. Overall, an annual energy efficiency gain can be expected (Ram *et al.* 2022).

The renovation of existing buildings in the EU will improve their energy efficiency through insulation, controlled ventilation, and replacing the heating system, which is often a gas boiler, with a heat pump and/or district heating. This should be done in ways that realise the potential health benefits for the occupants and minimise the embodied carbon emissions in the materials, components and processes used (EASAC 2021).

The energy efficiency of transport can be improved and its GHG emissions reduced by avoiding the use of motorised transport (more walking and cycling), shifting passengers and freight to low-carbon footprint transport modes (trains, buses, inland waterways), and improving the GHG emission performance of vehicles (electrification, fuels with a low-carbon footprint, improved vehicle designs) (EASAC 2019a). These measures will reduce the consumption of gasoline and diesel, but they will increase the demand for renewable electricity. Hence, until sufficient renewable electricity generation has been built, the electrification of transport will compete with demands for renewable electricity to replace natural gas in industry and buildings, and to produce renewable hydrogen and e-fuels.

3.3 Behaviour and personal choices can be influenced by concerns about health and climate change, as well as price

The success of the EU's energy transition to net zero by 2050 is strongly dependent on building more wind and solar power generators and increasing the capacity of the grid networks. One of the biggest barriers to this is opposition by local communities and delays in the permitting process. These barriers can only be removed by stronger engagement of policy-makers and project developers with citizens and communities across the EU, so that they become motivated to adopt positive attitudes towards the energy transition and choose to support its implementation.

Among the most powerful influences on behaviour and personal choices, alongside prices and affordability, are concerns about health and comfort (EASAC 2021), but choices can also be influenced by tradition, concerns about climate change, and by policies and regulations.

3.4 Inclusion of transitional natural gas activities in the EU Taxonomy should be reviewed

Investors are influenced by the availability of finance, and the financing community will in future increasingly follow the EU Taxonomy, which is intended to prevent greenwashing and to help investors identify sustainable economic activities. The Taxonomy has a delegated act on natural-gas-related activities (EC 2022r), which applies from January 2023 and sets requirements under which investments in the use of natural gas can be labelled as environmentally sustainable 'transitional activities', in the context of the six environmental objectives of the Taxonomy regulation (EU 2020).

Urgent investments in some natural-gas-consuming projects may be justified in response to the Russian invasion of Ukraine, and the Taxonomy-delegated act contains many constraints, including GHG emission limits, obligations to replace an existing high GHG emission (e.g. coal-fired) system, and to include future conversion to a renewable energy system. However, to label the unabated use of natural gas as an environmentally sustainable transitional activity risks giving the wrong signal to investors. Moreover, the recent growth in LNG imports increases the risks of GHG emissions, notably methane emissions from natural gas supply chains that could cancel out the GHG emission reduction benefits of replacing coal-fired generators with natural gas, given the high global warming potential of methane (section 4.6).

It follows that the inclusion of transitional natural gas activities in the Taxonomy should be reviewed, and that potential investors should instead be guided by the Taxonomy to prioritise projects in energy efficiency, low-carbon footprint fuels, or renewable energies that are unquestionably environmentally sustainable.

3.5 Acceleration of renewables deployment

3.5.1 The biggest obstacles to ramping up wind and solar electricity generation are slow permitting procedures and opposition from local communities

The recent Fit for 55 and REPowerEU proposals (EC 2022g) have raised the EU target for the share of renewable energy in gross final energy consumption to 45% by 2030. This will require major efforts by all sectors of society as well as major investments (Box 1).

Box 1 Speed up and scale up renewable electricity supplies

The phasing out of natural gas is expected to be largely achieved through electrification, together with the use of green gases, especially for industrial applications, so major increases in the production of renewable electricity will be needed.

As well as building more plants for renewable electricity and renewable heat generation, the capacities of electricity transmission and distribution grids must be reinforced, more systems must be built for storing electricity and heat, and more electrolysers deployed to produce renewable hydrogen.

More ambitious legislation and incentives are needed to make this happen, in particular to speed up permitting as proposed in the REPowerEU plan to accelerate the deployment of more renewable capacities (EC 2022h), to publish stable long-term permitting plans with maps showing agreed deployment areas, to simplify access to the grid, and to attract the required investments for example by using the leverage of public funding (EC 2022i) (Chapter 7).

The EU's energy market rules must also be adapted to accommodate much higher fractions of variable renewable electricity generation, and the growing roles of electricity and heat storage, electrolysers for renewable hydrogen production, and digital technologies, especially for demand response systems (EC 2023g).

To deliver the required increases in the deployment of offshore and onshore wind and solar farms, more marine spatial planning studies, environmental impact assessments, and electricity network analyses will also be needed.

Enhanced trade relationships through dedicated partnerships with countries outside the EU are foreseen and will be vital to accelerate the deployment of renewable energy supplies, and to establish agreed legal frameworks for global markets in sustainable fuels (EC 2022c).

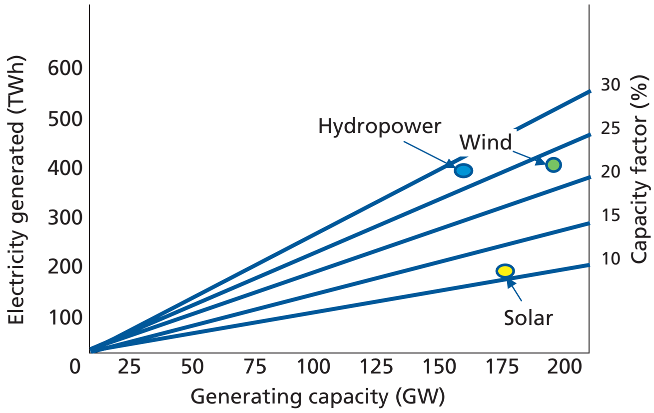


Figure 10 Electricity generated by wind and solar generators in the EU-27 in 2021 (Windeurope 2022a; Eurostat 2023a; SolarPower Europe 2023).

The energy generated by renewable electricity generators depends on their location and varies over the day and over the year, as the availabilities of the wind, solar, and water resources vary. In 2021, 913 terawatt-hours (TWh, 10^{12} watt-hours) of renewable electricity was generated in the EU, of which 381 TWh were generated by wind, 161 TWh by solar, and 370 TWh by hydropower generators (Eurostat 2023a).

An overview of the relationship between the installed renewable electricity-generating capacity (in gigawatts) and the annual total electricity generated (in terawatt-hours) can be seen in terms of an annual overall capacity factor in Figure 10, where the annual overall capacity factor is the ratio of electricity generated to rated output (terawatt-hours/(8,760 × gigawatts)).

The wind industry, which added 17 GW of wind generators in 2021 to its installed capacity of 189 GW, has said that this rate of installation would have to be increased to 39 GW per year to help deliver the EU's 45% renewables target by 2030. However, it expects to install only a further 17.6 GW per year over the period 2022–2026, unless planning and permitting requirements are improved (Windeurope 2022a; 2022b).

The wind industry reported that capacity factors (which depend largely on local weather conditions) of the entire wind fleet in the EU and UK were 24% on average in 2021 (3% decrease on 2020). Onshore turbines had 23% (down from 25% in 2020), and offshore turbines had 35% (a fall from 42% in 2020). Offshore fleet capacity factors are more variable than onshore because they occupy a smaller geographical area and are therefore more susceptible to local weather patterns. New turbines are built with larger blades to operate in areas with lower wind speeds and deliver higher capacity factors, typically between 30% and 35% onshore and between 42% and 55% offshore (Windeurope 2022a).

The solar industry, which added 41.1 GW of photovoltaic generators in 2022 to its installed capacity of 168 GW in 2021, has said it could increase its rate of installation to 100 GW per year from 2025, aiming towards about 1 TW of installed capacity by 2030 (Solarpower Europe 2023). This solar industry target is more ambitious than the target of 600 GW of installed photovoltaic capacity by 2030 set in the REPowerEU plan (EC 2022g).

The overall demand for electricity will increase over the period 2023–2030 owing to the electrification of buildings, industry, and transport; so, to deliver on the REPowerEU targets, every effort must be made to facilitate delivery of the ambitious generator deployment targets of the wind and solar industries. Although many areas with 'low hanging fruit' have already been exploited, and wind and solar electricity already had lower levelised costs of electricity than fossil fuels in 2019, further economies of scale are expected to deliver further cost reductions (IRENA 2020).

The wind and solar industries and the European institutions recognise that the biggest risks associated with delivering the required growth in renewable electricity generation are related to obtaining construction permits from local communities for the new generators and for their related infrastructures (EC 2022h), and to mobilising the required investments (IEA 2022k).

3.5.2 Only biomass resources with short carbon payback times can usefully replace natural gas

Bioenergy can be produced by the combustion of solid, liquid, or gaseous biomass, and has the advantages that the energy produced can be dispatched when needed and that the biomass can be easily stored. However, bioenergy can only be judged to be sustainable if the biomass resources used are able to deliver carbon emission reductions quickly enough to contribute positively to limiting global warming to less than the 1.5 °C target set in the Paris Agreement.

This implies, as explained in the EU Forest Strategy for 2030 (EC 2021l), that solid biomass resources, such as round wood from trees, with long carbon payback times (typically several decades), should not be used for power generation, advanced biofuels, or any other form of bioenergy until after they have been used for other possible applications with higher economic and environmental value in the biomass cascade (Figure 11). In line with the cascade principle (EC 2018b), priority should be given to using wood for long-lifetime

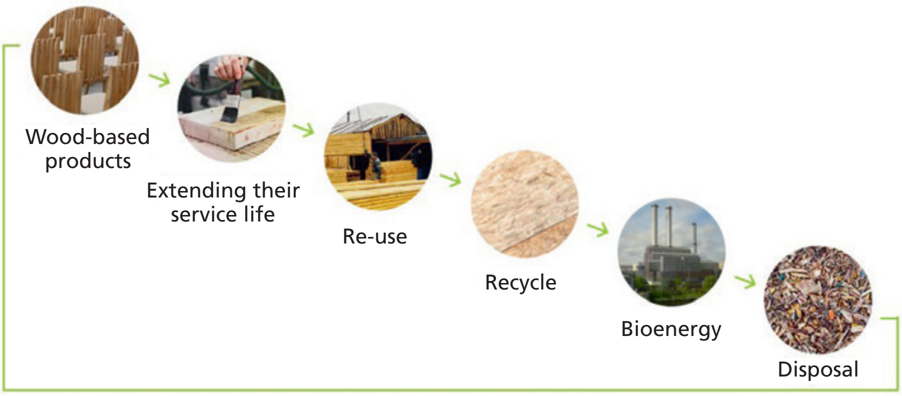


Figure 11 Biomass cascade: use forest biomass first for wood-based products with long lifetimes, then applications with highest economic and environmental value (EC 2021k; © European Commission, 2021).

products, such as construction timber and boards before it is used for bioenergy.

In contrast, sustainable biomass resources with short carbon payback times, can usefully replace natural gas. These include agricultural, industrial (e.g. food and forest-based industries such as pulp and paper), and municipal wastes including landfill, as well as biogas and other fermentation-based products, such as biomethane, bioethanol, and biobutanol (Chapter 5), provided they do not cause excessive GHG emissions from indirect land-use change (EU 2022a). However, their growth must be carefully managed to avoid causing reductions in biodiversity and other ecosystem services (EASAC 2018; 2021).

As an emergency measure until 2025 and in the short term until other grid flexibility management measures have been widely deployed (e.g. electricity storage, demand response, stronger interconnectors), it may be helpful to keep some existing bioenergy generators online and use them to burn unsustainable biomass during periods with low wind and solar photovoltaic generation. However, to minimise their GHG emissions, the burning of unsustainable biomass in such back-up generators must be strictly limited to periods of low wind and sun, and their unsustainable biomass consumption must be no more (preferably less) than in their current configuration.

3.5.3 Fossil-free 'drop-in' fuels could be useful in existing plant or equipment

As the unabated use of natural gas is phased out, there will be growing demands for fossil-free drop-in fuels that can be used in existing plant or equipment. If the existing plant or equipment can continue in use until the end of its economic life, which might take another 20–30 years, this would not only avoid or delay a capital investment but also avoid or delay creating the embodied GHG emissions that are produced when building a new plant.

Examples of drop-in fuels include biomethane, renewable methanol, bio-LPG (bio-propane and bio-butane), bio-DME (bio-dimethyl ether), and e-fuels. These fuels are discussed in Chapter 6.

3.5.4 Renewable energy investment risks must be addressed

The future deployment of renewable energies in the EU has the following potential risks that need to be addressed by governments, financing institutions, and investors:

1. Import dependency. The deployment of wind and solar energy systems currently involves making the EU dependent on technology imports including photovoltaic solar panels, wind turbine components, and electrolysers, and/or on critical raw material imports such as lithium, copper, and nickel (EC 2023c). The need for such imports reduces the security of EU energy supplies but can be addressed by adopting a more circular economy, using more resources from within the EU, increasing local manufacturing, and recycling more components and materials.

2. Impacts on competitiveness of EU industries. Obligations to reduce GHG emissions cause industries to invest in adapting their processes to use renewable energy sources, which will lead to lower operating costs than if they continued using fossil fuels. Nevertheless, some industries may need help with securing affordable financing for the capital investments in their process adaptations, even though they will reap returns when their energy costs go down and their customers agree to pay a premium for more sustainable (green) products and services. The Carbon Border Adjustment Mechanism will help to address the challenge of competition with cheap imports into the EU that have a high carbon content (EC 2022u).

3. Grid flexibility management. Electricity network operators manage the grid by balancing electricity demand with outputs of wind and solar electricity generators, which vary over the day and over the year. For this, they require a mix of dispatchable back-up generators, storage, demand response, and strong interconnectors.

4. Land use and local impacts. The deployment of renewable energies involves the construction of wind and solar generators together with electricity cables and infrastructure. Opposition to such developments typically arises from perceived or real local impacts related to land use and visual amenity.

Unfortunately for policy-makers and for businesses, no analyses can provide universal guidance on these important risks, so political and commercial decisions related to the future deployment of renewables must continue to be made case by case (using scenarios and models, where possible, to limit the risks), as illustrated for example by the recent work of the German Council of Economic Experts (GCEE 2022).

3.6 Demand response: digital system integration across sectors for managing flexibility

Substantial increases in the use of digitally controlled demand response systems are already being seen across the world; this trend is expected to accelerate as the need for flexibility increases on electricity networks (IEA 2022d).

The growing use of wind and solar generators is creating opportunities, and new businesses are emerging to maximise the benefits of these opportunities (SmartEN Europe 2022). If demand response is promoted through real-time electricity tariffs, it can reduce the need for centralised electricity and heat storage, and for flexible generation (powered by natural gas in the short term, and later by sustainable fuels in the medium to long term) to meet peak demands. It can also help with managing periods of low demand (valley filling).

In buildings, demand response can be implemented at relatively low cost in the short term, for example by optimising the timed use of heating systems and appliances using digital controls to fit with periods when local electricity demands and prices are low. If the building occupants have electric vehicles, then vehicle batteries can exchange electricity with the grid (store and supply electricity) in response to time-dependent tariffs that reflect the needs of the grid for flexibility management. In addition, buildings can be fitted with stationary batteries to perform such exchanges of electricity with the grid.

For industry, demand response has been available in many parts of Europe for years, using contracts with reduced prices if electricity supplies can be cut off at short notice. However, with the growth of renewable electricity generation, new business models will aim to address inter-seasonal variations in power generation, for example by offering reduced prices if an industrial plant is shut down during longer periods of high electricity demand.

3.7 Potential of carbon capture and storage is highly dependent on cost reductions and carbon price developments

When CCS (also called carbon capture, transport and storage, CCTS) is used to capture and store carbon emissions from natural gas combustion, it is known as 'abated' natural gas.

Carbon capture and utilisation (CCU) or carbon capture, utilisation and storage (CCUS) can be applied to the production of fuels, chemicals, and materials, and has been shown to add value in applications such as using carbon emissions from industrial processes to make long-life plastics or other elements for the construction sector (SAPEA 2018). In contrast, CCU or CCUS contributes little to the 2050 net-zero decarbonisation goals if it simply involves using the same carbon twice in a short period of time before it is released into the atmosphere, for example when captured carbon is used to make liquid transport fuels.

There are currently 29 CCS facilities in operation around the world, capturing and storing 40–45 Mt of CO_2 per year, and more than 140 CCS facilities under development globally (Global CCS Institute 2022a, IEA 2022c). Forty megatonnes of CO_2 per year is equivalent to about 0.1% of global CO_2 emissions which, in 2021, were the highest ever at 36.3 gigatonnes (Gt). The EU emitted 2.7 Gt of CO_2 in 2021 (IEA 2022b).

Many businesses are discussing and promoting the idea of using CCS to show that they are 'green', but progress with CCS in the EU over the past decade has been slow, many projects have been cancelled, and cost reductions have been difficult to achieve. Consequently, despite many public discussions and promotion campaigns, CCS is not yet widely deployed in the EU.

The value of CCS will increase with carbon prices, which in turn depend on the overall speed of the transition to a low-carbon economy, and this will improve the return on investments in CCS. Looking to the future, the EU's Carbon Border Adjustment Mechanism will help some businesses in the EU to justify investments in CCS because the prices of products with high carbon content that are imported into the EU will have to reflect their carbon content in the same way as products made in the EU (EC 2022u).

There are already some interesting CCS developments in Norway, the Netherlands, and the UK, which could help with the commercialisation of CCS technologies in some parts of Europe (IEA 2022c), with 73 ongoing projects in various stages of development across Europe and the UK (Global CCS Institute 2022b). However, there are fewer potential sites for CCS in landlocked countries (e.g. Eastern European countries) than in those with coasts bordering on the North Sea, and NIMBY ('not in my back yard') issues are important in some countries.

Some potential applications of CCS are discussed below:

- The cement industry is a major producer of EU carbon emissions (mainly from coal and natural gas) that could usefully deploy CCS, but lower costs would be needed to beat competition from cement imports with high embodied carbon emissions until the EU's Carbon Border Adjustment Mechanism has been fully implemented (EC 2022u).

- Grey hydrogen producers could use CCS with steam reforming of natural gas to produce blue hydrogen, but this would emit 30–120 grams of carbon dioxide equivalent per kilowatt-hour (gCO_2e/kWh), which is much more than the 10 gCO_2e/kWh emitted when renewable hydrogen is made using wind electricity (EASAC 2020). However, the carbon footprint of blue hydrogen could be reduced in the future by advanced auto-thermal reforming (Oni *et al.* 2022).

- The steel industry currently produces carbon emissions from fossil fuels (mainly coal). It should not need CCS because steel can be competitively produced using renewable hydrogen. However, if this is not available or its price is too high, then blue hydrogen could be used where CCS is available at competitive prices.

- Electricity generators that burn natural gas could use CCS if they are kept online for the short term to provide back-up power when wind speeds are low and the sun is not shining. However, to build CCS for generators that will be used for only a few days per year over the next few years would be costly and therefore not an attractive investment unless the storage facilities are shared with other facilities. The use and potential value of such generators will depend on future Emission Trading System (ETS) prices.

- The oil and gas industries could use captured CO_2 for enhanced oil or natural gas recovery in the short term because investment time horizons are typically quite short for that; however, for the medium and long term, such recovery applications are unlikely as the unabated use of oil and natural gas are to be phased out.

- The chemical industries can capture carbon from natural gas and use it to make fuels, such as methanol, long-life plastics, and other materials. Such CCU can make a valuable contribution to the reduction of global warming if it produces products with a lifetime of more than (say) 30–50 years.

- Bioenergy with CCS, for example burning wood instead of coal in power stations and connecting them to CCS, has been proposed as a way to remove carbon from the atmosphere and generate renewable electricity at the same time. However, although bioenergy with CCS would effectively remove carbon from the atmosphere if the biomass used were limited to agricultural or forest wastes and residues with carbon payback times of less than (say) 10 years, such biomass resources are limited. In contrast, bioenergy with CCS could not contribute much towards net zero by 2050 if whole trees were used because the carbon payback period of wood from whole trees is typically many decades (EASAC 2022a).

The future of CCS will depend strongly on its costs, and on how these compare with future carbon prices driven by the ETS. Given the limited experience with CCS in the EU so far and the uncertainties about future carbon prices, it is too soon to predict a future trajectory for CCS in the EU with confidence.

3.8 Technologies that will influence future demands for natural gas

3.8.1 Storage of electricity, heat, and low-carbon footprint gases

Heat, electricity and low-carbon footprint gas-storage capacities are expected to grow during the energy transition and to increasingly take over the day to day, week to week, and inter-seasonal storage roles that have been played in the past by natural gas storage. Some of the large caverns that are currently used for storing natural gas may be converted for storing low-carbon footprint gases, including hydrogen and biomethane.

Opportunities for new energy storage technologies, including advanced batteries, power to gas, power to liquid, low-carbon footprint hydrogen, green ammonia, and large-scale (hot) water storage systems, will be created by integration of the energy sector (EC 2020c).

3.8.2 Combined heat and power (cogeneration) may in future be powered by wastes and biofuels

The production of electricity and heat simultaneously in a combined heat and power (CHP) plant is typically a much more efficient way of using fuels than to produce electricity and heat in separate plants, and it has been promoted for many years by the EU to provide district heating and cooling as well as for applications in industry.

However, all carbon emissions must be reduced as part of the Green Deal, so the criteria for high-efficiency CHP have been strengthened as part of the Fit for 55 package and REPowerEU (EC 2021g). For example, high-efficiency CHP must now provide an accepted level (currently 10%) of primary energy savings compared with the separate production of heat and electricity, and its CO_2 emissions must be less than 270 gCO_2/kWh of energy output, including heating/cooling, power, and mechanical energy.

For many years, CHP in the EU has used fossil fuels including natural gas. As the unabated use of natural gas is phased out, the most attractive fuels for use in CHP plants for district heating or industry are likely to be biogas or biomethane, where these are available and not needed for higher-value applications such as aviation fuels or specialised industrial applications. Alternatively, CHP may be powered in the future by burning sustainable solid fuels such as agricultural wastes, food wastes, or municipal wastes or other forms of biomass with short carbon payback periods, although such bio-resources will be limited.

(Note: for discussion about the efficiency of district heating systems, see section 2.2.3.)

3.8.3 Fuel cells for cogeneration still face challenges

Although traditionally natural gas has been burned in boilers to produce heat for steam turbines or burned in gas turbines to produce electricity directly, fuel cells offer an efficient mobile or stationary alternative for converting gaseous fuels to electricity (and heat).

Solid oxide fuel cells can be used for CHP with high efficiency (80–85%); these are already being demonstrated in Japan and Korea to reduce CO_2 emissions from electricity generation (Weber 2021). These fuel cells have the advantage that they can be used initially with natural gas, followed later by a switch to hydrogen or another synthetic gas without creating stranded assets. The main challenges faced by users of solid oxide fuel cells are the high operating temperatures (around 750 °C) and high prices, but work is proceeding in Europe, Japan, and the USA to improve both (IEA 2021b; 2021c).

