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EASAC

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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), 12 (responsible consumption and production), 16 (peace, justice and strong institutions), and 17 (partnerships for the goals).

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Contents

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Foreword

Geopolitics and energy security are inextricably linked

Recent geopolitical events make it clear that our security depends on more than just defence and diplomatic strategies. It is at least as clearly linked to our energy supply. Energy is the heart of our society, the key to our welfare. Since Russia's war on Ukraine, the reduction in gas supplies in times of crisis has exposed Europe's vulnerability. Autocratic regimes use energy dependence as a means of exerting pressure. Cyber-attacks and acts of sabotage are on the rise. Pipelines, power grids, and liquefied natural gas terminals are potential targets.

These threats emphasise the need to strategically realign Europe's energy supply. Recent geopolitical developments also make it clear that Europe should strive for energy independence as much as possible. A diversified and resilient energy policy is not only an economic necessity, but a security priority. The expansion of domestic sustainable energies is crucial not only in economic and climate terms, but also to keep Europeans safe.

This report by a group of experts nominated by EASAC's member academies is intended to contribute to supporting this change with facts, analyses, and recommendations for action. It suggests that to think that energy security is about imports of gas and oil is outdated. It is wise, in the short term, to diversify fossil fuel supplies and store enough fossil fuels over the year to avoid blackouts and cold homes in the winter months. However, at the same time, Europe must transition away from fossil fuel imports and accelerate the transition to sustainable energy supplies.

Evidence shows that investing in sustainable energies increases security and is a clear no-regret option

Sustainable energy makes us less vulnerable to malicious attacks or geopolitical interventions that cause damage to energy supply chains, commerce or trade. It does not create dependencies on third countries for costly fuel imports that impact negatively on Europe's balance of payments but can be supplied using technologies that are made in Europe, thereby creating jobs and mobilising investments in Europe.

In contrast to some of the misinformation that has been circulating on (social) media in recent years, investments in sustainable energies will not increase but reduce the costs of the impacts of climate change on lives, businesses, infrastructure, and society at large. They will also reduce the costs incurred by malicious attacks on our energy systems.

EASAC's work relies on the input and contributions of Europe's leading scientists with a broad range of expertise and from many different disciplines, including the social sciences and cyber security. The report is an evidence-based contribution to support European policy-makers and stakeholders, as they work to deliver energy supplies that are secure, sustainable, and affordable during the transition from fossil fuels to net zero by 2050. It builds on earlier EASAC work on the Future of Gas, the Decarbonisation of Transport and Buildings, the EU Hydrogen Strategy, Electricity Storage, and Nuclear Waste Management.

I thank all the members of the Working Group who generously gave their time to make this project a success and to write such a comprehensive report.

Wim van Saarloos
EASAC President

Executive summary

Highlights

Europeans expect a secure energy system, with uninterrupted access to affordable energy supplies, but the energy transition and growing geopolitical volatility are introducing new security challenges. For more than 25 years, the European Union (EU) has developed policies to enhance energy security, and it must continue adapting to an evolving energy security landscape.

EU energy security is under attack

Global geopolitics has become more volatile, Russia has invaded Ukraine, war has broken out in the Middle East, gas supplies to the EU have been weaponised, undersea gas pipelines and electricity and communication cables to EU countries have been sabotaged, and the number of cyber-attacks in Europe has been growing rapidly. In response to the invasion, the EU has imposed sanctions on Russia, stopped imports of Russian oil, and substantially cut its imports of Russian pipeline gas. Russia's actions led to gas and electricity becoming more expensive in the EU, and therefore to rising costs of products manufactured in the EU, and reduced EU competitiveness in global markets. New challenges are also emerging from geopolitical developments pertaining to China and the USA.

The EU is responding by supporting its citizens and industries, and by diversifying its energy supplies

To make gas and electricity more affordable for households and industry, temporary interventions were made in EU energy markets (e.g. price caps), energy efficiency was made a key policy priority, and a platform for diversification of fuel suppliers and coordination of fuel purchasing was established. This platform contributed to a substantial increase in EU imports of liquefied natural gas, for which new floating regasification plants were quickly installed in several EU Member States. A significant part of the increased supply of liquefied natural gas to the EU still came from Russia, but a larger part came from the USA, which has introduced new energy security risks because the USA is becoming an increasingly volatile trading partner.