Other fuel-cell technologies are also under development, including polymer electrolyte membrane, which is already commercially available, and some of these technologies can also be used with either natural gas or hydrogen (IEA 2021c).

4 Gaseous fossil fuels

Where do EU gaseous fossil fuels (natural gas, liquefied natural gas, liquid petroleum gas, and dimethyl ether) and methanol come from, and how will that change and affect future European Union greenhouse gas emissions and security of energy supplies?

4.1 Natural gas supplies to the European Union must be sourced mostly from third countries

Natural gas has been supplied to the EU from four main sources in recent years: from producers in the EU, Russia and Norway by pipe networks, and as liquefied natural gas (LNG) from various sources supplied by ship (section 4.4). Smaller supplies of natural gas came through pipelines from Algeria, Libya, and the Caspian region (Figure 12). Natural gas consumption dropped during the COVID pandemic and bounced back in 2021 (Figure 1).

From 2019 to 2021, about half of the natural gas supplied to the EU came from Russia (pipeline and LNG), but this fell to about 40% at the beginning of 2022, and to about 10% by the end of 2022 (Figure 13).

Some European countries imported a much higher share of their natural gas from Russia than others before the invasion of Ukraine (Figure 14a), and the percentage of natural gas in final energy consumption (dependency on natural gas) varied significantly among EU Member States (Figure 14b).

4.2 European Union focuses on options to replace Russian natural gas supplies

EU policy for the short term is focused on rapidly phasing out natural gas supplies from Russia, and on finding alternative suppliers of either piped natural gas or LNG as well as reducing natural gas demand (EC 2022g).

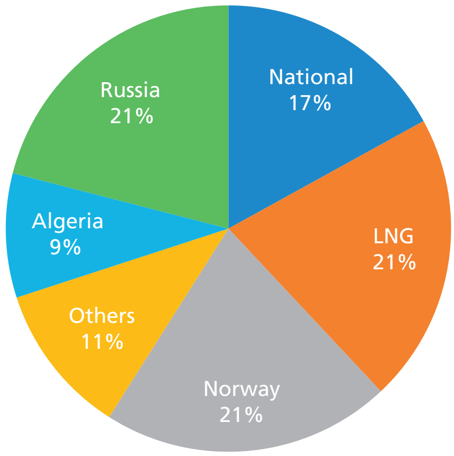


Figure 12 Natural gas supplies to the EU in 2022 (European Council 2022b).

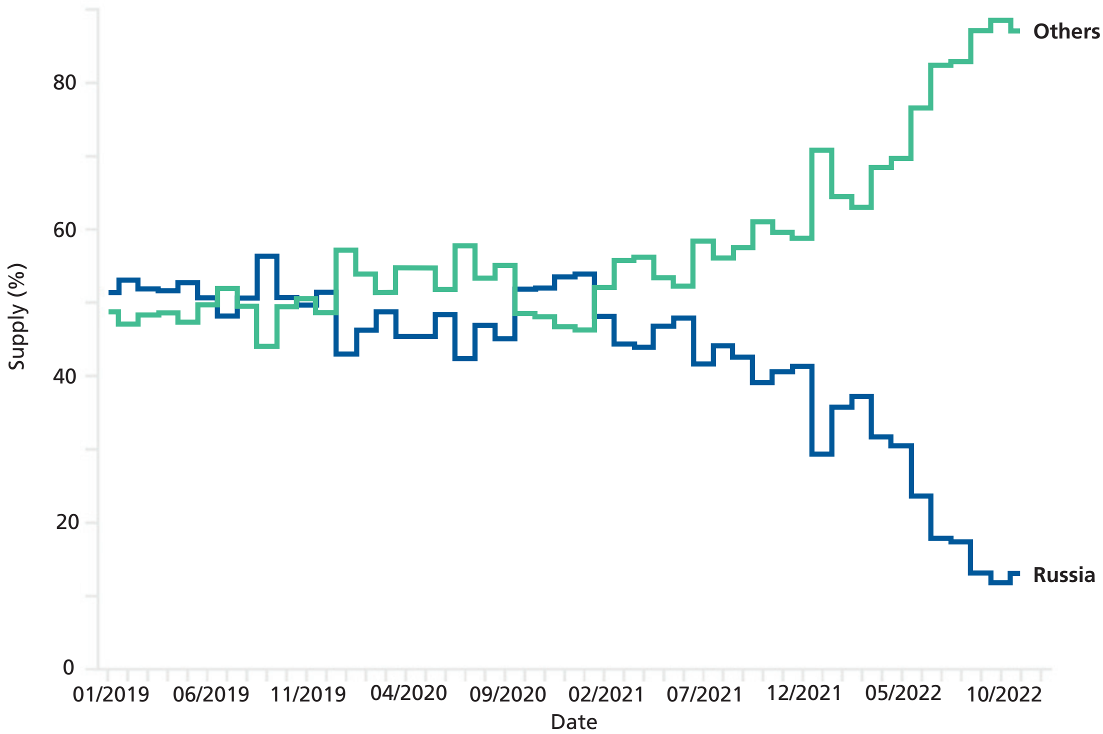


Figure 13 EU diversification of natural gas supplies: reduced supplies from Russia and increased supplies from other sources (European Council 2022b; © European Union 2023).

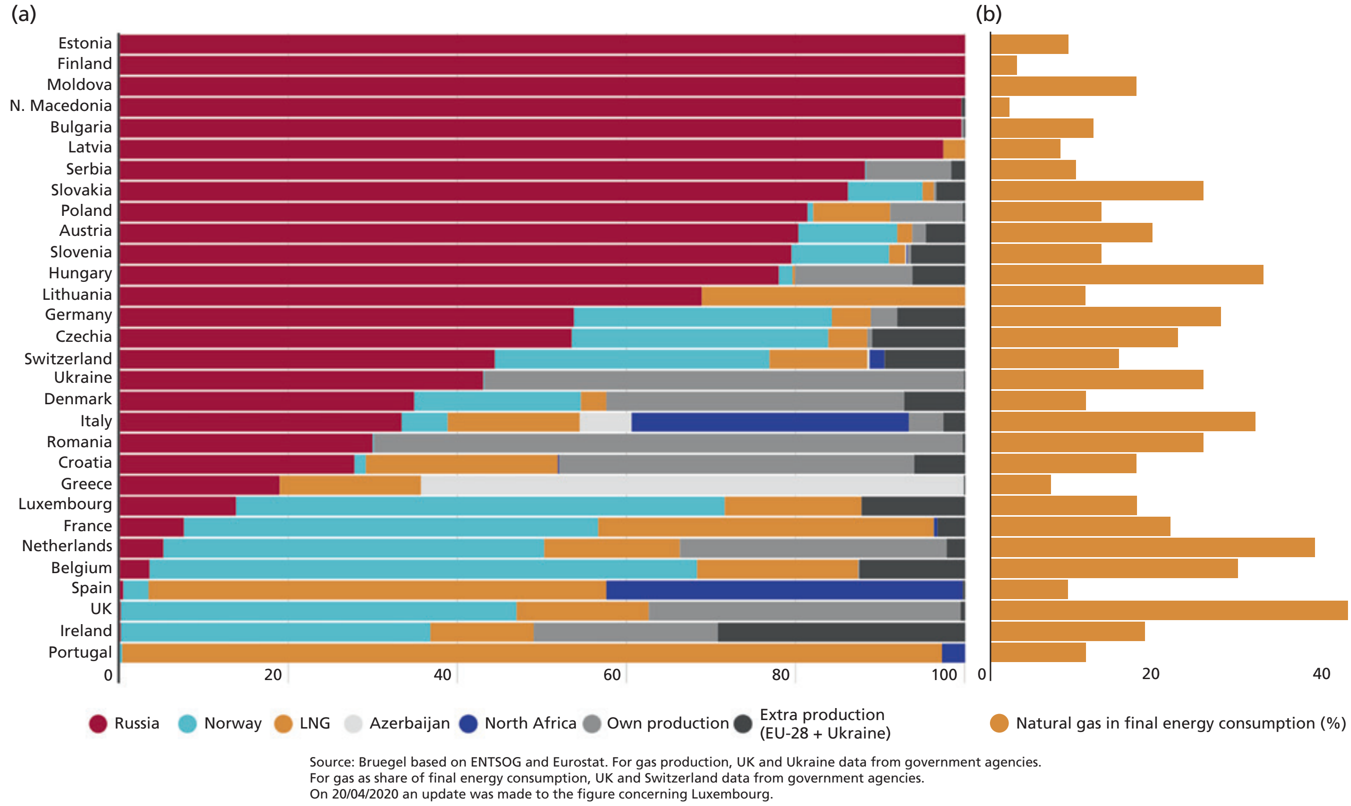


Figure 14 (a) Some EU Member States imported a much higher share (%) of their natural gas from Russia than others in 2021 (Bruegel 2022b). (b) In 2021, some EU Member States were more dependent on natural gas (higher percentage in final energy consumption) than others (Bruegel 2022b).

As part of this policy, natural gas purchasing must be well coordinated across the EU, immediately for filling natural gas storage systems, and then for the short term to achieve the best prices for LNG and piped natural gas imports. For this, the European Commission (EC) established an EU Energy Platform in 2022 (EC 2022m; 2023a) to facilitate the coordination of joint purchasing (section 8.7).

The Dutch Government has maintained its 2018 decision to phase out the extraction of gas in Groningen to reduce the risk of earthquakes and improve safety for the region's inhabitants (Government of the Netherlands 2022). Some piped supplies of natural gas to the EU can be expected in future to come from Norway, and the feasibility of increasing natural gas supplies to the EU through pipelines from Azerbaijan, EASTMed (Israel/Cyprus/Greece), and Iran/Turkey and the potential impacts of such increases on the future security of EU supplies will be addressed through the Commission's new Energy Platform.

4.3 Major new shale gas developments in the European Union are unlikely (fracking)

Fracking was initially developed in remote areas of the USA, where it could be implemented on a large scale with minimal regulations, and it produced shale gas that was distributed by pipelines to US consumers at very competitive prices. When EU natural gas prices were low in 2020, to import shale gas (released by fracking) in the form of LNG seemed to be expensive. However, the economics of natural gas supplies in the EU have changed since the invasion of Ukraine and, consequently, there is renewed interest in importing LNG into the EU, notably from the USA. The USA has a high number of LNG projects under construction or at an advanced stage of planning, with four projects taking a final investment decision in 2022/23 (Cheniere 2022; INEOS 2022; Venture Global LNG 2022).

Shale gas currently constitutes nearly 80% of the natural gas produced in the USA (US EIA 2022b), and the USA is likely to remain a major source of LNG to replace Russian gas in the EU over the next few years. Other suppliers of LNG may grow their market share in the EU once international methane emission monitoring and certification are implemented in line with the Global Methane Pledge (GMP 2021), provided it is adequately policed.

Recent studies of fugitive methane emissions from fracking suggest that these could be as high as 3.7% of the supplies involved in parts of the USA (Storrow 2020; Vaughan 2020). Such levels of fugitive methane emissions would generally cancel out the greenhouse gas (GHG) emission reduction benefits of replacing coal-fired generators with natural gas, given the high global warming potential of methane (section 4.6). Methane leakage can be caused by shale gas exploration and extraction, as well as from poorly sealed shale gas wells (which typically have a limited lifetime) after they have ceased production or when they are vented as part of operational procedures (Howarth 2019).

The available resources of shale gas in some parts of Europe have been found to be smaller and more costly than initially expected, and its production has been widely associated with causing local Earth tremors and with the pollution of underground water supplies, as well as local surface pollution caused by drilling and by the transport of chemicals. Consequently, although EASAC published a report on shale gas in 2014, emphasising the importance of strict compliance with the relevant regulations (EASAC 2014), fracking developments in Europe have largely stalled. Public opinion in the EU has discouraged fracking for environmental reasons, and the EU has published little on the topic since its early guidance documents in 2014 (EP 2014; Euractiv 2022a).

Looking to the future, given that the EU is committed to phasing out the use of fossil fuels including unabated natural gas, investors are unlikely to support major new shale gas developments in the EU. The market for LNG imports can also be expected to decline once the emergency measures adopted in response to the Russian invasion have been replaced by short-term actions aiming to deliver the EU's 2030 GHG emission reduction target.

4.4 Safeguards are needed to address higher global warming potential of liquefied natural gas

The EU (excluding the UK) has imported about 80 billion cubic metres (bcm) of LNG per year in recent years, but this increased to 98 bcm in the first 9 months of 2022, of which Russia supplied 17 bcm (EC 2022e). As shown in Figure 15, the USA became the EU's largest source of LNG in 2021 (US EIA 2022a) and, in 2022, the USA adopted a common declaration with the EU on increasing LNG trade (The White House 2022). Europe (including the UK and Turkey) was the main destination for US LNG exports in 2022, representing 64% of total US LNG exports (EIA 2023).

Supplies of LNG normally require large plants (taking years to build) to cool and liquefy natural gas to make LNG, special tankers to transport it, and large terminals and plants to import and regasify it before distribution. An overview of European LNG regasification terminals that were operational, under construction, or planned in February 2022 is provided in Figure 16.

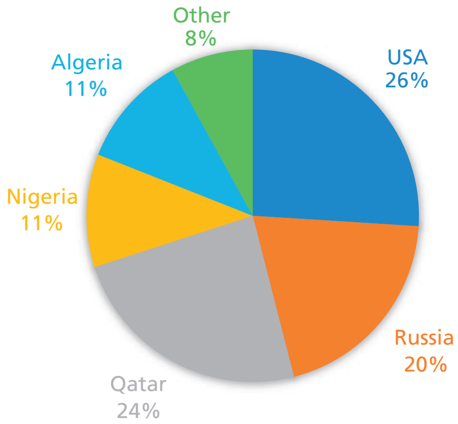


Figure 15 The USA became the EU's largest source of liquefied natural gas in 2021 (US EIA 2022a).

In addition to increasing, where possible, the flows through existing LNG terminals, one option to facilitate increased imports of LNG into the EU is to deploy floating LNG regasification terminals on ships (floating regasification and storage units, FRSUs). According to the International Energy Agency (IEA), EU countries had secured as many as 12 FRSU vessels during 2022 for their regasification projects, including five in Germany, two in the Netherlands, two in Italy, one in Finland, one in Greece, and one in Cyprus (IEA 2022e). Two new FRSUs arrived in Eemshaven and started operating in September 2022, increasing the Netherlands' regasification capacity by 8 bcm per year (Wilk 2022). Three FRSUs were delivered to Germany between December 2022 and January 2023 in Wilhemshaven, Lubmin, and Brunsbüttel (Deutsche Welle 2023).

When completed, the Alexandroupolis FRSU in Greece will provide 5.5 bcm of natural gas annually to the markets of Greece, Bulgaria, Serbia, and North Macedonia (Balkan Green Energy News 2022). This new infrastructure is tied to other ongoing interconnection projects, including the Gas Interconnector Greece-Bulgaria, which started commercial operation in October 2022 (Reuters 2022a), as well as important cooperation on 'vertical corridor' gas links between Greece, Bulgaria, Romania, and Hungary (Offshore Energy 2022). The IEA estimates that there is another 50 bcm per year of LNG import capacity under construction as of January 2023 and another 60 bcm per year at the planning stage (IEA 2023b).

FRSUs have the big advantage that they can be reused elsewhere when they are no longer needed, and therefore do not easily become stranded assets (apart from the associated jetty and pipeline to connect to the existing grid). Nevertheless, it seems that more onshore LNG terminals will be built in the EU in response to commitments to reduce dependency on natural gas imports from Russia. It is not clear where and how long

Figure 16 Overview of European liquefied natural gas regasification terminals in February 2022 (EC 2022l).

it will take to build them; so, to reduce the risks of these becoming stranded assets in the future, it has been proposed that they should be designed to be ready for importing hydrogen or ammonia when they are no longer needed for LNG. However, different systems and materials are needed for handling these different fuels, so hydrogen-readiness could have substantial economic implications (Fraunhofer 2022; GasforClimate 2022; IEA 2022g).

Although global LNG export capacity has expanded during 2022, much less capacity is expected to be added between the end of 2022 and 2025. Crucially, one of the largest LNG export projects under construction is Russia's Arctic LNG 2, which was initially expected to start in 2023, but which may be delayed by sanctions. There are also uncertainties about future LNG demand in China, which dropped by around 20% in 2022 thereby liberating LNG to supply the EU market.

The return of Chinese LNG demand could affect global markets. However, more LNG capacity is expected to become available in 2025 or later from the USA, Qatar (which was the EU's second largest supplier of LNG in 2022 and signed a 15-year supply contract with Germany in that year), Canada, and possibly Mozambique (IEA 2022e). It will be important for the EU to maintain adequate diversity of suppliers, for example by using the Commission's new Energy Platform (EC 2023a), to minimise the risks of becoming too dependent on any one source of LNG. In this context, it is worth noting that there have been calls recently from EU policy-makers to stop importing Russian LNG (Reuters 2023).

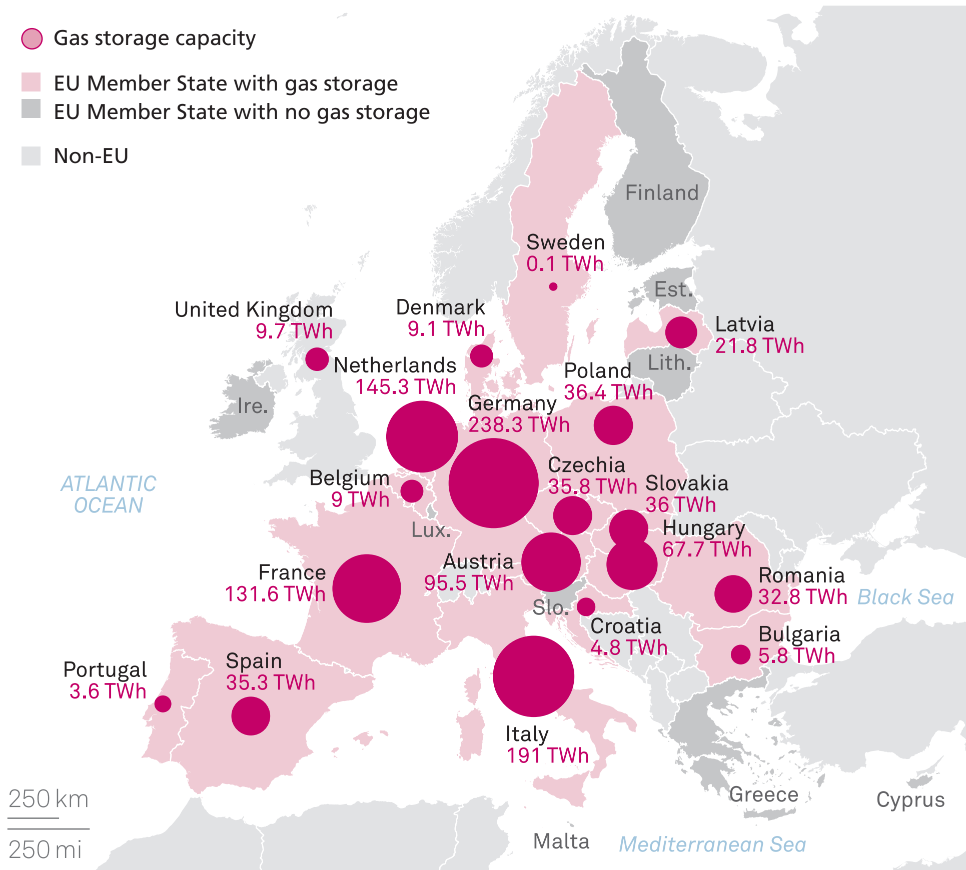
LNG has a higher global warming potential than piped natural gas because of the supply-chain GHG emissions involved in liquefying and re-gasifying it as well as in powering the ships to carry it across the world. Supplies of LNG from the USA are likely to include a growing fraction of shale gas, which typically has a high carbon footprint caused by leaks and fugitive emissions of methane (section 4.6) as well as by the energy used to extract it (Howarth 2019). It will therefore be very important for the EU to put in place reliable independent measurement and certification of the supply-chain GHG emissions of EU natural gas imports, including imported LNG as well as piped natural gas.

4.5 Close monitoring of natural gas storage must continue until the unabated use of natural gas is phased out

Storage has, over many years, been important for security of EU energy supplies throughout the year. Natural gas storage systems have traditionally been filled between April and October when prices and demand were low, and then discharged to meet high energy demands during cold weather periods in winter. Looking to the future, the natural gas storage capacity of the EU as a whole is about 1,000 TWh, which was about 25% of annual consumption in 2022. As EU demand for natural gas declines, the existing storage capacity should be able to cover an increasing share of consumption.

Following the invasion of Ukraine in 2022, the availability of natural gas storage was brought to the attention of EU policy-makers for several reasons. Firstly, because ahead of winter 2021/22, Gazprom did not fill the natural gas storage facilities that it owned and operated on European territory, but also because natural gas storage capacities in the EU Member States are not proportional to their needs (Figures 17 and 18). An additional challenge in 2022 was that some EU countries had their piped natural gas supplies from Russia greatly reduced during the spring and summer months, when storage systems would normally be refilled (Bruegel 2022a).

In response, EU policy-makers agreed to take emergency action to ensure that all the available natural gas



Sources: S&P Global Commodity Insights, GIE

Figure 17 EU Member States have very different natural gas storage capacities (S&P Global 2022a, based on GIE 2022; copyright 2022 by S&P Global Inc.; all rights reserved).

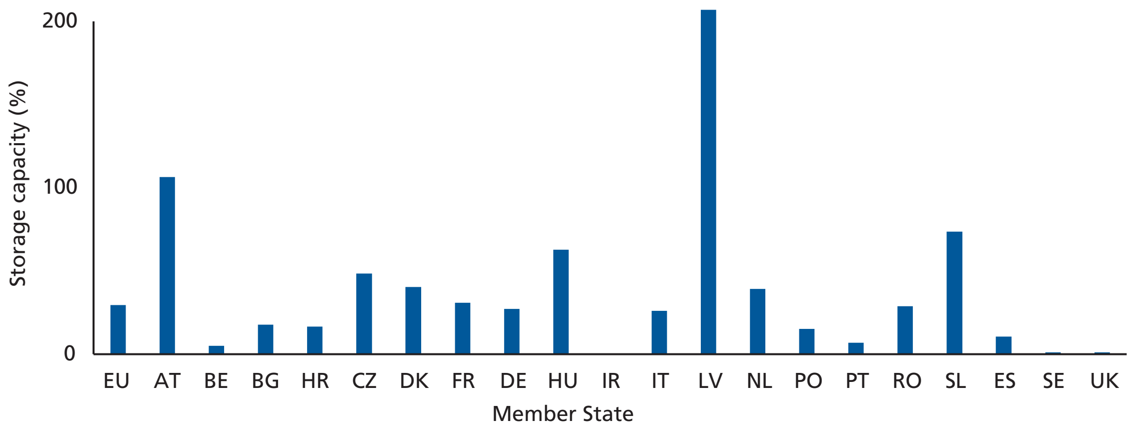


Figure 18 Natural gas storage capacity as a percentage of annual consumption shows that the storage in EU Member States is not proportional to their consumption (GIE 2022).

storage systems in the EU would be filled to at least 80% before 1 November 2022 and 90% before 1 November 2023. A combination of piped natural gas and LNG was successfully used to meet the 2022 deadline, but extra efforts may be needed to meet the challenges of delivering secure supplies of natural gas for winter 2023/24 and winter 24/25. Member States also agreed (through an EU regulation) to certify all storage operators, to share their storage facilities, and to find ways to minimise the impacts of future short-term natural gas shortages on EU households and businesses (EU 2022b; 2022e).