The transition to sustainable energies (EU Green Deal) improves EU energy security

In response to global concerns about climate change and as a signatory to the Paris Agreement in 2015, the EU adopted a Green Deal and a Climate Law to reduce its greenhouse gas emissions to net zero by 2050, and agreed to transition away from fossil fuels. Scientific evidence indicates that this transition from fossil fuels to sustainable energies, together with greater energy efficiency and reduced energy demand, will improve energy security for the following reasons.

- The transition offers new opportunities to invest in 'energy efficiency first', which will reduce energy demand, strengthen energy infrastructure, and lead to more secure, sustainable, and affordable energy supplies.
- It reduces greenhouse gas emissions and therefore reduces climate change impacts. Fewer climate change impacts benefits energy security because there will be less extreme weather, less damage to energy infrastructure and human health, and less cascading impacts on trade and finance.
- It reduces dependency on volatile supplies and prices of imported fossil fuels as these are replaced by sustainable energies, which are often available locally and can be more affordable.
- It shifts decision-making powers from large energy supplying industries to energy users, including small and medium-sized businesses, citizens, and local communities.
- It leads to more decentralised energy systems with infrastructure that is less vulnerable to damage from extreme weather and malicious attacks (but not necessarily to cyber-attacks).

Some technologies, fuels, and energy carriers play a strategic role in delivering energy security

Sustainable energy technology components and systems, notably solar photovoltaics and wind generators and batteries, have been largely imported into the EU in recent years with too little diversity of suppliers. Increasing the production of these in Europe would help to improve EU energy security and to create jobs and wealth. However, innovative approaches will be needed to reduce EU manufacturing costs so that products made in Europe can compete with imports in European markets.

Sustainable fuels and energy carriers will become increasingly important for EU energy security

As fossil fuels are phased out, the use of sustainable electricity (from hydro, wind, photovoltaics, sustainable biomass, nuclear, and to a small extent geothermal generation) will grow, along with hydrogen and sustainable fuels such as alcohols, biodiesel, biomethane, agricultural and forestry wastes, and solid, liquid, and gaseous biofuels. Some of these fuels and energy carriers will be made in the EU and some will be imported, but ensuring their sustainability will be challenging. Schemes for certifying their sustainability, such as those that are already recognised as compliant with the Renewable Energy Directive, must be recognised and effectively used both for EU products and for imports.

Sustainable heat from renewable energy sources will be more widely used

Solar, geothermal, and sustainable biomass can be securely supplied and efficiently used in cities by district heating systems together with low-temperature waste heat and heat storage. Heat mapping studies of urban areas suggest that the use of district heating could be substantially increased in many urban areas of Europe by 2050.

Critical and strategic raw materials are needed for energy security

Raw materials, metals, and rare-earth elements (including nickel, cobalt, lithium, graphite, and copper) are used in energy supply technologies and systems (e.g. wind and photovoltaic generators) and in end-use energy technologies (e.g. batteries and electric vehicles). Those that carry high supply risks are classified as critical raw materials or strategic raw materials. Many come from geopolitically volatile regions so it is wise to purchase them from diverse and trusted sources, and to build partnerships with suppliers. Actions required by EU policies for critical and strategic raw materials must be implemented by governments and industries to ensure Europe's future energy security.

Cyber protection is needed for all energy systems

Cyber-attacks are growing in number, and information technology (IT) systems are used in all stages of the electricity supply chain including transmission and distribution networks, as well as generators. Cyber-attacks or IT system failures are therefore very likely to cause disruptions (including brownouts or blackouts) in the energy system. Moreover, synchronisation signals for photovoltaic system inverters can be damaged by cyber-attacks even if photovoltaic systems are decentralised.

Cyber security legislation has been adopted but challenges remain

The EU Cyber Solidarity Act will strengthen capacities to detect, prepare for, and respond to threats and attacks, and the EU Cyber Resilience Act introduces mandatory requirements for hardware and software products, to improve transparency on their security for the benefit of business users and consumers. Nevertheless, organisations are responsible for their cybersecurity. Risk analyses are needed at operational levels where vulnerabilities emerge as well as at administrative levels.

The EU electricity system needs investments in infrastructure and in flexibility management

The EU electricity market design action plan for grids prioritises the strengthening of interconnections and more cooperation and coordination between system operators and countries on cross-border trading. The electricity market design regulation, directive, and network codes aim to incentivise the energy transition and deliver secure supplies of affordable electricity to domestic, commercial, and industrial consumers. This will require major investments in grid networks and management measures for grid flexibility, including electricity and heat storage, interconnectors, and backup generation together with demand response schemes to balance variable supplies from wind and solar generators with the changing demands of consumers. The electricity market design recognises prosumers and aggregators, who can strengthen their own energy security by producing electricity, participating in electricity markets, or joining local renewable energy communities. It also recognises contracts for difference and power purchase agreements, which can facilitate the deployment of sustainable power plants.

EU policies and legislation address most energy security threats, but implementation is crucial

Extensive work has been done to strengthen EU energy security policies and legislation but more work is needed to ensure that they are fully implemented. For example, lack of implementation of the energy security commitments, which were made following the Russian invasion of Crimea in 2014, left the EU ill-prepared for the invasion in 2022; this mistake must not be repeated.

No Security without Energy Security

Key Energy Security Threats

- Geopolitical disruption
- Increase of physical and cyberattacks
- Interruption of fuel and technology supply chains
- Volatile prices and growing energy poverty
- Escalating climate costs
- Lack of system flexibility

Old Thinking:
Import to Europe

98% 2022	98% 2022	45% 2022	45% 2024
Rare-Earth Elements (REEs)	**Crude oil and petroleum products**	**Gas from Russia**	**LNG from the USA**
Source: European Commission	Source: European Commission	Source: European Commission	Source: European LNG Tracker

New Thinking:
Invest in Europe

Put energy efficiency first with circular economy
Transition away from fossil fuels
Enhance cyber and physical security
Incentivise flexibility and market integration
Produce fuels and technologies in Europe
Prioritise decentralised systems
Empower communities with a fair transition
Diversify suppliers

More resilient systems
More value creation in Europe
Better trade balance
Fewer climate and health costs
Less energy poverty

Investments in sustainable energies are investments in Europe's energy security!

Recommendations

(Note: priorities will differ between countries.)

1 Phasing out fossil fuels and switching to sustainable energies will strengthen energy security

Priority should be given to technologies, systems, and fuels (including biofuels, hydrogen and e-fuels) that are manufactured in the EU, because this will reduce fuel import risks, create high-quality jobs in the EU, strengthen strategic autonomy, and be cheaper than adapting to climate change or repairing damage caused by climate change. Nevertheless, cheaper sources of sustainable fuels may be obtained through partnerships with suppliers in trusted third countries with high sustainable energy resources, for example in sunny and windy regions of the world, and steps may be needed to make EU-manufactured products economically competitive with imports from third countries.

2 Financing for strengthening electricity infrastructure and protection against cyber-attacks

Public and private financing are needed for investments in electricity grid infrastructure, including storage and interconnections, to minimise congestion and to facilitate the expected growth in electrification of buildings, industry, and transport. Critical energy infrastructure must be protected against cyber-attacks, extreme weather, and military or terrorist attacks.

3 Investments in implementation of energy security policies and commitments are key

The EU and its Member States should support investments in sustainable power generation and energy systems, and in reducing skills shortages to improve energy security when the market does not trigger the required investments. Energy security targets and criteria for monitoring progress would help to ensure implementation of commitments. For example, Member States should report in national energy and climate plans on progress for delivering on the criteria and benchmarks contained in the Net-Zero Industry Act and the Critical Raw Materials Act, as well as on progress with the diversification of fuel and technology suppliers.