The obligations set for Member States in the regulation to fill their natural gas storage systems will finish at the end of 2025, even though some natural gas will still be used after that date. However, the regulation requires Member States to continue to report on their natural gas storage activities after that date, so the European Commission should be in a good position to work with Member States to ensure secure supplies of natural gas in subsequent winters for as long as necessary, while the unabated use of natural gas is phased out.

4.6 Climate impact of methane emissions associated with European Union natural gas and liquefied natural gas supplies must be assessed over a shorter time horizon

The IEA estimates that around 60% of global methane emissions are produced by human activity (anthropogenic) (IEA 2022j), and the IEA's methane tracker (IEA 2022f) estimates that the global energy sector was responsible for around 40% of total methane emissions attributable to human activity, second only to agriculture. This corresponded to around 135 Mt of methane emitted into the atmosphere in 2021, including an estimated 42 Mt from coal mine methane, 41 Mt from oil, and 39 Mt from natural gas. The remaining emissions came from the incomplete combustion of bioenergy (used for cooking in developing countries) and leaks from end-use equipment. To avoid exceeding the global warming limit of 1.5 °C, the IEA concludes that energy-related methane emissions must be reduced by 75% by 2030.

The impacts of methane and other short-lived climate pollutants on global warming can be reliably assessed by integrated assessment models, but for policy-making purposes it can also be helpful to compare the impact of a given pollutant with that of CO_2 by using a simple metric (IPCC 2021). The most widely used metric for methane in recent years has been global warming potential (GWP), and the 100-year GWP has been adopted by the Intergovernmental Panel on Climate Change (UNFCCC 2022). However, the atmospheric lifetime for methane is estimated to be 9–12 years (IPCC 2021), so the 100-year value of GWP has limitations when considering global warming consequences over a shorter time horizon. Proposals to use metrics that better reflect the results of integrated assessment modelling for the potential global warming impacts of methane, such as the 20-year value for GWP, are therefore being discussed. The 20-year GWP value for methane is 84–87 (UNECE 2022) while the 100-year GWP value is 28–36. For policy-making purposes, at least for the short term, a GWP value for methane of about 85 would therefore seem to be appropriate. Note: alternative metrics, such as present global warming, have been proposed. The present global warming value for methane is 45–55 depending on the discount rate (Pomerantz and Kleinberg 2022).

Natural gas is usually composed of about 90% methane, and its supplies have average fugitive methane leakages of just over 1.7% but with big variations between countries (IEA 2017; 2022f). For example, the intensity of methane emissions of conventional Norwegian natural gas is much lower than that of other suppliers, but shale gas typically has significantly higher values. Fugitive emissions during exploration for natural gas (as well as during and after its extraction) were addressed by an EU Methane Strategy in 1996 (EC 1996), which was substantially updated during preparations for the Fit for 55 package in 2020 (EC 2020b). As many of the GHG emissions associated with the EU's consumption of natural gas are released in third countries before the natural gas reaches EU borders, they are not easy to regulate and efforts to reduce them have potential geopolitical implications.

A Global Methane Pledge to reduce methane emissions by 30% by 2030 was launched by the EU and USA at the COP26 meeting (26th Conference of the Parties to the United Nations Framework Convention on Climate Change) in Glasgow in November 2021 (GMP 2021). It was joined by more than 150 countries in 2022, and the USA and EU convened a Methane Ministerial at COP27. In the EU, this pledge was reflected in a proposed EU Regulation on methane emissions reduction in the energy sector (EC 2021c), which requires industry to measure, report, and verify methane emissions including those from natural gas that is imported into the EU. In addition, as explained in the European Commission's communication on external energy engagement, the EU will work internationally with the stakeholders involved to reduce methane emissions (EC 2022c). To monitor progress with these and other initiatives, new tools are available for measuring methane emissions, notably using satellite data and drones (ESA 2020; Tuzson *et al.* 2020).

In the USA, the Inflation Reduction Act (passed in August 2022) created a methane emissions reduction programme, which will impose fees on methane leaks above a certain threshold from 2024 onwards (US$900 per tonne of methane emitted in 2024, increasing to US$1,500 in 2026). These fee levels lie in the range of the social costs of methane emissions calculated by the US Environmental Protection Agency (US EPA 2022) and, according to the EPA, could create a powerful incentive for US companies to reduce methane emissions. The EPA's social cost calculations take many different factors into account; however, in terms of GHG emissions alone, assuming a GWP100 (global warming potential over 100 years) of 30 for methane, these fee levels would correspond to a carbon price of only about €30/tonne in 2024 and €50/tonne in 2026[8], which are much lower values than have been projected for the EU Emission Trading System by these dates.

4.7 Liquid petroleum gas can be replaced by bio-LPG

Liquefied petroleum gas (LPG) is a fossil fuel that normally contains a mix of propane and butane. It is produced from crude oil or natural gas liquids, either as they are extracted from the ground or in refineries. LPG is used in the EU for residential heating (48%), mainly in rural areas away from the natural gas grid, for road transport (33%), and for industrial power generation and heating (19%). The annual consumption of LPG in the EU was around 33 Mt (40 bcm) in 2019 (Liquid Gas Europe 2020). This was equal to approximately 10% of EU consumption of natural gas (400 bcm), and about 1% of global natural gas consumption.

Like all fossil fuels, the unabated use of LPG must be phased out. However, where it is effectively a waste from oil refineries, its rate of phasing out will reflect the speed at which the refining of crude oil is phased out. The industry is already working to replace fossil LPG by expanding production of bio-propane and bio-butane—commonly known as bio-LPG (section 6.4).

4.8 Dimethyl ether can be replaced by bio-DME

Dimethyl ether (DME, CH_3OCH_3) is a fossil fuel that can be made from coal, natural gas, or methanol. Estimates for the size of the global DME market in 2021 lie between 4 and 9 Mt. It is used mainly (>80%) for blending with LPG (to reduce soot, particulates, and other harmful emissions), but also as an aerosol propellant (approximately 8%), a transport fuel (like diesel, but with a high cetane number (similar to octane number but for diesel engines)), a fuel for power generation, and as a chemical feedstock (ETIP 2022a).

Like other fossil fuels, the unabated use of DME must be phased out, and the industry is already demonstrating the production of bio-DME (section 6.5).

4.9 Fossil-fuel-based methanol can be replaced by bio- and e-methanol

Methanol (CH_3OH) is included in this report, despite being liquid at ambient conditions, because it is a fuel that has a close association with natural gas. Almost all the methanol produced globally today is derived from fossil fuels, with approximately 65% from natural gas reforming, 35% from coal gasification, and less than 1% from renewable sources (ETIP 2022b).

It is a light, volatile, flammable liquid at ambient conditions, which is water-soluble and biodegradable. Methanol can be used as a fuel, a fuel additive or used to produce several industrial chemicals such as plastics, textiles, and paints.

In 2020, around 100 Mt of methanol were produced worldwide, of which more than 60% was used in

[8] Approximation assumes carbon price = Inflation Reduction Act methane emission fee/Global Warming Potential.

the chemical industry for producing, for example, formaldehyde, acetic acid, and olefines, which can be further processed to make products such as paints, plastics, and car components. The other 40% was used in the fuel industry as, for example, pure methanol, MTBE (methyl tertiary-butyl ether, a fuel additive in gasoline), biodiesel, or DME.

The unabated use of fossil-fuel-based methanol will need to be phased out as fossil fuels are phased out; however, depending on the availability of biomass resources and hydrogen, fossil-fuel-based methanol can be replaced by bio-methanol and e-methanol (section 6.6).

5 Hydrogen

How can hydrogen with a low-carbon footprint replace natural gas, how will this affect greenhouse gas emissions, security of energy supplies, and affordability of energy in the European Union?

5.1 Background

Like electricity, hydrogen is an energy carrier. Hydrogen can be used to carry energy, but first it must be produced using an energy source, such as fossil fuel or renewable energy.

Hydrogen was discovered in the 1770s and used in vehicle engines in the 1920s. A future hydrogen economy has been discussed since the 1970s, and Europe has been funding hydrogen research for more than 40 years. However, unlike electricity, which was discovered at about the same time, far fewer applications of hydrogen have become commercially competitive. It is therefore important for potential investors to understand the factors that might lead to competitive hydrogen markets in the future.

Growing demand for renewable hydrogen was foreseen in the EU Hydrogen Strategy (EC 2020d) and in EASAC's commentary on it (EASAC 2020). The key factors identified in the EU Strategy as leading to market growth were falling prices of renewable electricity, increasing carbon prices, falling costs of electrolysers, and the phasing out of fossil fuels. As it has done for the past century, hydrogen will nevertheless continue to compete in energy markets with electricity, but renewable hydrogen will compete in future with the renewable electricity from which it was made (with electrolyser efficiency losses). Hence, 'hard to electrify' applications will be where the main renewable hydrogen markets lie in the future. Hydrogen produced from fossil fuels with carbon capture and storage (CCS) may find its place in markets that are currently supplied by grey hydrogen, and in other industrial applications, depending mainly on the future costs of CCS.

5.2 European Union ambitions for renewable hydrogen production by 2030 correspond to twice the current European Union consumption of grey hydrogen

The world currently produces about 94 Mt of hydrogen per year and Europe produces (and consumes) about 8–10 Mt per year, mainly by steam reforming of natural gas or naphtha, and this is used primarily by fertiliser and oil refinery industries (FCHO 2022; IEA 2022g).

Global production of low-carbon footprint hydrogen was less than 1 Mt in 2021, and most of it was made using fossil fuels with CCS.

EU definitions of hydrogen are not yet fully harmonised (ICCT 2022) but the classifications used in recent EU documents and by EASAC are summarised in Box 2.

Compared with its Hydrogen Strategy (EC 2020d), the EU increased its ambitions in 2022 through the hydrogen accelerator initiative in the REPowerEU plan (EC 2022a). As shown in Figure 19, this reflects a political commitment to aim to produce 10 Mt per year of renewable hydrogen in the EU by 2030, plus 6 Mt per year of imported renewable hydrogen and 4 Mt per year imported in the form of green ammonia and other renewable hydrogen derivatives (EC 2022g).

5.3 Renewable (green) hydrogen

5.3.1 Overview

To deliver the REPowerEU commitments for 2030, to produce 10 Mt of renewable hydrogen in the EU, the European hydrogen industry has projected a needed electrolyser capacity of around 120 GW, plus a similar

Box 2 EU classifications of types of hydrogen

Grey hydrogen is produced from fossil fuels.

Renewable or green hydrogen: produced by electrolysis of water using renewable electricity from wind, solar, or hydropower, or grid electricity that meets the EU criteria for renewable fuel of non-biological origin, i.e. its greenhouse gas (GHG) emission intensity is less than 18 gCO_2e/MJ (EU 2023). It can also be produced by anaerobic digestion or gasification of biomass, and become carbon negative if coupled with CCS.

Blue hydrogen: produced from fossil fuels, together with CCS. Its carbon footprint is significantly higher than that of renewable hydrogen (section 5.8).

Low-carbon (footprint) hydrogen: a generic term that can include renewable and blue hydrogen as well as hydrogen produced by electrolysis of water using grid electricity that delivers a GHG emission reduction of at least 70% compared with fossil fuels.

Turquoise hydrogen: produced using pyrolysis of natural gas, which delivers a fine carbon powder as a by-product. It is still at an early stage of development but has the potential to become a cost-efficient process.

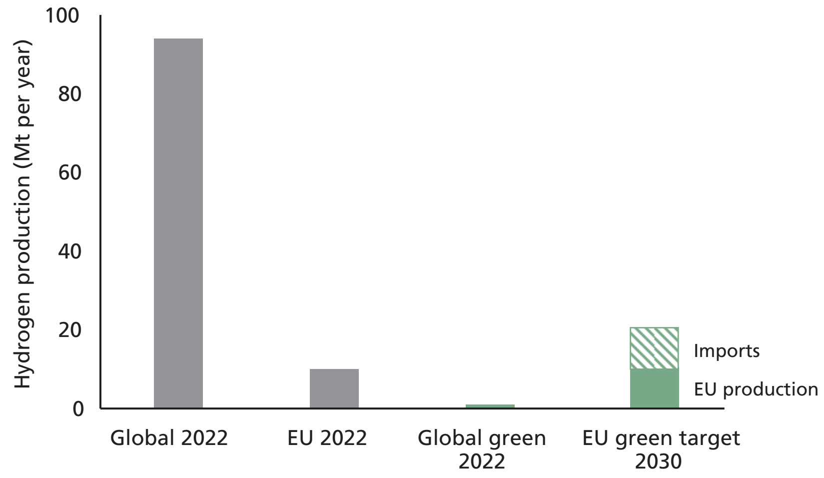


Figure 19 Hydrogen production (Mt per year): EU 2030 target is twice EU production in 2022.

capacity to produce 10 Mt of renewable hydrogen and its derivatives in neighbourhood countries by 2030 (EC 2022g). In total, 10 Mt of renewable hydrogen produced in the EU plus 10 Mt of imports would deliver about 660 TWh per year of hydrogen energy (Carlsson 2021), which is about 6% of the EU final energy consumption projected for 2030 in the EU Reference Scenario 2020 (EC 2021r)[9].

Renewable hydrogen can also be produced by reforming biogas (instead of natural gas), or by the biochemical conversion (e.g. anaerobic digestion) of biomass (EC 2020d), or by the gasification of biomass (Thunman *et al.* 2018; Lou *et al.* 2023). However, in view of the limited availability of biomass resources and the technology readiness and costs of the processes involved, these methods are unlikely to be widely used on a commercial scale.

5.3.2 Potential impacts of renewable hydrogen production on electricity supplies

Debates on the EU energy transition frequently question whether it is realistic to set a target of 10 Mt of renewable hydrogen production using renewable electricity in the EU by 2030. Such questions are of course addressed by energy system models, but it can also be reassuring to reflect on simplified analyses, as outlined below.

To produce 10 Mt of renewable hydrogen in the EU would require about 500 TWh of renewable electricity (Hodges *et al.* 2022). This corresponds to about 55% of the 913 TWh of renewable electricity generated in the EU in 2021 (Eurostat 2023a).

On the basis of the REPowerEU plan for 60% of final electricity consumption to be renewable in 2030, 500 TWh corresponds to about one-third of EU-27 renewable electricity consumption in 2030, which was projected in the Reference Scenario 2020 to be 1,583 TWh (EC 2021r). (Note: REPowerEU targets require higher renewable electricity consumption in 2030.)

The need to increase renewable electricity-generating capacity in the EU-27 to deliver the renewable hydrogen target can be seen in Figure 10, which shows that the total capacity of wind and solar generators installed in the EU in 2021 delivered only 542 TWh. This is little more than the 500 TWh needed to produce the 2030 hydrogen target of 10 Mt per year.

In other words, if the existing levels of renewable electricity consumption in the transport, industry, and buildings sectors were to be maintained without any expansion, then the existing wind and solar generating capacities would need to be approximately doubled to deliver the EU's 2030 renewable hydrogen target.

5.3.3 Legislation on renewable electricity for green hydrogen production is evolving

The European Commission's proposals for additional renewable electricity generation to be built in the same geographical area as hydrogen electrolysers have been hotly debated (Pototschnig 2021) and the European Commission's draft delegated act for this was rejected by the European Parliament in September 2022 (Recharge 2022).

Those in favour of imposing additionality requirements argue that they will be necessary to ensure that sufficient renewable electricity is generated to match the needs of hydrogen electrolysers and to prevent increases in electricity demand, caused by electrolysers,

[9] Final energy consumption in 2030 is projected in the EU reference scenario 2020 to be 10,467 TWh (EC 2021r).

from pushing up the price of grid electricity for all users. For example, they argue that renewable electricity should be prioritised for decarbonising the power sector before being consumed by electrolysers. There are also concerns that an increase in electricity demand caused by electrolysers could lead to an increase in fossil fuel generation if more renewable capacity is not deployed fast enough.

In contrast, those who were against imposing strict additionality requirements argued that, to help reduce the price of renewable hydrogen, producers should be free to negotiate prices and contract terms with any renewable electricity suppliers in the EU energy market, and that they should not be tied down to any one specific renewable generator.

Other analyses suggested that the EU's proposed additionality criteria for renewable hydrogen production could lead to increases in global CO_2 emissions (Schmidt *et al.* 2023).

There have been demands by France and other Member States for legislation to permit any electricity that has a GHG emission intensity below a given threshold to be called renewable electricity when used in hydrogen electrolysers.

Following many debates, a regulation was proposed in February 2023 that requires renewable electricity used in electrolysers to be certified as complying with at least one of a complex series of criteria that will evolve over time, including direct connections between electrolysers and recently constructed renewable electricity generators (EU 2023). Temporal correlation would be based on a monthly matching, progressing to hourly matching by 2030.

The proposed regulation would permit electricity used in electrolysers to be called renewable if it is generated with a GHG emission intensity of less than 18 gCO_2e/MJ and supplied through the grid. However, in this case, the producers of renewable hydrogen must have concluded directly, or through intermediaries, one or more renewables power purchase agreements with renewable electricity suppliers for an amount that is at least equivalent to the amount of electricity that is claimed as fully renewable, and the renewable electricity claimed must have been produced in this or these installations.

If the proposed legislation is adopted, then it will permit grid electricity in some regions, which are supplied predominantly by nuclear generators, to be called renewable when used in hydrogen electrolysers. However, for electrolysers that use renewable electricity supplied through the grid, the proposed legislation will impose a demanding administrative burden to track and monitor the sources of supply.

The industry, buildings, and transport sectors will increasingly compete in EU markets for more new and existing renewable electricity supplies as they strive to deliver the net-zero emissions obligations of the EU Climate Law with the lowest costs. In contrast, the emerging renewable hydrogen sector will need to negotiate complex renewable electricity supply contracts with demanding administrative burdens for their electrolysers, largely because of the EU funding and support being offered to deliver renewable hydrogen production targets. If the proposed legislation is adopted, then it should be regularly reviewed, and simplified as soon as possible.

5.3.4 Renewable hydrogen electrolysers also produce oxygen and heat

Some electrolysers will be located in EU waters close to offshore wind turbines, while others will be onshore close to hydrogen-consuming industries (Air Liquide 2021). To locate electrolysers close to centres of demand for hydrogen and oxygen may limit the need for gas infrastructure and may also attract additional income from the sale of heat.

Heat is produced by electrolysers and this can, for example, be used in district heating systems, depending on the locations of the electrolysers and the local prices for heat. In many cases, electrolysers can be air cooled, but in very sunny countries they may need to be fitted with water cooling systems linked to cooling towers, or to nearby rivers or the sea.

Eight times more oxygen than hydrogen (by mass) is produced by the electrolysis of water, so infrastructure is needed to transport large quantities of oxygen to potential consumers.

5.3.5 Costs of renewable hydrogen production depend on the price of renewable electricity (including flexibility pricing) and the sizing of electrolysers

The cost of renewable hydrogen depends strongly on the price of renewable electricity, and on the cost, efficiency, and load factor of the electrolyser. Hence, to minimise hydrogen costs, electrolysers should be sized to suit the expected demand and operate continuously and near to their nominal capacities. However, flexibility management on electricity grids will become a growing challenge for network operators as electricity supplies become increasingly dominated by wind and solar generation, so favourable tariffs should be made available to electrolysers that can offer demand response.

Electrolysers with hydrogen storage and fuel cells could potentially offer valuable demand response (grid flexibility) services, including preventing curtailment of wind and solar generators by absorbing peak generation, and feeding electricity back into the grid and/or reducing electricity demand during periods with low wind speeds, thereby effectively storing energy over periods of days or weeks (Mikovits *et al.* 2021). Such services would complement electricity storage in batteries and pumped storage systems, which are better suited for short-term balancing of diurnal variations in electricity use or minute-by-minute variations produced by solar photovoltaic generators (EASAC 2017). Large electrolyser operators should participate in balancing markets and may also trade in electricity spot and future markets.

It follows that, to minimise renewable hydrogen costs, electrolyser operators should be permitted to choose renewable electricity suppliers with the most favourable tariffs, provided they can prove that the electricity used is renewable.

5.3.6 Renewable hydrogen imports by pipelines may be preferred over long-haul transportation by ship

Renewable hydrogen imports are likely to come from very sunny and/or very windy countries, where the annual levels of solar radiation and annual average wind speeds could be up to three times those in large parts of the EU, and therefore renewable hydrogen production costs could be lower. However, imports must be produced under the same criteria as in the EU, and their renewable credentials must be proved, since many potential renewable hydrogen producers use an electricity mix with a high carbon content (for example in the Middle East or North Africa).

Liquefying hydrogen or converting it into another energy carrier, such as ammonia, and transporting it to the EU will add to its costs and carbon footprint.

Sea-water electrolysers that can operate without side reactions and corrosion problems have been demonstrated (Xie *et al.* 2022); however, until these are commercially available, the producing country will need adequate supplies of clean water for use in their electrolysers and for cooling electrolyser systems. Pre-treatment of water for electrolysers is normally only a small part of the overall system cost (Madsen 2022); however, if desalination is needed, for example to purify brackish or sea water, then this could add significantly to the costs.

Studies of importing options show that imports from the EU's southern neighbours by pipeline are likely to be preferred over long-haul transportation by ship from distant suppliers (IRENA 2022b). However, it is too early to predict future prices of renewable hydrogen imports. As some potential hydrogen exporters are planning to develop their industrial capacity, an emerging question is whether it might be more efficient in terms of GHG emissions and costs to import semi-finished industrial products rather than hydrogen or its derivatives.

5.4 Blue hydrogen is likely to be supplied by countries with large natural gas resources, such as Norway

Blue hydrogen is produced by steam methane reforming or auto-thermal reforming of natural gas, together with CCS. The extent to which it will be produced in the EU will depend on the price and availability of natural gas, and on the availability of CCS which, compared with some industry expectations, is delayed (section 3.7). Most of the planned CCS plants are located in the north of Europe, notably in Norway and the UK (Global CCS institute 2022b).

Existing producers of fossil-based (grey) hydrogen, which are located with oil refineries and fertiliser production plants, are likely to opt to produce blue hydrogen if they can access suitable CCS infrastructures nearby, and to use it where they currently use grey hydrogen.

If, as is widely predicted (section 5.6), there is soon to be a growing demand for low-carbon footprint hydrogen to decarbonise industrial and transport applications that are hard to electrify, then blue hydrogen is likely to be imported, along with renewable hydrogen and its derivatives.

A potentially important supplier of blue hydrogen to the EU is Norway, which has extensive reservoirs of natural gas and has been working on the development of CCS (IEA 2022c). Norway is well placed to transport blue hydrogen by pipeline to northern EU Member States, as demonstrated by the joint statement on hydrogen by Norway and Germany in January 2023 (Government of Norway 2023), and the agreement in January 2023 between Equinor and RWE (Equinor 2023). Other potential sources of blue hydrogen imports include countries that have large resources of natural gas, such as those in the Middle East, although such sources must be limited to minimise the risk of the EU becoming too dependent on supplies from any one third country.

5.5 Technology for turquoise hydrogen production is not yet ready

Turquoise hydrogen can be produced using pyrolysis of natural gas, which delivers a fine carbon powder (carbon black) as a by-product. This has the advantage that storing carbon powder is easier and cheaper than storing CO_2 (Diab *et al.* 2022). However, the efficiency is lower than blue hydrogen production, and the technology readiness of pyrolysis is lower than that of steam methane reforming and auto-thermal reforming.

5.6 Hydrogen demand will be greatest in hard-to-electrify sectors

5.6.1 Overview

As highlighted in section 5.1, the key factors that are expected to lead to new markets for green and blue hydrogen are the falling prices of renewable electricity, increasing carbon prices, falling costs of electrolysers, and the phasing out of fossil fuels. These conditions are all moving in a positive direction for a future hydrogen economy; nevertheless, the demand for hydrogen will come largely from sectors that are hard to electrify.

5.6.2 Hydrogen infrastructure: potential investors in infrastructure want a hydrogen market but there can be no market without infrastructure ('chicken and egg')

A challenge for policy-makers and investors, who must minimise the risk of wasting money on future stranded assets, is to find a solution to the 'chicken and egg' problem that investments in hydrogen supply infrastructure cannot be justified without a hydrogen market, but there can be no hydrogen market without supply infrastructure. Risk sharing with market stakeholders and subsidies with clearly defined sunset clauses are typically used to tackle such challenges, provided a strategic business case can be made.

5.6.3 Industry and transport are priority applications for a future European Union hydrogen market

Among the many applications of low-carbon footprint hydrogen and its derivatives that have been demonstrated in recent years (IRENA 2022a), the following are most likely to become commercially mature in the short term:

- Industry
  - Refineries and chemical industries
  - Fertiliser production
  - Steel industry
  - E-fuels and e-materials production
- Transport
  - Road (long-haul heavy-duty trucks, buses)
  - Marine (ferries, international shipping)
  - Aviation (production of sustainable aircraft fuels).

In contrast, renewable hydrogen is unlikely to be used for heating buildings (EASAC 2021) or for light-duty road vehicles (EASAC 2019a), because it is relatively easy to electrify these applications and renewable hydrogen will be more costly than the renewable electricity used to produce it.

5.6.4 Industry will have a growing demand for hydrogen

Europe's energy-intensive industries have been reducing their energy consumption by using energy efficiency measures for many years, but as fossil fuels are phased out and carbon prices are increased, they must focus on switching to more sustainable energy options. For some industries, the most attractive option is to switch to using hydrogen, but they need to be assured of secure and affordable hydrogen supplies before making major investments in changes to their production plant.

This poses a 'chicken and egg' problem for EU and national policy-makers because they should not risk using public money to build hydrogen supply networks that could become stranded assets; but they need to avoid losing industries to third countries that offer hydrogen supplies with attractive subsidies such as the incentives offered under the Inflation Reduction Act to attract industries to the USA (US EPA 2023). A recent study of this issue has been published for Germany (Egerer *et al.* 2023).

For refineries and the chemical industries, where CCS infrastructure can be built near to refineries and chemical industries, producers of grey hydrogen may decide to supply blue hydrogen to meet the demands of their existing plants. When doing this, some may be able to reap the benefits of economies of scale and supply blue hydrogen to other industries and to heavy-duty transport hubs, thereby creating a hydrogen valley in their area, with a local hydrogen distribution network.

Some refineries could in future produce low-carbon footprint ammonia for use as fuel or as a raw material for fertilisers. For example, blue hydrogen produced in the United Arab Emirates is being used to make low-carbon footprint ammonia that serves as a means of transporting low-carbon footprint hydrogen to Germany for use in metallurgical industries (ADNOC 2022). Several refineries in the EU are already starting to install electrolysers to produce renewable hydrogen, which will replace the production of grey hydrogen (OPIS 2021). Renewable hydrogen is being produced with a photovoltaic plant in Spain and used to produce green ammonia for making fertilisers (Iberdrola 2022).

Heat for high-temperature processes can be produced by burning renewable hydrogen where electrification is not a technically feasible option.

Sustainable polymers and plastics can be produced using renewable hydrogen as a feedstock together with carbon from biomass or from direct air capture. In the short to medium term, until circular processes for producing commodities such as plastics become available, plastic wastes may be used as a carbon source for chemical industries via synthesis gas from pyrolysis or gasification (Dogu *et al.* 2021).

Steel industries are expected to become major consumers of renewable hydrogen in the short to medium term, as demand for sustainable construction materials grows in the EU and in global markets. Pilot-scale tests of hydrogen-based steel production have been completed and full-scale deployment is expected in the next few years (SSAB 2023; IEA 2022g).

Hydrogen valleys can be expected to evolve in areas where clusters of hydrogen-consuming industries are located, and these will build local hydrogen distribution networks to meet their needs. Hydrogen transport pipework may be needed to bring hydrogen to a hydrogen valley from electrolysers or from hydrogen import terminals if it is not produced locally, and in the future to make connections between hydrogen valleys, so plans for this should be prepared in good time. However, to minimise the risks of creating future stranded assets, the starting point should be the establishment of hydrogen-consuming industry clusters and their local distribution networks (section 7.3).

5.6.5 Heavy-duty road and marine transport will have growing demands for hydrogen

For heavy-duty road transport vehicles, such as long-haul trucks and buses, it can be difficult to use batteries because of their size and weight. Hydrogen (with fuel cells), which can be refuelled rapidly, may therefore be the preferred solution.

For light road transport, instead of hydrogen, it is more efficient to use green electricity directly in battery electric vehicles, for example in cars and light-duty vans (EASAC 2019a).

For marine transport, an attractive solution for long-haul shipping is likely to be a hydrogen derivative, such as ammonia, which can be relatively easily transported and stored.

For aviation, today's batteries are too heavy and the use of hydrogen or ammonia are both still being studied by research and development teams, including in some of the world's big aircraft manufacturing companies. For the short to medium terms, the preferred low-carbon footprint options are sustainable aviation fuels (EC 2021d). These fuels typically include blends of fossil kerosine with sustainable biofuels or e-fuels, such as e-kerosine, which are made using renewable hydrogen and sustainable carbon. For e-fuels to be considered renewable, the carbon used in their manufacture should come from a sustainable source, such as sustainable biomass or from CO_2 that is captured directly from the air (EC 2021d).

5.6.6 E-fuels will be produced using hydrogen

E-fuels can be produced by combining renewable hydrogen with CO_2 captured from the air (as a carbon source), but the process is energy-intensive.

Alternatively, e-fuels can be produced by the gasification of biomass to produce syngas (carbon monoxide, CO_2, and hydrogen). By adding renewable hydrogen to syngas, the carbon from the biomass is converted into bio e-fuels. However, sustainable EU biomass resources may not be sufficient to meet the potential demand.

5.6.7 Renewable hydrogen would be uncompetitive for heating buildings

Heat for buildings will be increasingly provided by district heating systems or heat pumps rather than by renewable hydrogen that has been produced in the EU because the heat delivered by burning renewable hydrogen will always be more expensive than the renewable electricity used to produce it (section 2.2.9). Similarly, heating with imported renewable hydrogen will be more expensive than using district heating or a heat pump powered by renewable electricity.

A misguided idea has been put forward that more renewable hydrogen than would otherwise be needed could be produced and stored at times when electricity costs are near to zero because wind speeds are high and electricity demand is low. The idea is that this extra hydrogen could then be sold for heating at competitive (low) prices. However, this idea has two major flaws. Firstly, electrolysers are costly capital investments and are most efficient when they operate at their designed capacity. Hence, their operation will be managed to optimise their annual profitability by responding (e.g. hour by hour) to electricity prices in the context of demand response agreements with their renewable electricity supplier(s). The hydrogen that they produce will be stored and sold mainly to meet the needs of customers with hard-to-electrify applications. Secondly, when cheap electricity is available, it would be more profitable and more efficient to store it as heat in large hot water tanks and to extract the heat from the tank (with heat exchanger or heat pump) when it is needed to heat a building.

Similarly, it has been mistakenly suggested that boilers fuelled by hydrogen might be used to provide local back-up heating for electric heat pumps during periods of very cold weather or when wind speeds are low in winter. However, in addition to the issues discussed above, this flawed suggestion would require additional capital investments in hydrogen supplies and a hydrogen boiler, so it is unlikely to be widely adopted. More valuable would be for heating needs to be minimised by renovating the building envelope so that, when needed, heat can be supplied from local heat or electricity storage systems (section 2.2.7).

5.7 The European Union should assert leadership in shaping regulations for international hydrogen markets

As GHG emission reduction is implemented across the world, it will be important for Europe to assert technology leadership and help to shape the rules for emerging international hydrogen markets, for example by adopting hydrogen certification procedures and integrating hydrogen into its single energy market, because this will provide a solid basis for competitive international trading (EC 2023b; 2023e). The EU should also further develop partnerships with those countries that could become suppliers of renewable hydrogen in the future (IRENA 2022a).

Looking forward to the medium and long term, when most of the electricity will be generated using renewables or systems with low-carbon footprints, a different regulatory solution for green hydrogen production using grid electricity may be preferred to limit administrative burdens. For example, it may become sufficient to oblige suppliers of renewable hydrogen to demonstrate that the electricity used was produced within an Emission Trading System that complied with the rules of the EU ETS (Schmidt *et al.* 2023).

5.8 Carbon footprints and global warming potentials of blue hydrogen should be properly reflected in its labelling

EASAC concurs with the message in the European Commission's Hydrogen Strategy (EC 2020d) that potential investors should take into account the limited overall effectiveness (56–90%) of GHG capture from the multi-stage process when considering investments in fossil-based hydrogen production with CCS (blue hydrogen) (EASAC 2020). This message was supported by the International Energy Agency, which showed that blue hydrogen can have carbon footprints of 30–120 gCO_2e/kWh, compared with less than 10 gCO_2e/kWh for renewable hydrogen produced using wind-generated electricity (IEA 2019a).

The GHG emissions from blue hydrogen production are caused primarily by methane leaks and CO_2 capture losses, and these vary with the distance over which the natural gas is transported, and the production technology used. Hence, the carbon footprints for blue hydrogen in the scientific literature vary considerably. Sensitivity analyses of the effects of methane leakage and carbon capture at the different stages of the process indicate that the carbon footprint of blue hydrogen could in some cases be little better than that of natural gas combustion (Howarth and Jacobson 2021). Studies of the influence of different parameter sets and transportation options have led to calculated carbon footprints ranging from 112 to 319 gCO_2e/kWh for GWP20 (global warming potential over 20 years) and from 72 to 245 gCO_2e/kWh for GWP100 (Schippert *et al.* 2022).

The global warming impacts of hydrogen leakages along its supply chains are lower than those from natural gas supply chains (Cooper *et al.* 2022; EDF 2022), but work aimed to better understand the complex interactions with hydrogen in the atmosphere is continuing. Estimates of the global warming potential (GWP100) of hydrogen differ between experts, in the range 11 ± 5.

In the context of the EU commitment to limit global warming to less than 1.5 °C, it is a 20-year timeframe rather than a 100-year timeframe that needs to be considered, and recent analyses suggest that the GWP 20 for hydrogen could be three times its GWP100 value (Ocko and Hamburg 2022). In other words, a working value for the GWP20 of hydrogen should be between 30 and 35.

More research is needed to study uncertainties about how the leakage of hydrogen into the atmosphere will decrease the tropospheric concentration of hydroxyl radicals (·OH), the major tropospheric oxidant, and thereby increase the atmospheric lifetime of methane and its impact on climate (Derwent *et al*. 2020; Derwent 2022; Warwick *et al*. 2022). Recent research shows that there are very few verified and measured data available on hydrogen leakage along the hydrogen value chain, and many links in the chain (renewable hydrogen, uses in transport, high-temperature heat) are still under-developed (Fan *et al.* 2022). This is largely because devices to measure low rates of hydrogen leakage and regulations are still missing.

More attention should be given to monitoring small hydrogen leakages at a regulatory level, from a global warming perspective, and not only from a safety perspective. This should be done soon because it will be easier to address the issue of small leakages at the design stage than to fix problems after new hydrogen infrastructures and systems have been built. Further research on this would seem to be justified.

6 Other gaseous fuels with low-carbon footprints

How could they replace natural gas, how would this affect greenhouse gas emissions and security of energy supplies in the European Union?

6.1 Biogases of any form should only be considered renewable if produced from biomass with a short carbon payback period

In this chapter, other sustainable gaseous fuels (for hydrogen, see Chapter 5) that can be expected to replace natural gas are discussed, including their suitability for use as drop-in fuels to replace fossil fuels in existing plant and equipment.

All forms of bioenergy, including biogas and biomethane, are widely assumed to be renewable sources of energy, with net-zero carbon emissions. However, bioenergy can only be renewable in the context of the EU's 2030 target for carbon emission reductions if it is produced from biomass with (1) a carbon payback period that is less than the time remaining until 2030, for example agricultural and forestry residues and wastes, or food industry or municipal wastes, and (2) no significant greenhouse gas (GHG) emissions caused by indirect land-use change (EC 2022a) (section 3.5.2). In view of evolving geopolitical impacts on trade, and climate change impacts on water resources and food production, projections for the future availability of sustainable bio-resources for energy, such as those by the International Energy Agency (IEA 2020b) and the Joint Research Centre of the European Commission (Prussi *et al.* 2019), will need to be kept under review.

6.2 Biogas has value but limited potential

Biogas typically consists of a 50:50 split of methane and CO_2. It is commonly produced by the anaerobic digestion of animal manure, the organic fraction of municipal solid waste, crop residues, energy crops, food waste, or sewage (Figure 20). It can be used directly for some applications (e.g. heating), but it does not meet the standards required for injection into EU natural gas networks unless it is refined to biomethane (section 6.3).

Like all forms of methane, biogas is a GHG with high global warming potential (section 4.6). From a global perspective, Europe is the largest producer of biogas today and Germany is by far the largest market, hosting two-thirds of Europe's biogas plant capacity (IEA 2020b).

Anaerobic digesters used to produce biogas offer a parallel income stream from digestate for use in agriculture, and biogas collected from landfill sites offers an extra income stream for waste disposal businesses. In addition, the managed anaerobic digestion of biomass to produce biogas brings the added benefit of avoiding uncontrolled biomass decomposition and its resulting emissions of methane into the atmosphere, especially from animal manure and the organic fraction of municipal solid wastes at landfill sites. The allocation of carbon credits to reflect these environmental benefits is a potential topic for future climate policies (IEA 2020b).

Biogas can also be produced by the thermal gasification of biomass, for example in modified fluidised bed boilers (e.g. in district heating networks and in pulp, paper, and sawmills), or in oil refineries and petrochemical plants. Work on pilot and demonstration gasification plants is well advanced, notably in Sweden (Thunman *et al.* 2018). Although demonstration plants, such as GoBiGas (Larsson *et al.* 2018), proved to be too costly at the 20 MW scale compared with market prices for natural gas in 2018, the recent increases in natural gas prices may have substantially changed the commercial viability of such biogas-producing systems (Thunman H *et al.* 2019). Nevertheless, the carbon payback period of any woody biomass used must be reflected in the carbon price attached to biogas produced using gasification (section 3.5.2).

6.3 Future of biomethane depends on limited sustainable biomass resources and regulation of hard-to-electrify sectors

Biomethane can be produced by upgrading biogas from anaerobic digesters (Lai *et al.* 2021), which is how approximately 90% of biomethane was produced in 2018, or by gasification of solid biomass (IEA 2020b).

The Joint Research Centre estimated that in 2015 less than 7% of biogas in Europe was upgraded to biomethane (Scarlat *et al.* 2018), and the IEA estimated that in 2018 around 10% of biogas production was upgraded to biomethane, although in some EU Member States the percentages were much higher (IEA 2020b). The EU Member States with the biggest production of biomethane in 2018 were Germany (10,018 GWh), the Netherlands (2,226 GWh), Denmark (1,425 GWh), Sweden (1,281 GWh), and France (1,207 GWh), which can be explained largely by the size and nature of their subsidies (Decorte *et al.* 2020).

Biomethane represented about 0.1% of global natural gas demand in 2020 (IEA 2020b) but its production is projected in the REPowerEU plan (EC 2022g) to increase from its current levels of around 2 billion to 3 billion

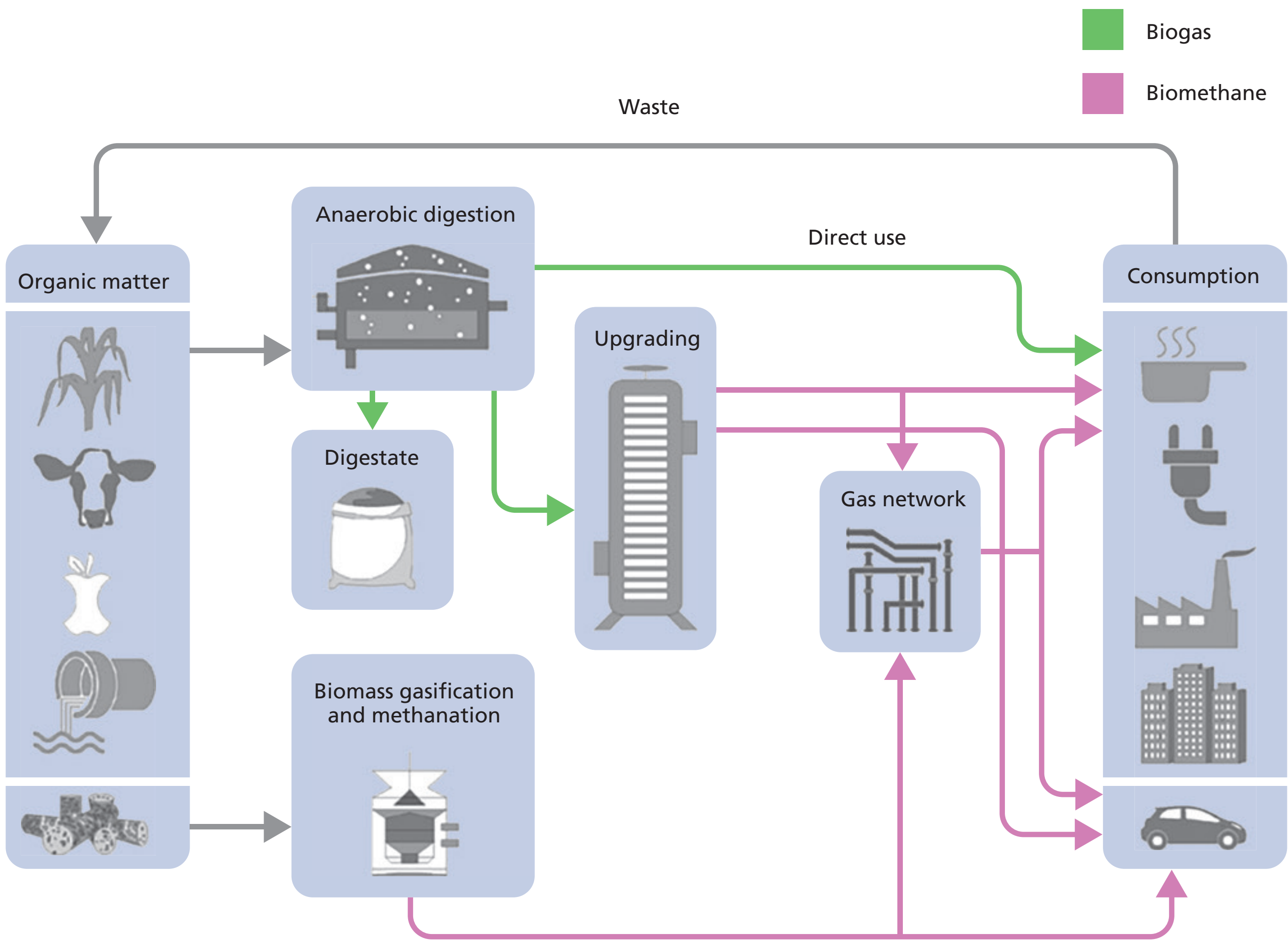


Figure 20 Biogas and biomethane can be produced by anaerobic digestion or gasification of sewage or agricultural, forestry, food, or municipal wastes (IEA 2020b).

(10^9) cubic metres (bcm) to 35 bcm per year by 2030 and substantially higher than this by 2050 (EC 2022b). This plan assumes that new production will come only from sewage and other bio-wastes; however, the biomethane industry is keen to promote other ways to increase biomethane production such as sequential cropping, namely producing two crops per year on the same land (Guidehouse 2022a).

Biomethane can be readily refined to meet the required gas quality specifications set by European Standard EN 16723-1 for injection into natural gas grids or the quality specifications set by standard EN 16723-2 for it to be used as bio-compressed natural gas or bio-liquefied natural gas for road transport (Prussi *et al.* 2019).

Biomethane is a limited and precious resource and is therefore unlikely to be used in the medium to long term in domestic gas boilers (section 2.2.5). The proposal, which is included in the REPowerEU plan, to distribute biomethane to households for heating (EC 2022g) may be viable in the short term, but biomethane will be too costly and its supplies too limited for it to compete on a large scale with electric heat pumps in the future.

In the short term, biomethane is nevertheless being increasingly blended with natural gas in networks, and it will become increasingly valuable for hard-to-electrify applications as the use of unabated natural gas is phased out. In the medium term, the IEA foresees substantial growth in the production of biomethane in the EU by 2040 (IEA 2020b). In the long term, biomethane will have to compete for biomass resources with other high-value hydrocarbon fuels for use in shipping and long-distance road freight transport, and with carbon feedstock for chemical industries; so the future of biomethane will depend on how the regulations for these markets evolve.

6.4 Bio-liquid petroleum gas (bio-propane and bio-butane) is a potentially attractive option to replace liquid petroleum gas

As discussed in section 4.7, fossil liquefied petroleum gas (LPG) can be replaced by bio-propane and bio-butane (bio-LPG) which have the same chemical composition. Bio-LPG can be made from vegetable oils or other bio-resources, or from renewable hydrogen plus CO_2 captured from the atmosphere, and therefore has a much lower carbon footprint than fossil fuels.

For most applications, bio-LPG can be used as a drop-in fuel with existing plant and equipment that runs on fossil LPG, so it is a potentially attractive replacement option for when the use of unabated fossil LPG is phased out. Several forms of bio-LPG are already recognised in the Renewable Energy Directive (see its Annex III) as renewable fuels (EU 2022a). The production of bio-LPG in the EU in 2018 was small at about 0.2 Mt per year (Liquid Gas Europe 2021), but its potential as a replacement for natural gas and/or fossil LPG could be much higher.