4 Integrated energy markets will improve energy security, sustainability, and affordability

European countries should work more strongly together on energy security, sustainability, affordability, and open strategic autonomy in an integrated energy market. This could be linked with climate crisis mitigation, biodiversity protection, tackling the cost-of-living crisis, and industrial competitiveness. Closer cooperation and coordination would reduce costs, encourage investment in manufacturing sustainable energy technologies and fuels in the EU, and help with building international partnerships to strengthen sustainable fuel and technology supply chains. Methodologies for assessing the adequacy of electricity generation will continue to evolve, taking into account the whole integrated energy system, including district heating and cooling, production of sustainable fuels, backup generation, and interconnections.

5 Citizen engagement can reduce societal tensions and promote the energy transition

Consultations with citizens and local communities help to replace misinformation about the energy transition with verified information on energy security, costs of energy options, how energy markets work, and support schemes for low-income households and vulnerable groups. Well informed and active citizens who participate in energy markets, for example as prosumers, are less likely to block or delay the deployment of wind or solar farms and grid infrastructure in their areas, and can help to improve energy justice. Public authorities and project developers should engage with households and local energy communities when planning investments in networks and renewable energy systems, for example through one-stop-shop energy advisory centres.

6 'Energy efficiency first' for electrification of end uses with sustainable electricity supplies

Energy efficiency is a 'no regrets' option for investors in end-use energy systems because it reduces energy demand, which improves energy security. Switching from fossil fuels to sustainable energy supplies will involve substantial growth of electrification. It will improve energy security by avoiding fossil fuel imports and will also reduce greenhouse gas emissions and air pollution in urban areas. Nevertheless, increased dependency on electricity must be safeguarded by protecting electricity infrastructure against military, terrorist, and cyber-attacks, as well as damage by extreme weather. Distributed electricity generation by prosumers and local energy communities will reduce some of these risks and will empower local communities and citizens to improve their own energy security and reduce their electricity costs.

7 Grid flexibility management is becoming increasingly important

Grid flexibility is managed using a mix of demand response, storage, backup generation, and interconnectors. Demand response schemes with time-of-use tariffs and smart meters can reduce the required peak generating capacity, thereby reducing investment costs, and engage energy consumers in the transition. A variety of storage options are available to suit the local conditions in different European countries, including pumped hydro, batteries, storage of sustainable liquid and gaseous fuels, heat and cold storage integrated into buildings and/or district heating systems, and power to sustainable liquid or gaseous fuel production. Further research on storage can be justified: see Annex 3.

8 Backup electricity generation will be needed for the long term, notably for long dunkelflauten

The current safety-net of excess backup (dispatchable) generation may soon be decommissioned on economic grounds unless it is adequately remunerated (e.g. by capacity mechanisms). To include backup generation in electricity markets may be cheaper than to fund it separately under risk preparedness and crisis legislation. Backup is needed when supplies from wind and solar generators are low for long periods (dunkelflauten) and supplies from demand response, interconnectors, storage, and so on have been exhausted, but the impacts of climate change on the frequency and duration of future dunkelflauten are unclear. Backup generation can be provided in the short term by maintaining existing gas turbine generators on standby because they will seldom be used and will therefore produce few greenhouse gas emissions per year. For the longer term, generators using biomethane, hydrogen, or e-fuels will produce fewer greenhouse gas emissions.

9 A more circular economy will improve energy security by reducing energy demand

Recycling and reusing components and materials, together with using sustainable materials and smart system design, will typically deliver services with less energy than is currently consumed, and will therefore improve energy security. For example, sustainable materials such as timber can be used for constructing buildings instead of steel and cement (which have high levels of embodied energy and greenhouse gas emissions), and the same wood can later be used for other applications (such as transportation pallets) before being burned to produce electricity and heat. Similarly, low- and high-temperature waste heat from data centres or industrial processes can be used to supply district heating systems or for heating horticultural buildings or fish farms.