6.5 Bio-dimethyl ether offers substantial greenhouse gas emission reductions and could be used in modified diesel engines, but its costs remain high

As discussed in section 4.8, bio-dimethyl ether (bio-DME) is a very clean renewable fuel that can be made in several ways, including biomass gasification, renewable hydrogen plus CO_2 captured from the atmosphere, or from bio-methanol or bio-based syngas, and it could replace fossil DME as unabated fossil fuels are phased out. Bio-DME is a gaseous fuel that liquefies at moderate pressure (about 5 bar) and it is non-toxic and non-carcinogenic. Its physical and combustion properties are very similar to LPG and it can be mixed with LPG up to 25% (by mass) for use in existing LPG equipment. With minor changes it can be used in higher concentrations, up to 100%.

Bio-DME has a high cetane number (similar to octane number but for diesel engines) and can be used to fuel modified diesel engines, where it burns without forming soot. This means that the pollutant emissions from an internal combustion engine running on bio-DME can be extremely low since the nitrogen oxide emissions can be minimised without risk of increasing soot emissions (an important dilemma for current diesel engines). It has been identified as having among the highest well-to-wheel efficiencies and lowest well-to-wheel emissions of all renewable fuels (Prussi *et al.* 2020). The potential production cost of bio-DME is among the lowest of the advanced biofuels options that have a sufficiently high technology readiness level to be used in the short term, but its current high costs and low production levels limit its use today mainly to demonstration projects (IRENA 2019; 2021a).

The environmental impacts of making and producing bio-DME and methanol from bio-resources have been compared and both have been shown to offer substantial GHG emission reductions (82–86%) compared with fossil fuels (Matzen and Demirel 2016).

6.6 Bio-methanol markets could emerge for road transport, shipping, and aviation

Bio-methanol can be produced from biomass, such as forestry and agricultural wastes, biogas, sewage, municipal waste, and black liquor from the pulp and paper industry. It can also be produced from CO_2 and renewable hydrogen, and it is then called e-methanol. Bio-methanol and e-methanol are chemically identical to fossil-fuel-based methanol (section 4.9) but are recognised in the Renewable Energy Directive (see its Annex III) as renewable fuels (EU 2022a).

Currently, less than 1 Mt per year of bio-methanol (and e-methanol) is sold in global markets, which represents less than 1% of the global methanol market (section 4.9). However, research, development, and demonstration projects are continuing in the EU and globally to advance several different ways of producing bio-methanol and e-methanol. The aim of these projects is to develop and expand the markets for applications in all three of the main transport sectors: road transport, shipping, and aviation (ETIP 2022b). Bio-methanol can also be used to produce other carbon-containing fuels, such as bio-DME.

6.7 Synthetic methane (e-methane) could be supplied through existing gas infrastructure, but its commercial potential is not yet established

Synthetic methane can be produced using power-to-methane, which means that renewable hydrogen is produced using renewable electricity and combined using chemical synthesis processes with CO_2 to produce e-methane. To facilitate hydrogen imports into the EU, for example into the European Green Energy Hub in Wilhelmshaven, which is planned to come on stream in 2027, e-methane could be liquefied, so that it could be transported by ship, and then either used directly or re-transformed into hydrogen (TES 2022).

E-methane produced in this way would have equivalent properties to normal methane, but its commercial potential is not yet clear, given the currently limited availability and high costs of CO_2 with a sustainable origin, the conversion losses of the production process, and the remaining technology learning curves (CEPS 2019).

The appeal of synthetic methane to the natural gas industry is that it could be transported and supplied using the same infrastructure. However, e-methane will be much more expensive than natural gas (before the Russian invasion of Ukraine), and further work is needed to establish its commercial potential.

6.8 Green or blue ammonia, made using renewable or blue hydrogen, could be used to transport and store hydrogen or for fertiliser production

Ammonia is the foundation for the nitrogen fertiliser industry, and it is currently made mainly by using atmospheric nitrogen and grey hydrogen, produced by steam reforming of natural gas.

Instead of using grey hydrogen, green ammonia could in future be made using renewable hydrogen (EC 2021b). Looking ahead to the medium term, as the prices of electrolysers fall, prime locations for their use in the EU may be close to where fertilisers are produced.

Alternatively, blue ammonia could be made by using blue hydrogen produced by steam reforming of natural gas with the resulting carbon emissions captured and stored using CCS. The production of blue hydrogen in the EU will be influenced by the availability of natural gas, natural gas prices, and the availability of CCS (section 3.7). Blue and green ammonia produced in the EU are likely to be prioritised, at least in the short term, for making fertilisers to support agriculture and food production rather than for energy, but they may also be imported as foreseen in the REPowerEU plan.

Ammonia is a toxic substance, but it can be used as a hydrogen storage medium because it is easier and less costly to transport ammonia at –33 °C and atmospheric pressure than to transport liquid hydrogen. Ammonia also has the advantages that it contains more hydrogen per unit volume than liquid hydrogen, and there is no boil-off of hydrogen during the storage or transportation of ammonia. With appropriate safety precautions, ammonia could therefore be safely imported, for example from Australia (Egerer *et al.* 2022b). In this way, ammonia could be used as a means of transporting hydrogen imports into the EU. If ammonia is used in such applications away from ports, then appropriate regulation and a safe transport solution must be deployed. To recover the hydrogen, ammonia must be cracked (decomposed into hydrogen and nitrogen) using a catalyst, but more work is needed to develop systems for cracking ammonia at scale.

Ammonia can also be used as a transport fuel for ships or heavy-duty road vehicles, or potentially in the power sector as currently envisaged by Japan (METI 2022). However, before it can be deployed on a large scale as a transport fuel, it will be crucial to de-risk its use for such applications. This is something that companies specialised in testing and certification are already working on (Bureau Veritas 2022). For ship owners, the key challenge is to prevent accidental ammonia leaks during ship operations and bunkering. Furthermore, adequate measures must be taken to limit nitrogen oxide emissions from ammonia or ammonia/hydrogen combustion in maritime engines (Dinesh and Kumar 2022).

6.9 Sustainable syngas production will have to compete for limited sustainable resources

Syngas, also known as synthesis gas, synthetic gas, or producer gas, is mainly produced today by the gasification or pyrolysis of fossil fuels (coal, oil, and natural gas) or related fossil-based materials such as plastics.

Sustainable syngas can be produced from sustainable resources that contain carbon, such as sustainable biomass, municipal waste, or similar materials; however, as discussed elsewhere in this report, such resources will be increasingly in demand for many different applications and will be insufficient to meet future demands.

Syngas is typically composed of hydrogen (20–40%), carbon monoxide (35–40%), CO_2 (25–35%), methane (0–15%), and nitrogen (2–5%), depending on the chemical composition of the feedstock. It is widely used in integrated processes by chemical industries and can be upgraded using gas separation technologies (Prussi *et al.* 2019). Sustainable syngas can also be used as a feedstock for sustainable aviation fuels or for low-carbon fuels for marine transport.

7 Energy infrastructure

How will the European Union's energy infrastructure (gas and electricity networks) evolve as use of unabated natural gas is phased out?

7.1 Local communities must be engaged in replacing natural gas to reduce greenhouse gas emissions

Individual consumers (households, companies, organisations) will be encouraged over the next few years (e.g. by national or regional incentives), and eventually required, to replace their natural gas boilers with alternatives, such as electric heat pumps or district heating.

Growing numbers of such decisions will lead not only to falling flow rates in natural gas networks, but also to growing needs for reinforcements of electricity distribution grids, and in some areas to the need to change from single to three-phase electricity supplies to buildings.

Similarly, the introduction or expansion of decarbonised district heating systems will decrease the demand for natural gas and increase the demand for low-carbon footprint electricity, solar and geothermal heating, and heat storage. Heat maps showing heat densities in urban areas can provide a solid basis for local heat planning for district heating (section 2.2.2) and are available in the Pan-European Thermal Atlas (PETA 2022; HRE 2023).

Energy-intensive industries have developed traditionally near to where fossil-based energy is available, which has allowed the benefits, including jobs, to stay in the region. As the transition to renewable energy sources and low-carbon footprint gases progresses, such regions may, for example, become hydrogen valleys and re-use existing gas pipe networks or be fitted with new infrastructure for hydrogen distribution, and be connected to new energy sources by longer and stronger energy supply infrastructures.

To mitigate public resistance to such developments, local communities must be engaged and given roles in the new energy systems. Discussions may also be held between regions, and in some cases between Member States, with a view to sharing the benefits and costs of relocating energy supplies and/or energy-consuming industries and their required infrastructures.

7.2 Permitting for electricity transmission and distribution infrastructure must be accelerated

Electricity and natural gas infrastructures and systems will become increasingly interlinked (known as sector coupling) as the energy transition progresses, and both will need to be adapted to accommodate a better integrated and decarbonised future energy system.

An urgent issue to be addressed by EU and national policy-makers in relation to energy infrastructures is the acceleration of permitting procedures, for which the EU has already made recommendations to its Member States (EC 2022h). Permitting procedures for grid infrastructures differ between EU Member States and need to be tackled urgently.

7.3 Infrastructure for natural gas and hydrogen transmission and distribution

7.3.1 Hydrogen users need supplies from transmission and distribution pipework, but investors must avoid creating future stranded assets

Investments in new gas infrastructure and in repurposing the existing gas infrastructure must be managed to maintain a cost-effective energy supply framework and to avoid creating stranded assets. They must also accommodate an evolving mix of energy demands as the use of unabated natural gas is phased out and low GHG emission gases are phased in.

EU policy-makers have already foreseen the need to make and publish plans for investments in adapting and reinforcing existing gas networks to carry hydrogen, as shown by the EU Regulation on guidelines for trans-European energy infrastructure (EU 2022d). In response, some planning and strategic work is already being done by the transmission system operators and the European Clean Hydrogen Alliance (EC 2020j) at EU level.

In line with the principles of sound financial management, public funding to support the construction or adaptation of gas networks to carry hydrogen should be awarded only to consortia involving hydrogen-consuming industries and stakeholders that are committed to developing competitive, sustainable, and strategic hydrogen markets and to sharing the risks of creating stranded assets. Such a partnership approach would also reduce the risk of premature decisions by industries to move out of the EU to countries that offer attractive financial incentives (section 5.6.4).

The needs for investments in infrastructure will evolve over time and will be different in different Member States and regions, but international coordination must be prioritised because potential bottlenecks could increase the costs of the energy transition and inhibit the EU from playing a leading role in future global energy markets.

Progressively repurposing existing gas transmission pipework is likely to be the cheapest option for carrying imported hydrogen over long distances from third countries into and across the EU. It may also be used for carrying hydrogen from electrolysers to clusters of industrial demand and/or supply hubs for transport fleets. Similarly, where they are hydrogen-compatible, existing local gas distribution networks are likely to be the cheapest option for distributing hydrogen to industry clusters and refuelling stations for heavy-duty vehicles.

Where suitable pipework is not available, some new dedicated hydrogen pipelines are already being built by major EU industrial actors to connect producing with consuming plants in industrial centres, and these may be expanded to supply more nearby industries in the coming years (Air Liquide 2021). Other EU industries that are planning to use hydrogen in the future must be given confidence that the potential benefits of operating in the EU will be higher than those offered by governments of third countries (section 5.6.4).

EU gas network operators have studied the extent to which the existing natural gas infrastructure in Europe could be used to transport hydrogen. For example, the Re-stream study found that most offshore pipelines could be reused for hydrogen, while 70% of onshore pipelines could be reused (Carbon Limits and DNV 2021). Network operators have proposed investments of €80 billion to €143 billion in a European hydrogen backbone with 50,000 km of pipelines of which 60% would use repurposed natural gas pipes by 2040 (EHB 2022; Guidehouse 2022b). This work is continuing and is reflected in regularly updated in visionary maps for future hydrogen pipeline infrastructure (EHB 2023).

Infrastructure for distributing hydrogen blended with natural gas is also being studied, but to supply blends across the EU would bring negligible GHG emission reductions and high technical risks, as discussed in section 2.2.6. Investments in infrastructure to facilitate the distribution of hydrogen blends across the EU cannot therefore be justified.

7.3.2 Storage of hydrogen (and other sustainable gaseous fuels) must be increased for energy security and to manage variations in renewable electricity supply

Natural gas storage is well developed across the EU (section 4.5).

Hydrogen can be stored physically as either a gas or a liquid. Storage of hydrogen gas typically requires high-pressure tanks (350–700 bar), and storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is –252.8 °C. Both of these storage options carry a high energy penalty, either to compress the gas or to cool it. Hydrogen storage in tanks is particularly important for its use in transport applications, and to facilitate the transportation of imports from third countries into the EU. Hydrogen stored in tanks may also be used to meet industry needs when supplies of renewable electricity to electrolysers are limited or cut off.

Hydrogen can be stored for long periods in large quantities in underground salt caverns, and projects on this are already underway. The future locations of large hydrogen storage sites will be determined mainly by the availability of suitable underground structures.

As renewable hydrogen displaces fossil fuels, its storage could become increasingly valuable for energy security, rather like natural gas storage is today. Natural gas is stored mostly to meet (seasonal) variations in demand, while hydrogen demand is likely to be more constant because in the short term it will come mainly from industrial customers (primarily steel, ammonia, and high-value chemicals). Renewable hydrogen storage will therefore be needed mainly to meet variations in supply, caused by variable renewable energy sources (wind and solar), and it is likely to be located close to production rather than demand sites (IRENA 2022a). However, this may be constrained by the availability of adequate geological infrastructure to store hydrogen in large quantities. If the production and storage of hydrogen is located in exporting countries, then this could raise energy security concerns in importing countries that lack buffer storage capacity for offsetting potential supply disruptions (US Government 2023).

Salt caverns are currently considered to be the most promising solution for large-scale storage of hydrogen over long periods (Andersson and Grönkvist 2019), and most of those that are currently being used for natural gas storage could be converted to store hydrogen. However, because hydrogen has a lower energy density than natural gas, any natural gas storage facility that is filled with hydrogen would hold only around 24% of the energy content of the same volume of natural gas (GIE and Guidehouse 2021). In other words, four times as much storage volume would be needed to maintain the current energy storage capacity. Globally, until 2022, hydrogen has been stored in only six salt caverns: three in the UK and three in Texas, USA.

Ramping up geological storage of hydrogen calls for careful planning, because some storage sites are likely to be used for storing methane, biomethane, or even CO_2 during the continuing energy transition, and possibly also for the long term. Security of supply concerns may lead to rather little of the existing storage capacity being released for storing hydrogen in the EU.

7.3.3 Infrastructure for hydrogen derivatives where hydrogen is transported by ship

Liquid hydrogen can be transported by ship over long distances in several different ways. It can be cooled to a cryogenic temperature of −252.8 °C, but this necessitates a significant energy input and additional expense for high-pressure- and low-temperature-resistant storage tanks, as well as substantial boil-off gas losses. Additionally, its low energy density is disadvantageous for long-distance transport.

Alternatively, there is a choice of hydrogen carriers (derivatives) that could be used for shipping, of which the following are widely discussed: (1) liquid ammonia, (2) liquid organic hydrogen carriers, such as toluene-methylcyclohexane or dibenzytoluene, and (3) methanol (Runge *et al.* 2020; Patonia and Poudineh 2022). Some projects in the EU are also considering the option of transporting hydrogen using e-methane as a carrier (section 6.7). All these carriers require additional processing steps and reduce the amount of hydrogen delivered per unit of primary energy input.

It is not yet clear which will become the most widely used option for storing and transporting hydrogen over long distances (Andersson and Grönkvist 2019). It seems likely that ammonia and methanol will have roles to play because they avoid the need to use cryogenic ships, and they can be used directly in industrial processes or as fuels for ships. However, more work is needed to develop a process for cracking ammonia at scale (Splash 2022).

7.3.4 Financing is required for gas and electricity infrastructure, but the first priority must be to incentivise and finance more renewable electricity production

Financing is needed urgently to reinforce the EU's natural gas grids, in particular to facilitate access to new liquefied natural gas (LNG)-importing terminals.

Policy-makers must work with financiers to guide and prioritise major investment decisions on the reinforcement of electricity transmission and distribution grids to deliver the additional electricity needed as buildings, industry, and transport are electrified. Major financing sources can be leveraged and attracted to such investments by public funding, for example from the Connecting Europe Facility, as proposed in the REPowerEU plan (EC 2022g).

Energy projects of common interest have been funded under the Trans-European Network Regulation and Connecting Europe Facility for many years (EC 2022i), and the 2022 call prioritised emergency projects to deliver the REPowerEU plan (EC 2022q). However, future priorities must move away from emergency projects and focus on delivering an affordable transition to a fully decarbonised and secure energy system that relies more heavily on the use of electricity.

Financing is needed for investments in physical infrastructures to deliver hydrogen to those industries that wish to use it. Some industries may also need financing and support to de-risk the gap between hydrogen supply and demand by facilitating the purchase of renewable hydrogen. The European Commission recognised this need in September 2022, when it pledged to create a European Hydrogen Bank, which would use money from the Innovation Fund to support the development of the EU's hydrogen market (EC 2023h).

For renewable hydrogen in the EU, it must be emphasised that the first priority is to finance (and permit) the deployment of renewable electricity generators to run the electrolysers that produce it, because there can be no European production of renewable hydrogen without adequate supplies of renewable electricity.

Incentives are already being provided in some countries, notably through the Inflation Reduction Act in the USA, to drive down production costs and promote growth in their hydrogen markets, which is likely to help them to build a dominant position in international markets (US EPA 2023). The Inflation Reduction Act essentially supports the production of hydrogen either through production tax credits or investment tax credits and using a technology-neutral approach that focuses on the carbon intensity of the hydrogen produced. This approach is complemented by the Department of Energy's programme to develop hydrogen hubs across the country, which should contribute to developing the demand. From an EU perspective, the Inflation Reduction Act incentives in the USA are a cause for concern because they could encourage EU industries to move out of the EU to access them, which could weaken the EU's position in global markets.

7.3.5 Regulatory frameworks for gas and electricity infrastructure should permit changes in capacities and in energy carriers with minimal new permitting requirements

The value of gas and electricity infrastructure lies as much in the land through which it runs, the permits to operate, and the rights to transport energy carriers along the route as in the pipes, valves, and other system hardware. Regulatory frameworks that permit changes in capacities and in energy carriers with minimal requirements for new permits, environmental impact assessments, and audits can therefore be very valuable.

Many of the existing regulations for natural gas will need to be adapted to cover the transportation of hydrogen in EU natural gas networks, notably to cover health and safety, management, and market rules to ensure non-discriminatory access for all appropriately sized hydrogen producers and consumers, within Member States and across national borders. Important steps in this were taken in December 2021 by the European Commission in its proposal for a directive on common rules for the internal markets in renewable and natural gases and in hydrogen (EC 2021n), and further steps could be taken as the electricity market rules are updated (EC 2023g).

Also important will be standards for the quality of low-carbon footprint fuels and for their storage and handling. Standards will need to be harmonised across the EU for the design of nozzles for filling vehicles, and regulations will be needed to limit small leaks of hydrogen from infrastructure, because these contribute to global warming (section 5.8).

Capacity building on infrastructure for low-carbon fuels will also be important, through information and communication programmes to raise the knowledge, skills, and engagement levels of key stakeholders across the EU.

8 Security of energy supply

What does it mean and how can it be managed?

8.1 The Russia–Ukraine war has disrupted the energy landscape

There is no universally accepted definition of security of energy supplies, but it is commonly viewed under four main headings: availability, reliability, sustainability, and affordability (Steinberger-Wilckens *et al.* 2017). For some analyses, indicators and indices, such as the Shannon–Wiener–Neumann index (Neumann 2007) have been used to quantify aspects of energy security, such as import dependency.

As fossil fuels are phased out in response to the EU commitment to net zero by 2050, it will be crucial to ensure that the transition to a decarbonised energy future is made in a secure way, without reducing the security of the EU's energy supplies.

In 2022, the security of energy supplies became an urgent priority for EU policy-makers when Russia invaded Ukraine. Russia disrupted natural gas supplies and this highlighted the need for greater diversity of suppliers and resources.

In addition, the war in Ukraine highlighted the geopolitical risks associated with the operation and maintenance of natural-gas supply infrastructures (including pipe networks and storage systems) in third countries and in the EU if these are owned (completely or partly) or operated by companies based outside the EU.

As Russian natural gas supplies are replaced by imports of natural gas, liquefied natural gas (LNG), and other fuels from alternative international suppliers, and as demand for natural gas is reduced, so issues about the security of supply need to be kept under regular review because additional steps may have to be taken.

8.2 Steps to address new challenges to the security of European Union energy supplies

Urgent measures were needed and taken by the EU to secure supplies of natural gas for the winter of 2022/23 by filling natural gas storage systems over the summer, installing floating regasification and storage units to facilitate increased imports of LNG, and negotiating urgent increases in piped natural gas imports from non-Russian natural gas suppliers.

EU Member States also took steps to increase supplies from other energy sources, including restarting mothballed coal-fired power plants, delaying the closure of coal-fired power plants, and extending the operating lives of nuclear power plants. Delaying the closure of coal-fired power plants can only be justified for a short period as an emergency response to cuts in the supply of Russian gas, and their carbon emissions should still fall within the Emission Trading System (ETS), to ensure that the EU's commitments to greenhouse gas (GHG) emission reductions are not put at risk. Prolonging the lifetimes of nuclear plants should only be done with due consideration of safety issues, their potential vulnerability to attack from terrorists or from Russia, and nuclear waste disposal.

Piped natural gas imports from other suppliers into Europe could be increased for the short term, which would offer increased diversity of supplies and help to spread security of supply risks. Supplies through the Eastern Mediterranean (EastMed pipeline from Israel, Cyprus, and Greece) are not expected until after 2025, but more can be expected earlier from North Africa. For example, it is anticipated that Algerian gas supplies to Europe will increase in 2023, notably from the Berkine South gas fields (ENI 2022).

Following the urgent measures discussed above, the security of energy supplies can be improved by reducing the demand for fossil fuels through investments in energy efficiency:

1. In buildings, installing more insulation and better system controls, and by replacing natural gas boilers with heat pumps (EASAC 2019a).
2. In industry, facilitating and incentivising accelerated transitions to more energy-efficient systems and processes, such as electrification and heat recovery.
3. In transport, facilitating and incentivising the use of public transport and electric vehicles and discouraging the trend towards ever bigger passenger cars with internal combustion engines (EASAC 2019a). (Note: this will decrease the demand for liquid fossil fuels but increase the demand for renewable electricity (section 3.2).)

Energy security can also be improved by investing in cross-sectoral measures, such as planning new urban developments with integrated transport infrastructures to facilitate carbon-free mobility between residential buildings and working spaces, and district heating systems that can use renewable energies and waste heat from nearby industries or commercial premises.

The transition from dispatchable fossil fuels to variable renewable energy supplies is vital for reducing carbon emissions but it is not without operational challenges that can affect the reliability of energy supplies. For example, the output of wind turbines varies with the local wind speed, and the output of solar generators varies with the solar radiation over the day and over the year. The reliability of electricity supplies must therefore be managed using electricity and heat storage systems, digitally controlled demand response, reinforced network interconnections, and by using flexible generators powered either by sustainable fuels (such as biomethane or hydrogen) or by natural gas together with carbon capture and storage.

In this context, it is important to emphasise the future value of ensuring that all consumers are supplied with smart meters (e.g. for each apartment in multi-occupancy buildings) so that they will be able to contribute to the security of energy supplies by responding to electricity price signals in the form of real-time electricity tariffs. Smart meters will allow consumers to participate in demand response schemes, which help to reduce the need for expensive flexible generation to meet peak demands. In addition, all data and data management systems must be protected by appropriate measures to ensure cyber security.

The transition towards more renewable energy sources and low-carbon footprint fuels will help to strengthen the security of EU supplies for the short, medium, and long terms, because these energy sources can be produced largely within the EU. In addition, imports of low-carbon footprint hydrogen and its derivatives from third countries are expected in the future (Chapter 5). It will be important to minimise the transportation of gaseous fuels with low energy densities over long distances because transportation increases their carbon footprints and costs. The security of supply risks associated with energy imports should be regularly assessed and adequate diversity of suppliers ensured as global trade in sustainable energy sources grows.

Last but not least, it is important to address the supply-chain reliability of plant and equipment, including spare parts. Operators must plan and prepare for the routine maintenance and eventual replacement of their existing and new renewable energy-generating plants. Where possible, priority should be given to the selection and deployment of generators and systems that contain few critical raw materials and are designed for ease of component replacement, so that they can be routinely maintained to give maximum reliability.

8.3 Security of energy supplies should not be used as an excuse for delaying climate action

Ensuring the security of EU energy supplies must not become an excuse for reducing the rate of EU GHG emission reduction or for delaying the deadline for delivering net-zero emissions beyond 2050. Nor should it be used for outsourcing energy-intensive industrial production to countries outside the EU.

The European energy system will be decarbonised during the energy transition largely by increasing wind and solar power generation, but this will not be without security of supply risks if a substantial fraction of the new wind turbines and solar photovoltaic panels continue to be imported from third countries, notably from Asia, as they are today. The need for such imports can be addressed by adopting a more circular economy, using more resources from within the EU, increasing local manufacturing, and recycling more components and materials.

Hence, to protect Europe from future problems of security of supply, notably with wind and solar power generators (and their spare parts), grid cables and batteries, more sustainable energy systems must be manufactured in Europe (Grimm *et al.* 2022). For EU production of sustainable energy technologies to offer high levels for supply security, priority must be given to designs that minimise the need for imported critical materials such as rare metals and silicon chips (IRENA 2021b). Re-shoring the EU's renewable energy manufacturing industry, including photovoltaics and batteries, will be particularly important, and is therefore part of the EU Green Deal industrial plan (EC 2023d).

8.4 The European Union should step up its efforts to build strategic partnerships in global energy markets

The political and economic reactions of international energy suppliers and of the EU's other international partners to the phasing out of natural gas are difficult to predict. The REPowerEU plan therefore includes an action to increase 'EU external energy engagement in a changing world' through dedicated partnerships with financial support, technical assistance, technology transfers, and/or enhanced trade relationships (EC 2022c).

Dialogue and agreements with EU neighbourhood countries that currently supply the EU with natural gas, such as Norway, Azerbaijan, and North African countries, will be particularly important, to ensure that the phasing out of natural gas deliveries is managed in the context of broader energy-sector cooperation and increases in the use of other energy options.

An enhanced engagement by the EU with developing countries and emerging economies on energy issues could help to bring global climate benefits. For example, joint initiatives to reduce carbon emissions and on phasing out the use of fossil fuels will bring regional benefits, for example in the context of EU policies and programmes for international development and, in particular, EU partnerships with Africa, the Caribbean, the Pacific, and Asia.

Key elements of such initiatives should include managing the links between water supplies and hydrogen production (see also section 5.3.6) and managing the priorities between GHG emission reduction in the EU and the trading of renewable energy technologies with developing countries and emerging economies.

8.5 Resilience and cyber security are becoming increasingly important

Resilience has been defined as '*the ability not only to withstand and cope with challenges but also to undergo transitions, in a sustainable, fair, and democratic manner*' (JRC 2020). Specifically, for the energy sector, the term 'resilience' describes the ability to survive and quickly recover from extreme and unexpected disruptions, such as extreme weather, which is the cause of most energy supply disruptions, and cyberattacks, which are still a minor, but rapidly increasing concern for EU citizens and businesses (Jasiūnas *et al.* 2021).

The cyber security of gas and electricity networks and of key energy-consuming systems is becoming increasingly important to the EU, as reflected in the EU Security Union Strategy (EC 2020k). The relevant legislation will need to be continuously updated to protect the security of EU energy supplies (EU 2017).

8.6 Physical security of energy infrastructure should be protected

The sabotage of the Nord Stream 1 and 2 gas pipelines in September 2022 showed that critical infrastructure can be targeted and destroyed. The investigation into this case is continuing, but it demonstrates that adequate technical capabilities and personnel to carry such acts exist. This is particularly worrying for other suppliers to the EU, notably Norway, which during the second half of 2022 has become Europe's largest supplier of natural gas. According to the Norwegian Petroleum Safety Authority, the Norwegian Government has initiated measures to strengthen emergency preparedness for all infrastructure on the continental shelf (PSA 2022).

8.7 Future contracts for natural gas and liquefied natural gas supplies to the European Union should guarantee not only secure supplies at affordable prices but also acceptable carbon footprints

Geopolitical decisions by Russia to reduce or to cut off natural gas supplies to the EU, and EU policies to phase out the use of Russian gas, have greatly reduced trade in natural gas between Russia and the EU.

There were therefore urgent moves in 2022 to buy natural gas from other suppliers on the spot market (typically supplies for 2 years or less) and, where possible, to establish new long-term (typically for 20 years) natural gas supply contracts with a wider diversity of suppliers. For example, contracts to supply LNG to the EU for 15 or 20 years were signed in 2021 and 2022 (Venture Global 2021; Aljazeera 2022; INEOS 2022). However, the number of contracts signed by EU companies (excluding aggregators) was relatively limited compared with Chinese companies, which signed for around 60 billion (10^9) cubic metres (bcm) per year of LNG contracts during 2021 and 2022 (Corbeau and Yan 2022).

To address these challenges, a new EU Energy Platform was established by the European Commission in 2022 with a mandate to play a key role in pooling demand, coordinating infrastructure use, negotiating with international partners, and preparing for joint natural gas (and hydrogen in the future) purchases. It also aims to avoid EU companies outbidding each other to refill storage, thereby driving prices to very high levels as was the case in August 2022 (EC 2022y). The Energy Platform brings together the European Commission and EU Member States to make optimal use of the collective political and market weight of the EU when purchasing natural gas and LNG (EC 2022v).

Commercial experience is needed for contract negotiation, and companies must remain responsible for all stages of the supply chain but leave system operators in control of how gas is released into networks, especially during winter months. The European Commission therefore set up an industry advisory group for the Platform, as shown in Figure 21.

The Energy Platform must operate in a transparent EU energy market and ensure that potential new contracts are compatible with existing ones (Bruegel 2022c). Policy-makers must ensure that the purchasing processes used by the Platform are compatible with EU competition law. They must also keep borders and markets open and protect the EU's single energy market. These challenges are addressed in the European Council Regulation on establishing a market correction mechanism to protect citizens and the economy against excessively high prices, which creates a temporary alternative benchmark to the Dutch spot price (Title Transfer Facility) for a period of 1 year (EC 2022x; European Council 2022d).

The price of natural gas sold in the EU is important for retaining the EU's energy-intensive industries because the USA, for example, has established an attractive investment climate (US EPA 2023), and Russia is increasing its supply of potentially cheap natural gas to the EU industry's competitors in Asia, for example delivering natural gas by pipeline to China (Reuters

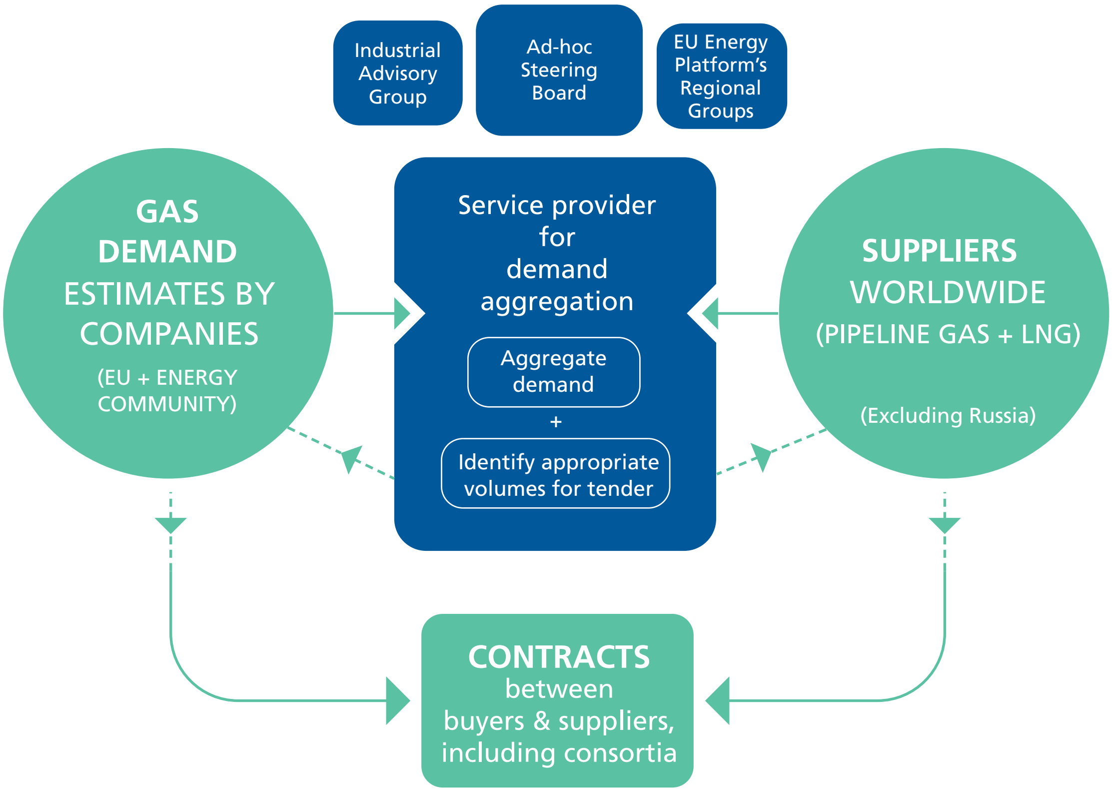


Figure 21 EU Energy Platform (EC 2022v).

2022b). Many investment and operating costs along the supply chain influence gas prices, and the EU has goals for phasing out the unabated use of natural gas. Hence, industry experience, together with the weight of the EU institutions, will be crucial for the EU's future international contract negotiations on natural gas and LNG supplies.

As discussed in section 4.6, it will be important for the EU to put in place reliable independent certification of the supply-chain GHG emissions of EU natural gas imports, including imported LNG as well as piped natural gas. Hence, difficult decisions must be taken about the selection of suppliers, because suppliers of natural gas and LNG to the EU should not only guarantee secure supplies at affordable prices, but also acceptable carbon footprints, which could be a problem if they require long-distance transport.

8.8 Managing security of supplies for the long term requires a new vision

It will be important to develop a new vision for how the security of energy supplies should be managed in the long term, when the energy economy of Europe will be dominated by renewable and low-carbon footprint fuels.

The energy market is designed to resolve scarcity issues in the short term through price increases, as has been seen in its response to the reduced availability of Russian natural gas, but this can cause unacceptable social problems, including energy poverty for low-income groups and unmanageable challenges for businesses, leading to bankruptcies. Emergency steps have therefore been taken at EU and Member State levels to reduce the impacts of unacceptable energy price increases in the short term (EC 2022g).

Looking to the future, long-term measures will be needed to further adapt the EU energy market and state aid rules to fit with the EU's transition to net-zero carbon emission by 2050. The new measures must leave in place incentives to save energy and reduce GHG emissions, but provide targeted support for vulnerable groups and households, and, where necessary, also protect the competitiveness of key EU industries (Chapter 9).

9 Affordability

How to minimise energy poverty and make the transition to net zero affordable for households and businesses

9.1 Introduce targeted support schemes for vulnerable groups, not price caps or subsidies that hide important price signals for potential greenhouse gas emission reduction

A 'fair' transition to a decarbonised (and secure) energy system means that basic energy services for all sectors of society must be affordable, leaving no one behind (EC 2021m). Energy prices paid by consumers are influenced by many factors, including the price of carbon, which is expected to increase in the future.

Price caps and fuel subsidies should both be avoided because they hide important price signals, including those relating to potential carbon emission reductions and energy savings, as well as peak demand reduction. Also, those who benefit most from subsidies are the highest energy users, typically the rich. Instead, competition between suppliers should be encouraged to keep retail prices low and the EU and national governments should provide support schemes that target those who cannot afford the energy services that they need: low-income households, vulnerable groups, and businesses that perform key roles in society but risk being bankrupted by high energy bills.

Affordability is determined both by running costs and by investment costs; similarly, fuel poverty is created by a lack of capital (or access to capital) for investment as well as by low levels of income (Scott *et al*. 2008). For example, when rising natural gas prices in 2022 resulted in an increase in the heating and electricity costs for most households in Europe, those living in energy poverty were not only unable to afford to use their existing heating systems, but they were also unable to afford to invest in energy efficiency measures, such as insulation, or in more efficient types of heating.

9.2 Complement the European Union energy market and adapt its rules to reduce energy poverty

The main argument for liberalising energy markets was to promote competition between suppliers and hence to deliver low and affordable costs to consumers. The EU's energy market has been progressively developed over more than 20 years. Energy suppliers that were vertically integrated monopolies (largely government owned) in most Member States have been replaced by increasingly unbundled and competitive structures with multiple companies competing in liberalised wholesale and retail markets. The EU Agency for the Cooperation of Energy Regulators was established in 2011 as an independent body to foster the integration and completion of the European Internal Energy Market for electricity and natural gas (ACER 2022).

The rises in global energy prices in 2022 not only caused problems for consumers but, in some countries, also led to bankruptcies of energy supply companies, which had been operating on tight margins to attract customers in highly competitive liberalised markets, and could not increase their retail prices in time to save their businesses (Ofgem 2022).

In the light of the problems experienced by energy companies and consumers in 2022, the European Commission stated publicly that '*This (electricity) market system does not work anymore. We have to reform it, we have to adapt it to the new realities of dominant renewables*' (Euractiv 2022b). In May 2022, the European Council called on the Commission to optimise the functioning of the electricity market, including the effect of gas prices, to withstand future excessive price volatility, deliver affordable electricity, and fit a decarbonised energy system, while maintaining incentives for the transition, and preserving the security of supply (European Council 2022a).

Work therefore continues on adapting the EU energy market rules to make the market more resilient, and to ensure that it will deliver secure and affordable decarbonised energy supplies, for example in the European Commission's proposed reform of the EU electricity market design (EC 2023g). This work should not, however, introduce price ceilings or subsidies that effectively discourage (e.g. by removing or counter-balancing incentives) measures that could increase energy efficiency and/or greenhouse gas (GHG) emission savings.

Liberalised energy markets must be complemented by targeted support for low-income and vulnerable households. Support schemes for vulnerable groups may be different in each country because they must fit with the national and local social care mechanisms.

9.3 Redistribute emission trading revenues to vulnerable groups and businesses, and to support development and deployment of systems that reduce greenhouse gas emissions

The EU's Climate Law and the many policies that form the EU Green Deal are leading to an ambitious package of measures that require huge investments in the short term, together with significant increases in energy prices created by emission trading systems or carbon pricing for households and businesses.

The overall success of GHG emission reduction measures will depend on their affordability and acceptability to a wide range of EU citizens, but this is not guaranteed. Indeed, there are already some early signs, for example the demonstrations in France by 'gilets jaunes' in 2018, that there could be a significant level of public resistance to, and eventually rejection of, some of the proposed carbon pricing and emission trading measures.

A recent study of carbon pricing schemes in Canada and Switzerland has explored the outcomes of using climate rebate programmes in which the revenues of carbon pricing are handed back to citizens and businesses to encourage acceptance of the price increases created by carbon pricing. The results, however, suggested that these rebate programmes had limited impacts on public support for carbon pricing (Mildenberger *et al.* 2022). Nevertheless, the carbon tax on natural gas in Sweden, which has been in place since 1991 (Government Offices of Sweden 2022), has been increased slowly over many years and continues to discourage the use of natural gas for heating buildings.

The main carbon pricing scheme in most of the EU is the Emission Trading System (EU ETS). This has made the costs of heating a building with electricity in most Member States higher than those of heating with natural gas boilers, because small gas boilers have been excluded from the EU ETS. However, many Member States have already started to address this by introducing bans on the installation of new natural gas boilers for heating buildings, and the latest revisions to the ETS directive will bring natural gas boilers of all sizes into the EU ETS (European Council 2022c). Together, these measures are expected, over the next few years, to lead to growing rates of replacement of natural gas boilers in the building sector, for example with heat pumps. However, the capital cost of a heat pump, potentially coupled with building renovation (notably insulation and draught proofing), is likely to be unaffordable for low-income households and vulnerable groups, so these groups will need to be given targeted support (section 9.6).

To accelerate the rate of GHG emission reductions, driven by carbon pricing systems such as the EU ETS, governments must communicate clearly to their citizens that unmitigated consumption of fossil fuels will become increasingly more expensive. They must also take important decisions concerning the uses made of the revenues that they generate. Firstly, to maximise the acceptance of carbon pricing by EU citizens, the revenues from the schemes (e.g. EU ETS) should be used to provide support to low-income households and vulnerable groups, which are affected most by the higher costs caused by carbon pricing. Secondly, to reduce the future needs for carbon pricing, the revenues should be used to support the development and large-scale deployment of technologies and systems that can lower the costs of reducing GHG emissions (Feindt *et al.* 2021).

9.4 Eurostat should regularly publish data on energy poverty in the European Union

Eurostat publishes EU statistics on income and living conditions, which include data on poverty, living, and housing conditions (Eurostat 2022), but it does not publish data on energy poverty itself.

Some key data have been brought together to highlight the main parameters that contribute to energy poverty (Odyssee-Mure 2021a), and an EU-wide survey by Eurostat in 2020 (published at the end of 2021) concluded that 8% of the EU population claimed they were unable to keep their home adequately warm (EC 2021j). The problem varied across EU Member States (Figure 22), with the largest percentage of people saying they were unable to keep their home adequately warm in Bulgaria (27%), followed by Lithuania (23%), Cyprus (21%), and Portugal and Greece (both with 17%).

Such a survey of people's opinions has limitations because, for example, it does not take into account the large differences that exist between people's homes in urban and rural areas and in different parts of the EU (EC 2022w). Moreover, energy price rises coupled with the cost-of-living crisis in 2022 made the problem worse. It would therefore be helpful in future if Eurostat could establish a statistical methodology for compiling objective and meaningful data on energy poverty and publish annual maps (such as that in Figure 22) to show how well energy poverty in the EU is being reduced.

9.5 The European Union should publish analyses of national energy and climate plan reports on vulnerable groups and national definitions, indicators, criteria, and progress on energy poverty reduction

In recent years, even before energy poverty was highlighted in 2019 as part of the Clean Energy for all Europeans package (EC 2019c), the importance of energy poverty and vulnerable consumers had been given growing priority by EU policy-makers.

Specific requirements for Member States to define the concept of vulnerable customers and to publish criteria for assessing energy poverty were enshrined in the EU Directive on electricity market rules (EC 2019b), and a recommendation on energy poverty (EC 2020a) was published by the European Commission in 2020. The EU went further in the recast Energy Efficiency Directive that was adopted in 2019, which included a definition of energy poverty together with obligations on Member States to establish national definitions, indicators, and criteria of energy poverty, and concepts of vulnerable customers. This directive also required Member States

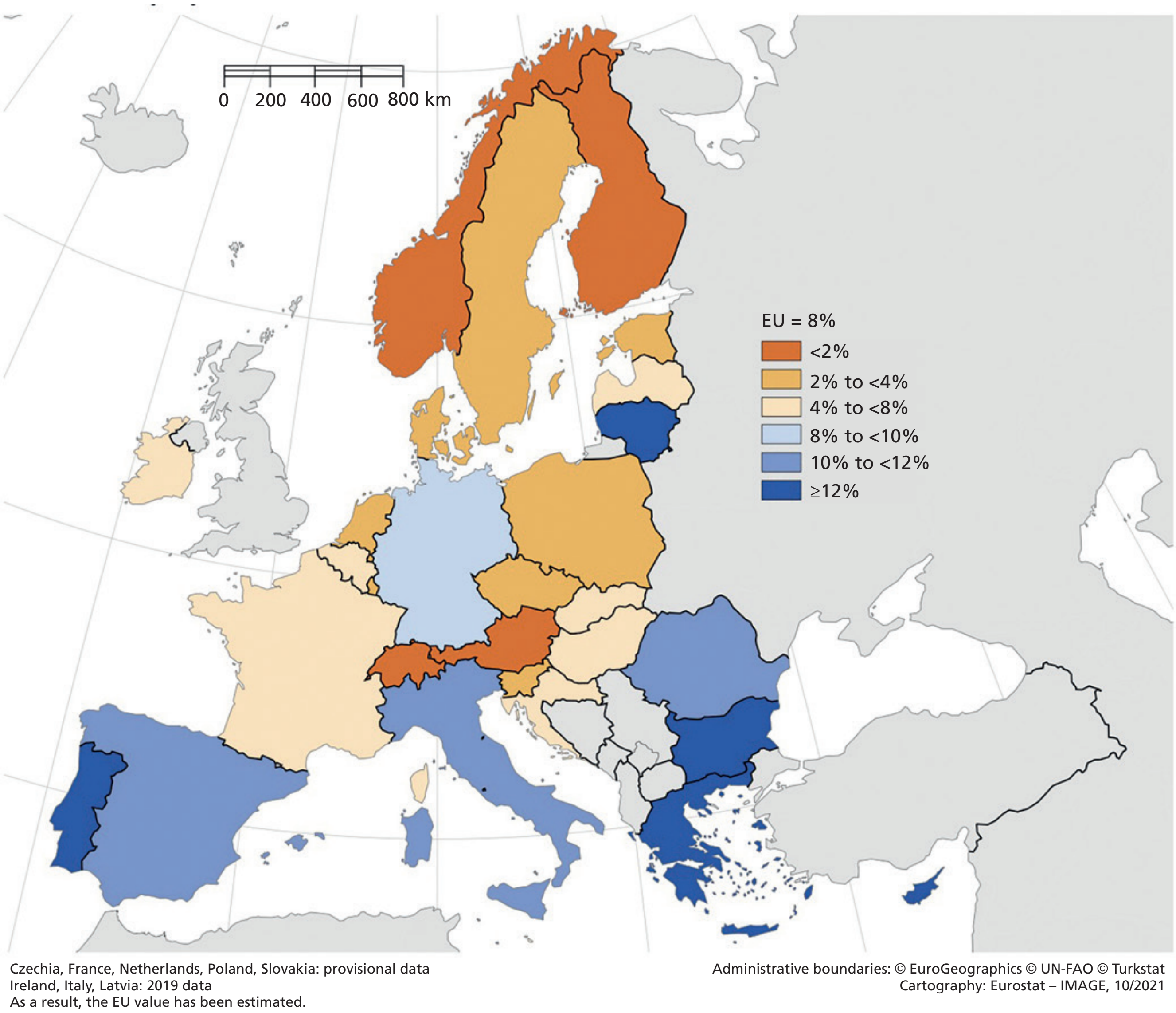


Figure 22 Eurostat survey of EU Member States in 2020 concluded that 8% of the EU population were unable to keep their home adequately warm (EC 2021j).

to report on these in their national energy and climate plans (NECPs) (EC 2021g).

However, despite the growing number of official EU documents that refer to energy poverty, the requirements in EU directives for Member States to publish national definitions and criteria, and to report on their progress in addressing it, many Member States have not yet met these requirements and there is not yet EU-wide agreement on a single definition of energy poverty, or on how it should be measured (EPRS 2022a).

This lack of progress by Member States was emphasised by the European Parliament in June 2022 in its adopted amendment to recital 12 of the proposed EU Regulation on the Social Climate Fund, which stated, '*there is still no standard Union-level definition of energy poverty and only one third of Member States have put in place a national definition of energy poverty. As a result, no transparent and comparable data on energy poverty in the Union is available, limiting the capacity to effectively monitor and assess the level of energy poverty. Therefore, a Union-level definition should be established to effectively address energy poverty and measure progress across Member States*' (EP 2022a).

In contrast to the statement by the European Parliament (above), the European Commission recently established an energy poverty advisory hub (EC 2022p) that has published a Guide to Understanding and Addressing Energy Poverty (EC 2022s). This Guide argues that a common definition for energy poverty across the EU may not be the most helpful way forward. It notes that energy poverty is commonly defined as the inability of households to ensure their energy needs, but it emphasises that energy poverty is a complex, multifaceted challenge that is linked to a combination of factors, there is not one type of or reason for energy poverty, and its nature can vary even at the local level. The guide suggests that, where definitions of energy poverty are not in place, broad proxies can be used, such as registers of people on disability or other state benefits.

The sudden rise in natural gas prices in 2022 affected all Member States, regardless of the degree of liberalisation of their energy market, the income levels of their vulnerable groups, and the nature and coverage of their social care system. The obligations in the Energy Efficiency Directive for Member States to publish in their NECPs not only their definition and criteria for energy poverty, but also the details of their energy poverty supporting schemes and their progress in reducing energy poverty are a very important step forward. Analyses by the EU institutions of the energy poverty reports in the next updates of the NECPs should therefore provide important guidance for future policy on this very important topic.

9.6 Identify energy poverty reduction budgets in European Union and national funding instruments and raise awareness of energy poverty at all levels

Adequate budgets for reducing energy poverty are needed in each Member State for use through targeted support schemes to provide low-income households, vulnerable groups, and small businesses with the following:

1. Income support that can be used to pay for energy costs in the short term.
2. Investment support that can be used to buy technologies and systems that will deliver energy savings and emission reductions immediately and for the long term.

Long-term investment financing schemes (like mortgages) can be used to accelerate 'energy efficiency first' investments, and to trigger the replacement of natural gas boilers with heat pumps and renewable heating, as well as building renovations that will reduce energy demand and thereby reduce the need for income support in the long term.

Targeted support for vulnerable groups is recommended by the Organisation for Economic Co-operation and Development as a policy response to the impact of the war in Ukraine on energy prices (OECD 2022). In particular, it comments that price caps are easy to implement but tend to disproportionately benefit large energy consumers with higher incomes. At the same time, price caps mute price signals, thereby limiting the incentive for energy savings and use of renewables. The World Bank comments that price caps can also create large financial losses for energy companies and fiscal burdens for the countries involved, thereby discouraging new infrastructure investment (Guenette 2020).

How support for vulnerable groups should be funded is subject to political debate, and options such as windfall taxes on energy companies lie in the hands of governments. These should be assessed in terms of their impacts on long-term investments in the sector, which are crucial to reducing the EU's dependency on gas.

The EU is committed to providing funding through several instruments to help Member States to address energy poverty, including the Social Climate Fund (SCF) on which provisional agreement was reached between the European Council and Parliament in December 2022 (EP 2022a). In addition, the governance regulation (EU 2018) and proposed SCF regulation (EC 2021q) require Member States to regularly monitor and report on their progress in dealing with energy poverty, and to include the numbers of existing and supported vulnerable groups (e.g. micro-enterprises, vulnerable transport users, and energy-poor households) in their NECPs. A recent analysis of policies and measures related to energy poverty that have been reported in NECPs shows that most Member States are active and working to address energy poverty, but there is a wide diversity of approaches and more needs to be done (Life Biobalance 2022).

To maintain consistency of EU policies, other financing instruments in the EU's Multiannual Financial Framework (such as the Recovery and Resilience Facility and the Just Transition Fund) should address energy poverty in the same way. Each Member State should be allocated an appropriate fraction of the available EU funding to reduce energy poverty on their territory, and they should be required to use a common definition and criteria when reporting in their NECPs on their progress and plans for further reducing energy poverty (EU 2018; EC 2020g; Unify 2022).

Member States must also improve awareness of energy poverty at national and local levels, and regularly update their targets for reducing it. Private financing and/or EU co-financing of national initiatives could help to reduce energy poverty in some areas, and national registers and maps of energy-poor households could help with the tasks of prioritising actions and monitoring progress towards agreed reduction targets for energy poverty.

Local instruments, managed by cities or regional administrations, can be helpful in some contexts, for example using energy service companies to mobilise long-term investments in energy-saving measures. Investments by other bodies, for example by social housing organisations, can be helped by guarantees from national administrations, which can deliver the planned objectives without the need to provide grants or other forms of public funding. In addition, a growing number of foundations and private investment fund managers are adopting green financing principles to invest in projects that deliver the UN Sustainable Development Goals and lead to GHG emission reductions. Such green financing can also make important contributions to energy poverty reduction (Green Finance Institute 2021).

9.7 The size of the Social Climate Fund should be linked to the amount of funding needed to tackle energy poverty, not to Emission Trading System revenues

As part of its revisions to the Emission Trading System (ETS) Directive in the Fit for 55 package, the EU proposed to set up an SCF to address the growing problem of energy poverty (EC 2021i).

It was proposed that the size of the fund should correspond to a dedicated share of the revenues from the auctioning of ETS allowances for the buildings and transport sectors. However, there was no obvious link between the resulting size of the SCF and the amount of funding needed to tackle energy poverty.

A further challenge was that the proposed SCF regulation required Member States to provide co-financing (EP 2022a). The aims of the SCF are so important to the EU's commitment to 'do no harm' (EC 2021m) that solutions will need to be found if sufficient funding from the ETS and Member States does not materialise.

The SCF is expected to provide funding to Member States to support measures and investments for increased energy efficiency of buildings (EC 2021g), GHG emission reduction in buildings, including the integration of renewable sources, and improved access to zero- and low GHG emission mobility and transport. These measures and investments must principally benefit vulnerable households, micro-enterprises, and vulnerable transport users. However, prioritising the vulnerable groups will be left to each Member State. The SCF is also expected to finance temporary direct income support for vulnerable households, and it may support awareness raising, capacity building, and technical assistance (EP 2022a).

Although an overall policy and SCF funding are to be provided at EU level, actions will be implemented at Member State level, together with existing social care policies for vulnerable groups. Examples are available in Finland (Kela 2022), and in France (Selectra 2022) and the UK (UK Government 2022). The implementation of national policies to reduce energy poverty requires reliable data on the amounts and costs of different energy sources used for heating, on the different types and sizes of residential buildings, and on the different sizes of families and their incomes. It also needs all these data to be analysed and brought together so that energy-poor households can be identified and targeted for support. Recent studies in Bulgaria suggest that such analyses can be challenging (Peneva 2019; 2021).

10 Conclusions and messages for policy-makers

10.1 Discussion

The EU is committed to reduce its greenhouse gas (GHG) emissions to net zero by 2050, which will require phasing out the use of all unabated fossil fuels (including coal, oil, and natural gas) and replacing them with renewable electricity and other low-carbon footprint energy sources.

This must be done while maintaining secure energy supplies and delivering affordable energy services to all energy consumers, which is a massive challenge for policy-makers, businesses, and individual citizens (Figure 23).

The EU's energy transition requires an integrated approach because it is already creating competition between the buildings, industry, and transport sectors for low-carbon footprint energy sources, notably renewable electricity. The transition will not be implemented in the same way in every Member State because of differences in the mixes of energy supply and demand and in national and international gas and electricity infrastructure (including importing facilities and pipelines).

Implementation of the transition is influenced by the availability of renewable energy resources, and local building and industry structures, as well as cultures and traditions. Nevertheless, updating the EU policy and regulatory framework is an urgent priority for all Member States because construction of renewable generators and their related infrastructure is often delayed by permitting procedures and financing for the required investments is difficult to secure without a solid regulatory base.

Financing will be more of a challenge in some Member States than others, but long-term capital investments

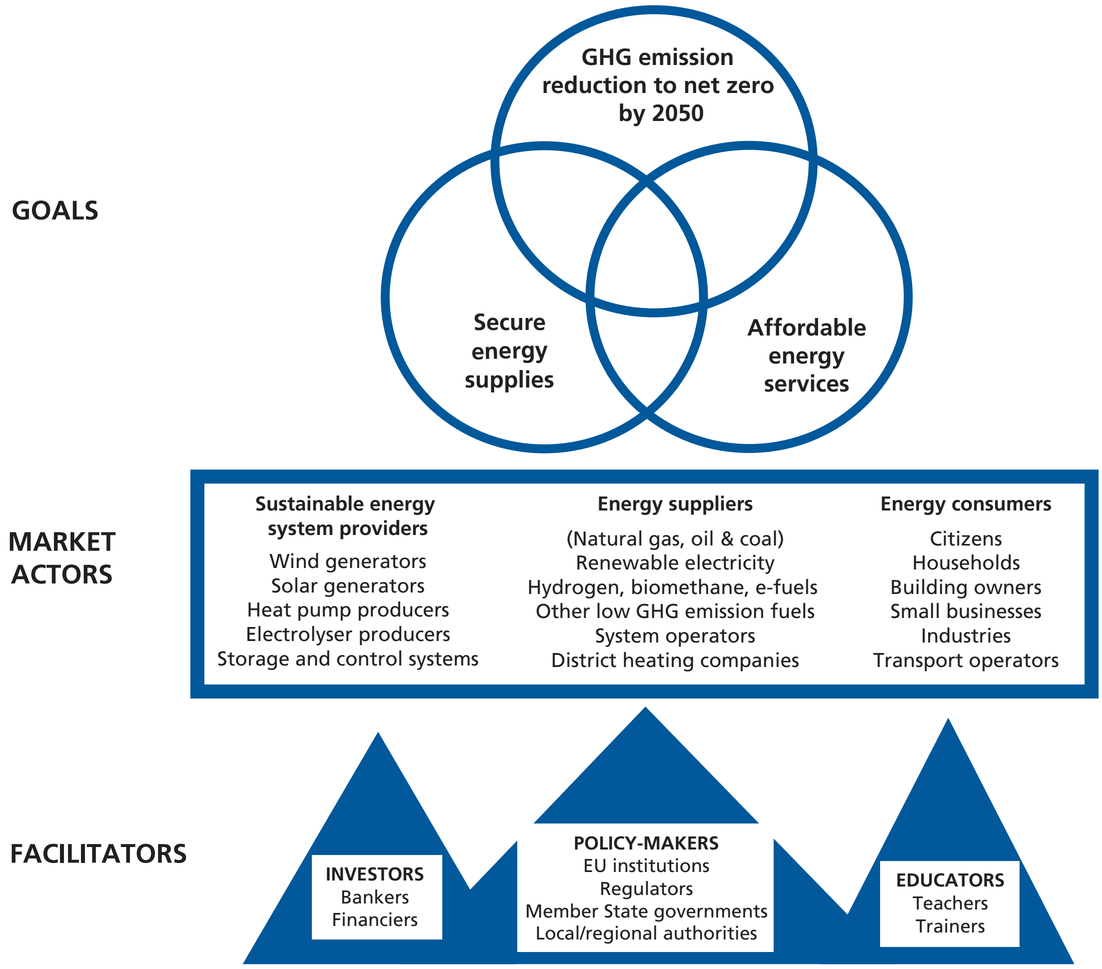


Figure 23 EU energy transition: a challenge for everyone.

are required in renewable electricity and heat generation, electricity and gas supply infrastructure, and in sustainable fuel production, as well as in new systems for using sustainable energy. Hence, Member States and industries will need money up-front from the EU and major financing institutions, including the European Investment Bank.

The modelling of future scenarios for EU policies and the EU energy mix is an important tool for policy-making. Models have been developed and calibrated over many years by the European Commission, the International Energy Agency, and by teams of researchers and academics across the EU. Although there are still many assumptions and uncertainties, models have been used to study scenarios, and to develop targets for guiding the energy transition to net zero by 2050. Informed by modelling results, highly ambitious and demanding climate- and energy-related targets for 2030 and 2050 have been set by political agreement. These targets commit the EU to the timely delivery of GHG emission reductions for limiting global warming, while at the same time respecting EU responsibilities to maintain secure and affordable energy supplies for EU households, businesses, and industry.

EASAC's messages for policy-makers on the policies, legislation, and investments needed to deliver the politically agreed Green Deal targets are presented below for each of the main goals: GHG emission reduction, security of energy supplies, and affordability. Following the implementation of emergency measures (until 2025), two timeframes for action are identified for each goal: short term (2023–2030) and medium/long term (2030–2050).

An overview of EASAC's messages is given in Tables S1a and S1b in the Summary of this report. Many of EASAC's messages are inter-dependent, but they fall into two broad categories: 'policies' that justify special attention and 'actions' to be taken by the responsible stakeholders.

Proposals for addressing some of the policies highlighted in EASAC's messages have already been put forward by the European Commission so, in these cases, the messages relate to ongoing discussions before adoption by the European Parliament and Council of the EU, and/or to policy implementation at EU, national, and local levels.

10.2 Emergency measures

The urgent measures, which were agreed under the REPowerEU plan (EC 2022g) and implemented through cooperation agreements and negotiations for winter 2022/23, will need to be followed up to secure adequate energy supplies for households and businesses until at least spring 2024 and possibly until spring 2025. Similarly, as highlighted in the EU regulation on an emergency intervention to address high energy prices (EU 2022c), emergency measures will be needed until at least the second half of 2023, and probably for longer to keep energy affordable, especially for vulnerable groups.

1. Negotiate with a diverse group of suppliers of natural gas and liquefied natural gas (LNG) to fill gas storage annually for the next two to three winters. Support this by extending the EU Implementing Regulation for 2023 (EC 2022k).

2. Accelerate deployment of renewables (with infrastructure), heat pumps, and gas boiler replacement using policies and funding. The short-term measures discussed below must be implemented in the period until 2030, which is a short time, so preparations must be made/strengthened urgently.

3. Promote energy-saving campaigns with advice on 'no cost' measures, for example adjust thermostats, switch off systems not in use. Heating, lighting, and other equipment can easily be switched off when not in use, and 'low cost' natural-gas saving measures can be implemented quickly. The demand for natural gas falls as its price increases, but some consumers do not respond to energy price signals, so incentives may also be needed to promote switching to other energy sources. Information campaigns and local 'one-stop shops' can help to encourage behaviour change and provide independent guidance to households and businesses on low-cost energy-saving products and services with short payback periods, such as draught excluders and insulation (JRC 2021).

4. Compensate vulnerable households and businesses for high energy bills to limit energy poverty and bankruptcies. If end-user price caps are used, they should apply for only a short period until targeted measures are in place, because caps hide the price signals that drive energy and GHG emission savings.

5. Temporarily extend lifetimes of existing coal, natural gas, oil, and nuclear plants to operate in the EU Emission Trading System (ETS), but only until more renewable energy sources are built. Fossil-fuelled power and heat-generating plants may be needed to keep homes warm and maintain electricity supplies without Russian gas over the winters of 2023/24 and 2024/25, but these life extensions must be time limited. In parallel, accelerate the deployment of more renewable energy plants, so that fossil fuels, including unabated natural gas, can be phased out and EU emission reduction targets

for 2030 delivered on time. EU Member State commitments to phase out coal at the latest by 2030 must be respected.

6. Expand education and training courses, starting immediately, to build a stronger EU workforce with sustainable energy skills. It can take years to educate skilled professionals and to train the craftsmen required to make and install GHG-emission-reducing plant and equipment. Training centres and university courses should therefore be expanded, and student numbers increased urgently to meet the needs of the EU energy transition.

10.3 Short (2023–2030), medium-, and long-term (2030–2050) measures

10.3.1 Greenhouse gas emission reduction

GHG emissions must be reduced urgently if there is to be any chance of stopping global warming from overshooting the target of 1.5 °C.

Short-term GHG emission reduction (2023–2030)

1a Policy: replace unabated natural gas

1.1 Ban installation of new natural gas boilers. Advance and monitor deadlines for banning installation of new natural gas boilers in buildings and for connecting natural gas supplies to new buildings. Replacement of existing natural gas boilers by heating systems with low GHG emissions should be incentivised because boilers consume approximately 40% of the natural gas used in the EU, and lock-ins to gas, created by new boilers, can last for more than 20 years.

1.2 Accelerate EU ETS 2 to reduce GHG emissions from buildings and transport. The ETS has been shown to be one of Europe's most powerful tools for delivering GHG emission reduction.

1.3 Measure, verify, and limit methane emissions of imported natural gas and LNG, with independent monitoring and certification as required by EU regulation (EC 2021c) and Global Methane Pledge (GMP 2021). For example, oblige procurement contracts to have binding methane leakage/emission limits (e.g. below 2%).

1.4 Review Taxonomy for natural gas. Urgent investments in some natural-gas-consuming projects may be justified in response to the Russian invasion of Ukraine, and the Taxonomy's delegated act contains many caveats. However, to label the unabated use of natural gas as an environmentally sustainable transitional activity risks giving the wrong signal to investors. Moreover, the recent growth in liquefied natural gas imports increases the risks of GHG emissions, notably methane emissions from natural gas supply chains. Hence, the Taxonomy should not justify 'transitional' investments in natural gas but rather guide investors to prioritise projects in energy efficiency, low-carbon footprint fuels, or renewable energies that are unquestionably environmentally sustainable.

1.5 EU Heating and Cooling Strategy: update. The Strategy (EC 2016) must be updated to reflect the many changes that have been included in the Fit for 55 and REPowerEU packages, and to demonstrate to potential investors that there is a stable policy framework within which they can invest with confidence. Such a strategy is important because nearly 40% of EU residential buildings were heated by natural gas boilers in 2018, and gas-fired heating must be urgently replaced.

1.6 Hydrogen leaks (high GWP): measure and regulate. Hydrogen production and use must be regulated not only for safety issues but also to limit the contributions to global warming caused by small leaks to the atmosphere. There is an acute need to collect better data on leakage rates across the hydrogen value chain, because many sources of production and future uses do not exist at scale today. This is important because of the high global warming potential of hydrogen. The GWP100 of hydrogen is approximately 11, but its GWP20 is about three times higher.

1.7 Sustainable fuels: certification scheme. A scheme for certifying low-carbon footprint and renewable fuels will help the EU to establish a global leadership role in the certification of hydrogen and e-fuels produced in the EU or imported for use in marine transport and aviation. Of particular importance will be the certification and labelling of blue hydrogen, which can typically have a carbon footprint in the range 30–120 gCO_2e/kWh (compared with 10 for renewable hydrogen produced using wind-generated electricity). An ETS-based component of the certification scheme for renewable hydrogen should be prepared for use in the medium term.

1b Action: accelerate deployment of renewable energies with energy efficiency

1.8 'Energy efficiency first': promote it. For example switch to heat pumps in buildings. Investments in 'energy efficiency first' will help to reduce fossil fuel consumption in all sectors (buildings, industry, and transport) in the short term, and the demand for renewable energy in the medium and long terms. This principle can be adopted by individual citizens, who can invest, for example, in reducing GHG emissions from their dwellings and personal transport vehicles, and by industries that can reduce GHG emissions from their processes and freight transport vehicles. Even without using 100% renewable electricity, heat pumps offer more efficient heating with less GHG emissions than natural gas.

1.9 Permitting for renewable electricity generators and infrastructure: speed it up. Renewables deployment rates are limited by the time taken to obtain construction permits. Permitting procedures must therefore be accelerated for renewable electricity and renewable heat (notably wind, solar, and geothermal), and for their related infrastructure, which typically takes longer to build than renewable generators (EC 2022h). As well as streamlining permitting procedures, staffing levels should be increased in the responsible permitting and judicial authorities. Spatial plans should be regularly reviewed, and dialogue strengthened between electricity and heat network developers and other local stakeholders. Renewable electricity is key to delivering the EU's commitments to GHG emission reductions because it will be used to electrify buildings, industry, and transport, as well as to produce renewable hydrogen and e-fuels.

1.10 EU workforce: re-skill for making and installing low GHG emission technologies. More skilled workers are needed in renewables and building sectors, and for switching industrial processes from natural gas to electricity or low-carbon footprint gases. The numbers of training courses must be increased, and incentives provided for the existing workforce to upgrade their skills.

1.11 Local heat maps: show options to replace natural gas. Heat maps should show where to replace gas grids with district heating, and provide clarity to local authorities, homeowners, businesses, and suppliers. They should be made widely available as indicated in the proposed revision to the EU renewables directive (EC 2022t).

1.12 Financial guarantees and project development assistance for buildings. Market-based solutions, including financial guarantees and energy service companies, can help to mobilise investments in GHG emission reduction. Project development assistance can help cities and local/regional authorities to secure financing for clusters of sustainable energy projects involving the renovation and construction of low-emission buildings and district heating systems. Banks typically find it easier to finance one big project than lots of relatively small projects. Also, economies of scale reduce individual project costs (EC 2022j; EIB 2023).

Medium- to long-term GHG emission reduction (2030–2050)

1c Policy: long-term instruments

1.13 Emission trading: EU ETS with clear future trajectory to end by 2050. The EU ETS has already successfully demonstrated its ability to reduce GHG emissions, but as the EU approaches net-zero GHG emissions by 2050, its revenues will fall and its role must evolve. Until now, the focus has been on maximising its impacts in the run up to 2030, but work will be needed to maintain investor confidence by defining and explaining its trajectory in the run up to 2050.

1.14 Guarantees: to facilitate financing for long-term investments. Financial guarantees and recognised schemes, such as mortgages for buying or renovating houses, will be needed by households and businesses because delivering net zero by 2050 will be capital intensive. Priority must be given to financing energy-efficient investments that will deliver services with low GHG emissions.

1.15 Targeted (temporary) incentives for innovative technologies: to accelerate market uptake. Targeted, but temporary, incentives with clearly defined 'sunset clauses' may be needed to build experience with innovative technologies and to bring down their costs. EU ETS will play an important role in driving the replacement of unabated natural gas (and other fossil fuels) by renewables (wind, solar, and geothermal), and by low GHG emission energies such as fossil fuels with carbon capture and storage, and nuclear. However, targeted incentives may also be used to guide the energy transition, for example to stimulate the use of strategic technologies, such as back-up generators with low-carbon footprint gases (e.g. biomethane, hydrogen, or its derivatives), distributed battery and large-scale heat storage (hot water, solid thermal mass, or phase change materials), and sustainable biofuels for some hard-to-electrify applications. In addition, targeted incentives may be needed to maintain the competitiveness of key European industries and businesses where EU ETS (including the Carbon Border Adjustment Mechanism) is insufficient to drive investments in innovative sustainable technologies and systems: for example, in low GHG emission steel and cement production, renewable electricity generation, hydrogen electrolysers, and carbon capture and storage.

1.16 Energy market rules: update to manage competing electricity demands of integrated energy market. The EU's energy market rules must be adapted to accommodate much higher fractions of variable renewable electricity generation, and the growing roles of electricity and heat storage, electrolysers for renewable hydrogen production, and digital technologies, especially for demand response systems. They must also ensure non-discriminatory access for all appropriately sized hydrogen producers and consumers, within Member States and across national borders. Important first steps are included in the proposed framework of common rules for the internal markets in renewable and natural gases and in hydrogen (EC 2021n) and in the proposed revision to electricity market rules (EC 2023g).

1d Action: stop using unabated fossil fuels

1.17 Buildings: design/renovate to run without gas, for example on renewable electricity and/or district heating. New buildings should be designed, and existing buildings renovated to deliver nearly zero operating GHG emissions and minimised embodied GHG emissions. The use of natural gas for heating must be replaced by renewable electricity with heat pumps and/or on-site renewable (solar or geothermal) heating systems, or by renewable and energy-efficient district heating (EASAC 2021).

1.18 Industry: switch processes from natural gas to renewable electricity or hydrogen as appropriate. Industries must adapt their natural-gas-fired processes and systems to use renewable heat, and/or low-carbon footprint gases such as biomethane or renewable hydrogen or blue hydrogen (where carbon capture and storage facilities are available). Where grey hydrogen is used as a feedstock for the chemical industry, it must be replaced with green or blue hydrogen.

1.19 Road transport: switch to renewable electricity and hydrogen where needed (e.g. in long-haul trucks). Transport consumes very little natural gas, but it will become a major source of demand for renewable electricity either in electric vehicles or through electrolysers for hydrogen powered vehicles. Hence, to avoid delaying the electrification of buildings (replacing gas boilers) and of natural-gas-fired industrial processes, the future renewable electricity demand for transport must be reduced by shifting passengers from cars to buses, trains, and trams, by shifting freight from roads to trains and inland waterways, and by building infrastructure to promote walking and cycling (EASAC 2019a).

1.20 Maritime transport (long-haul shipping): stop using liquefied natural gas. Switch to low-carbon footprint fuels made using renewable electricity. Most ships are hard to electrify, so they are likely to be fuelled in future by low GHG emission fuels such as renewable ammonia, liquid renewable hydrogen, or renewable hydrogen derivatives.

1.21 Aviation: make sustainable aviation fuel (SAF) using sustainable bio-wastes or renewable electricity. The family of SAFs is likely to include sustainable biofuels, made using sustainable biomass wastes (municipal wastes, food industry wastes, agricultural and forest residues) and e-fuels (made using renewable electricity). Aeroplanes do not use natural gas and are difficult to electrify, but the production of sustainable e-fuels for aviation (using renewable hydrogen and CO_2 from the air) will create a demand for renewable electricity that will compete with the electrification of buildings (replacing gas boilers) and of natural-gas-fired industrial processes.

10.3.2 Security of energy supplies

In the short term, the focus must remain on maintaining adequate and reliable supplies of fossil fuels to keep the lights on and industries operating, but the replacement of fossil fuels with reliable supplies of renewables and fuels with low-carbon footprints, together with infrastructure and efficient energy-consuming systems for using them, must be accelerated.

Short-term security of energy supplies (2023–2030)

2a Policy: diversify supplies

2.1 Renewable energy technologies: ramp up EU manufacturing capacity for wind, solar photovoltaic and heat, heat pumps, and geothermal systems. These should be built using raw materials resourced in the EU as far as possible, and their production should lead to economies of scale. Suppliers and installers of air-source and ground-coupled heat pumps should be incentivised to optimise system sizes, minimise the need for electricity grid reinforcements, and to minimise impacts on peak electricity demands in winter when wind speeds are low.

2.2 Low GHG emission fuels: negotiate (using the EU Energy Platform) with diverse suppliers. The production of sustainable gaseous fuels, including hydrogen, biomethane, and e-fuels, must be expanded in the EU, and use locally available raw materials as far as possible. In parallel, negotiations with diverse international suppliers of low GHG emission fuels are needed, notably certified renewable and blue hydrogen for industry and transport applications.

2.3 Critical raw materials and components: negotiate with diverse suppliers. These are particularly important for the manufacture and maintenance of renewable energy technologies and systems.

2b Action: diversify and reduce demands

2.4 Buildings: reduce energy demand by renovation, digital controls. Switch from natural gas to heat pumps, renewables, or district heating. Renewable options to be encouraged include active and passive solar heating and ground-coupled heat pumps, as well as on-site photovoltaic generation and using renewable electricity from the grid (EASAC 2021).

2.5 Industry: switch from natural gas to renewables or low GHG emission fuels. Invest in energy efficiency to reduce the overall energy demand.

2.6 Transport: switch from fossil fuels to green electricity or hydrogen, SAFs, or e-fuels. The switch to renewable electricity and renewable hydrogen for transport will add to demands for renewable electricity from buildings and industry, so steps should be taken to reduce the demand for mechanised transport, and to use it efficiently (EASAC 2019a).

2.7 Ammonia-based fertiliser: reduce demand, switch to other fertiliser options. Fertilisers are made today largely using ammonia produced from atmospheric nitrogen and grey hydrogen from natural gas. They could in future be made using renewable ammonia, produced from renewable or blue instead of grey hydrogen. However, other crop fertilisation options with low-carbon footprints are also available, including bio- or insect-based fertilisers, and regenerative agricultural practices (EASAC 2022b).

2c Action: strengthen energy infrastructure

2.8 Electricity grids: urgently increase capacity. The capacities of electricity transmission and distribution grids need to be expanded urgently to accommodate the electrification of buildings and industries that currently use natural gas, as well as the electrification of transport vehicles that currently use liquid fossil fuels. The scale of the capacity increases needed will vary across the EU, depending on the geographic distribution of the renewable generators and the centres of electricity demand. Transmission grids will need to be reinforced to carry large flows of wind and solar electricity across the EU in response to changing weather conditions. Distribution grids will need to be reinforced to power electric vehicle chargers and heat pumps in buildings, as well as public charging points. Some supplies to buildings may need to be upgraded from single-phase to three-phase supplies. In addition, the resilience and cyber security of digital controls and grid management systems may need to be improved.

2.9 Temporary gas grids: build/adapt to import non-Russian natural gas and liquefied natural gas. Investments in gas grids can only be made to facilitate secure energy supplies for the short term because, after that, natural gas imports for unabated uses will be phased out. Floating regasification and storage units are a good example of temporary natural gas infrastructure investments that can be released without major lock-in effects when they are no longer needed.

2.10 Hydrogen grids: commit to develop, share risks with hydrogen market stakeholders. In line with the principles of sound financial management of public finances, public funding to support the construction or adaptation of gas networks to carry hydrogen should be awarded only to consortia involving hydrogen-consuming industries and stakeholders that are committed to developing competitive, sustainable, and strategic hydrogen markets, and to sharing the risks of creating stranded assets. Such a partnership approach should reduce the risk of premature decisions by industries to move out of EU to countries that offer financial incentives. To avoid delays caused by permitting procedures, where possible natural gas pipework should be adapted to carry hydrogen.

Medium- to long-term security of energy supplies (2030–2050)

2d Policy: expand diversity of supplies

2.11 Renewable (and blue) hydrogen: long-term contracts for EU from global markets. The EU Energy Platform should remain actively involved in supply negotiations to ensure that hydrogen-consuming industries in the EU do not become overly dependent on a small number of international or EU suppliers.

2.12 SAFs for aviation: increase imports and EU supplies. The EU Energy Platform should remain actively involved to ensure that adequate supplies are in place to meet the needs of aeroplanes flying to and from EU airports. It must also ensure that adequate storage for SAFs is built and filled for bunkering in the EU, and that the EU does not become over-dependent on storage by suppliers outside the EU.

2.13 Ammonia and hydrogen derivatives: increase imports and EU supplies. The EU Energy Platform should remain actively involved to ensure that adequate supplies are in place to meet the needs of shipping that docks at EU ports and works in inland EU waterways. It must also ensure that adequate storage for these fuels is built and filled for bunkering in the EU, and that the EU does not become over-dependent on storage by suppliers outside the EU.

2.14 Ammonia-based fertiliser: promote switch to low GHG emission fertilisation options. Mineral fertilisers will increasingly be made using renewable ammonia, produced using renewable or blue hydrogen. Alternatively, other crop fertilisation options with low-carbon footprints will be used, including bio- or insect-based fertilisers, and regenerative agricultural practices (EASAC 2022b).

2f Action: reinforce electricity infrastructure

2.15 Transmission interconnectors: upgrade. As the electrification of buildings, industry, and transport progresses, interconnectors will need to be strengthened within and between Member States to transport renewable electricity from generators (mainly wind and solar) and from nuclear generators to centres of electricity demand.

2.16 Large-scale electricity and heat storage: build more for grid flexibility management. Increased capacities of electricity and heat storage will be needed for managing hour by hour, day by day, and inter-seasonal variations in renewable electricity supplies, notably from wind and solar generators.

2g Action: reinforce fuel supply infrastructure

2.17 Gas transmission networks: adapt to carry imports of hydrogen to demand centres. Most of the existing natural gas transmission pipework could be adapted to carry 100% hydrogen, but how that might be done in practice before the use of natural gas has been completely phased out will depend on the local network and conditions at the time. New dedicated pipework and pumping systems may be the preferred option of some industries.

2.18 SAFs and ammonia: build infrastructure for transportation to centres of demand. New infrastructure will be needed for transportation of these fuels and for storing them at airports and ports.

10.3.3 Affordability

Fossil fuels must not be subsidised, even in the short term, because subsidies hide price signals for potential carbon emission reductions and energy savings. Instead, support schemes should target vulnerable groups that risk falling into energy poverty because they cannot afford the energy services that they need, and businesses that perform key roles in society but risk being bankrupted by high energy bills.

Short-term affordability 2023–2030

3a Policy: reduce energy poverty

3.1 ETS revenues: redistribute through Member State support schemes that target vulnerable groups and businesses. ETS revenues are expected to provide resources for the EU Social Climate Fund, which will be used differently in different Member States depending on the structure of their social care systems.

3.2 EU funding instruments: energy poverty reduction budget for each Member State. Each EU funding instrument, including the Recovery and Resilience Facility, Just Transition Fund, and Social Climate Fund, should contain an identified budget for each Member State to use for energy poverty reduction. Use of these funds for energy poverty reduction should be monitored.

3.3 Energy poverty reports in national energy and climate plans: EU to analyse and publish definitions, criteria, targets, and progress reported. The obligations of Member States to report on their energy poverty reduction activities in their national energy and climate plans should be subjected to a comparative analysis by the EU institutions. This should be published with details of support schemes, budgets, and numbers of vulnerable households and groups addressed, so that overall progress in reducing energy poverty across the EU can be monitored and reviewed.

3.4 Eurostat: add energy poverty data and maps to EU Statistics on Income and Living Conditions reports. This would provide a valuable input for EU and Member States policy-making and budgets.

3.5 Energy poverty maps: publish at national and local levels. In addition to EU maps to be published by Eurostat, national and local maps should be published by Member States to guide their national and regional energy poverty reduction activities.

3b Action: protect EU industries

3.6 Strategically important industries (e.g. renewable generators, heat pumps, sustainable fuels): support for growth of production in the EU. Key energy technology-producing industries must grow quickly in the EU to deliver the systems needed for the planned energy transition.

Growth of an industry is a difficult and risky process to manage, so such industries may seek support to remain based in the EU and to achieve competitiveness in EU and global markets. How to provide such support is a complex political challenge with potential state aid and international trade implications.

3.7 Energy-intensive industries: support for switching from fossil fuels. Energy-intensive industries, such as steel, cement, and chemicals, are typically very large and have plants in several countries as well as international ownership. The Carbon Border Adjustment Mechanism may help their competitiveness in the EU, but how to keep them in the EU when third countries offer subsidies or cheaper energy with a similarly developed institutional and regulatory framework (i.e. the USA) is a complex political challenge.

Medium- and long-term affordability (2030–2050)

3c Policy: support energy poverty reduction

3.8 Energy poverty reduction: prioritise in climate, energy, and social care policies. Energy poverty reduction must remain a priority for EU climate, energy, and social care policies throughout the energy transition to net zero by 2050. Relevant data on vulnerable households and groups should be collected so that progress with energy poverty reduction can be monitored.

3.9 Financial guarantees: for investments in sustainable energy projects to help vulnerable groups. Guarantees from public bodies can require less funding than grants or loans and are attractive because they reduce risks for investors.

3.10 EU funding for energy poverty reduction: regularly review needs and support options as ETS revenues fall. Regular assessments should be made of the funding needed to keep energy poverty under control, and of the available funding, as ETS revenues fall in the run up to net zero in 2050. New sources of funding must be identified before they are needed.

3d Policy: foster investor confidence and protect EU industries

3.11 EU policies and targets: minimise changes, so investors in sustainable energy projects perceive risks to be low. The costs of financing investments typically increase if they are perceived to be risky. Stable policies that are not often changed can help to give confidence to investors that markets will be stable, and that returns on investments will be delivered. Policy certainty can also lead to cost reductions as shown in recent years, for example, by solar photovoltaics.

3.12 EU ETS and Carbon Border Adjustment Mechanism: regularly monitor impacts on EU industries and adapt. As progress is achieved in reducing GHG emissions during the energy transition, the impacts of the ETS and Carbon Border Adjustment Mechanism on EU energy and related product markets will evolve. These impacts should be monitored, and the instruments adapted accordingly.

Abbreviations

bcm	Billion cubic metres (10^9 m^3)
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
CHP	Combined heat and power (cogeneration)
COP	Conference of the Parties
DME	Dimethyl ether
EASAC	European Academies’ Science Advisory Council
EC	European Commission
ETS 2	Amended Emission Trading System Directive, provisionally agreed in December 2022
ETS	Emission Trading System (EU)
EU	European Union
FRSU	Floating regasification and storage units
GHG	Greenhouse gas
GWP	Global warming potential
LNG	Liquefied natural gas
LPG	Liquid petroleum gas
NECP	National energy and climate plan
SAF	Sustainable aviation fuel
SCF	Social Climate Fund (EU)
UN	United Nations

Working Group composition and timetable

The project was approved by EASAC's council in November 2021, and EASAC's member academies nominated experts to form a Working Group in the first quarter of 2022. The work was done from spring 2022 to winter 2023, and the report was finalised in spring 2023.

Co-chairs

Anne Neumann, Norwegian University of Science and Technology, Norway

Neven Duic, University of Zagreb, Croatia

Working Group members

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William Gillett	EASAC Energy programme director	EASAC Secretariat	UK

All Working Group meetings were held by Zoom because of the COVID pandemic.

A draft working document was produced using e-mail inputs in spring 2022, and the first Working Group meeting was held as a kick-off workshop by Zoom in three sessions on the 21 and 28 March and on 4 April 2022, with invited speakers from the European Commission and other leading stakeholders. Most of the work was done by e-mail, with Working Group meetings by Zoom on 11–12 May, 28–29 June, and 17 November 2022.

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Peer reviewers

EASAC thanks the following academy-nominated experts for their peer reviews (in February 2023):

Johannes Schmidt	Austrian Academy of Sciences, Austria
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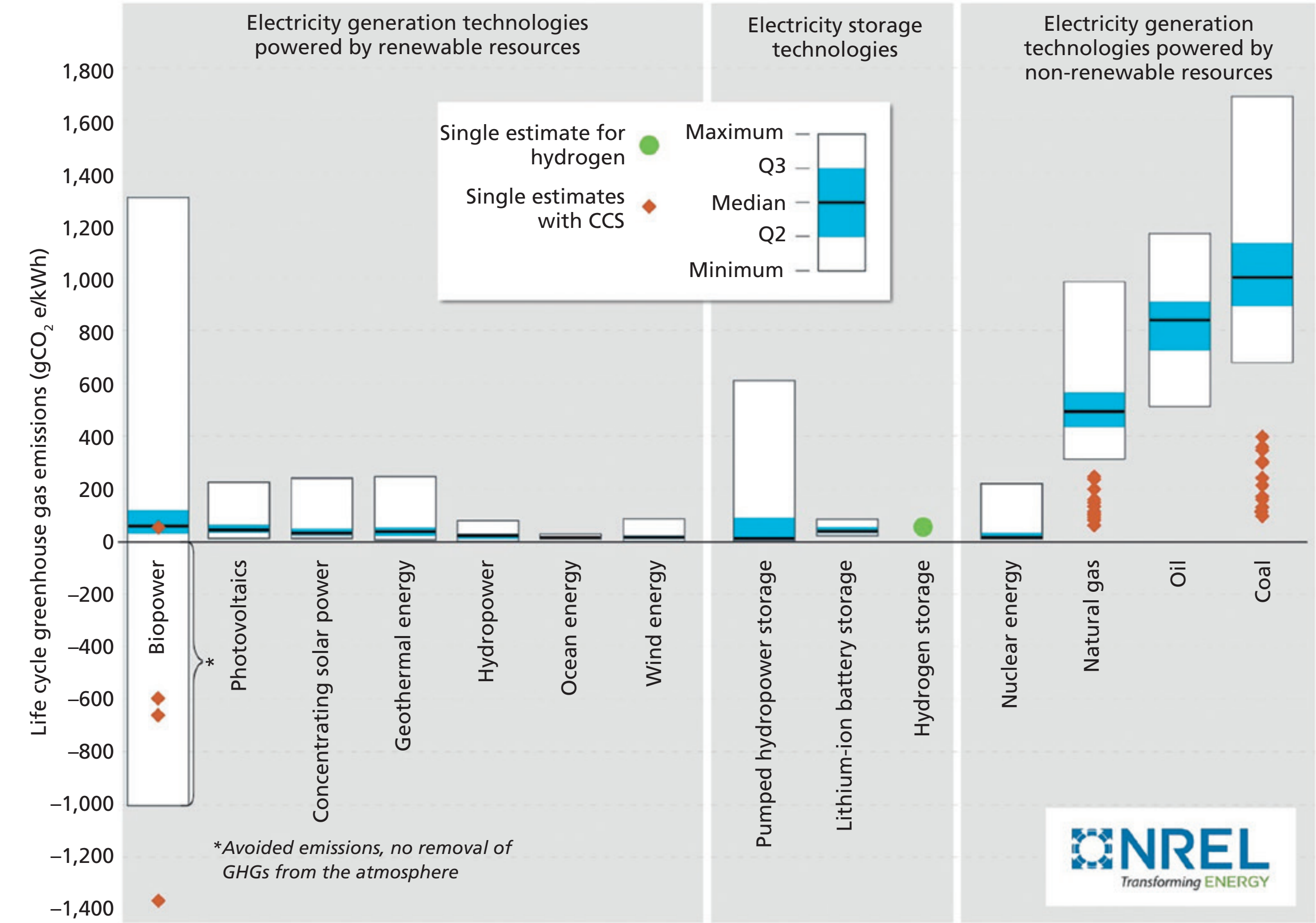
Annex 1 Life-cycle greenhouse gas emission estimates



Estimates	276 (+4)	46	36	35	149	10	186	16	29	1	99	80 (+13)	24	164 (+11)
References	57 (+2)	17	10	15	22	5	69	4	3	1	27	47 (+11)	10	53 (+9)

The number of estimates is greater than the number of references because many studies considered multiple scenarios. Numbers reported in parentheses pertain to additional references and estimates that evaluated technologies with CCS.

Annex 1 Figure Life-cycle greenhouse gas emission estimates for selected electricity generation and storage technologies, and some technologies integrated with carbon capture and storage (CCS) (NREL 2021).

Annex 2 Uncertainties that seem to justify further research

The aim of this EASAC report is primarily to focus on using the results from research, development, and innovation that has already been completed, namely 'science for policy'. It therefore does not include messages on priorities for future research, development, and innovation activities, namely 'policy for science'.

Nevertheless, it must be emphasised that continuing research, development, and innovation programmes will be crucial to the success of the EU's energy transition and to future EU competitiveness. In addition, rapidly growing programmes of near-to-market research, development, and innovation are required to remove market barriers, to reduce costs, and to improve the performance of products and systems, notably to deliver greenhouse gas emission reductions and to improve the security of EU energy supplies.

Substantial risks and uncertainties continue to exist in relation to the EU's proposed energy transition and the assumptions in the energy system models used to study it. Further independent studies of the following uncertainties would therefore seem to be justified:

- Wind and solar power generation: potential deployment rates across the EU.
- Externalities of renewables: for each of the renewable energy sources.
- Import potentials: mid- and long-term potentials for importing low-carbon footprint fuels into Europe.
- Use of flexible electricity generators for back-up: technical and economic feasibilities of keeping existing and new flexible generators (e.g. gas fuelled generators) online to provide back-up during periods of low wind speeds and no sun.
- Costs and life-cycle emissions of back-up generation: overall annual costs per megawatt-hour and life-cycle greenhouse gas emissions per megawatt-hour for different back-up power generation options (for periods with low wind and little sunshine) when the future integrated EU energy system is dominated by wind and solar power generation with electricity and heat storage, and demand response.
- Long-term energy storage: review the long-term variability of renewables (e.g. on decadal time periods) to understand how much back-up energy/fuels will need to be stored.
- Electricity grid balancing: potential deployment rates for electricity grid balancing tools, including electricity and heat storage, and digitally controlled demand response.
- Carbon capture and storage: rates at which carbon capture and storage can be deployed at scale in the EU on an economically viable basis.
- Hydrogen uses: rates at which hydrogen can replace natural gas in hard-to-electrify applications in industry and transport. This will depend on the rates of development of hydrogen-consuming technologies (e.g. combustors) as well as electrolyser deployment rates, and growth rates for blue hydrogen production and hydrogen imports.
- Hydrogen leakage along the hydrogen value chain from a global warming perspective. Measured and verified data and devices to measure low rates of hydrogen leakage are needed soon because it will be easier to address small leakages at the design stage than to fix problems after new hydrogen infrastructures and systems have been built.
- Availability of sustainable biomass resources that could be used for power or heat generation and/or for transport fuels (including sustainable aviation fuels) without increasing net carbon emissions before 2030 and 2050.
- Reductions in hydropower outputs as climate change reduces the available water resources, for example outputs in France were reported to be 25% down in the first half of 2022 compared with 2021 (Politico 2022; Corbeau *et al.* 2023).
- Climate and energy policy coherence: interplay of the many EU Green Deal-related policies.

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