10 Diversity of suppliers and coordinated purchasing are needed for fossil and sustainable fuels

The processes that were established through the EU platform in 2022 will be needed for the foreseeable future, not only in the short term for fossil fuels, but also in the long term for enriched uranium fuels for nuclear power generation and for sustainable fuels, including hydrogen, biomethane, ammonia, biofuels, and e-fuels. A coordinated approach may also be helpful for purchasing critical and strategic raw materials and sustainable energy technologies.

11 Improved foresight of geopolitical developments would help with managing energy security

Geopolitical developments, including military conflicts and trade disputes, which might affect energy security by increasing the numbers of cyber-attacks or by restricting imports of fuels, electricity, energy technology components, or raw materials, must be regularly assessed. The outcome of each assessment, together with relevant science-based advice, should be passed to business and public service personnel who have been trained to manage energy security.

12 Much can be done with proven technologies, but further research and innovation is justified

Remaining uncertainties and topics justifying further research that could contribute to improving EU energy security are identified and briefly discussed in Annex 3.

1 Introduction

1.1 Overview

The European energy system can be made more secure by reducing the demand for energy, for example by making energy consuming systems in industry, buildings, and transport more energy efficient, by renovating the building stock, and by switching from fossil fuels to sustainable energy sources. In the energy transition to net-zero greenhouse gas (GHG) emissions by 2050, it will therefore be crucially important for policy-makers and stakeholders not only to address energy supplies, but also to reduce energy demands through energy efficiency. Energy demand can also be reduced by promoting the adoption of energy sufficiency, which involves deliberate behaviour change to reduce energy consumption, and consistency, which requires the development of new technologies with minimal environmental impact (Rudolf and Schmid 2025).

There are many definitions of sustainable energy but, for this report, the term 'sustainable energy' is used for energy that can meet the needs of the present without jeopardising the energy needs or climate of the future. Therefore, renewable energy, which is defined in the Renewable Energy Directive (EC 2024d)[1], and nuclear energy both have a role to play in a decarbonised and secure energy system.

The transition from fossil fuels to sustainable energy sources will inevitably result in a substantial increase in the amount of energy delivered by electricity. Indeed, in the European Commission's impact assessment for its 2040 targets, EU gross electricity generation and the share of electricity in final energy consumption will both more than double between 2030 and 2050 (EC 2024a). The EU's electricity market design (EMD) is complex, has been the subject of extensive discussions by policy-makers in the EU institutions in recent years, and is expected to continue to evolve for some years to come (EU 2024b). The electricity industry, transmission system operators (TSOs), and regulators continue to work on the EMD, but only those aspects of it that are strongly related to the security of sustainable energy supplies are addressed in this report. The importance of adopting an integrated approach to energy policies and markets is highlighted because integration strengthens the security of energy supplies, but more detailed analyses of electricity market operations, which may affect EU energy security, such as the evolution of single intraday coupling and the EU Target model for an integrated intraday market (ENTSO-E 2025a), lie outside the scope of this report.

1.2 Characteristics of energy security include more than the uninterrupted availability of energy services at an affordable price

Energy security began to attract interest during and after the 1970s oil crises, and became a specific focus of academic research in the 2000s. One of the most cited academic references defines energy security as 'low vulnerability of vital energy systems' (Cherp and Jewell 2014), although there are more than 50 definitions of energy security in scientific literature (Sovacool 2011) covering technical, human, and natural risk sources (Winzer 2012). This means that policy-makers should define energy security clearly in their policy and legislative documents.

The International Energy Agency (IEA) refers to energy security as 'the uninterrupted availability of energy sources at an affordable price' (IEA 2022), which has the merit of simplicity but fails to address sustainability.

The Joint Research Centre of the European Commission identifies five properties of the security of electricity supplies: operational security, flexibility, adequacy, resilience, and robustness. It also identifies four dimensions of energy security: infrastructure, source, regulation and market, and geopolitical (JRC 2016).

A simple way to grasp the meaning of energy security is to answer three questions:

1. Are uninterrupted supplies of my required form of energy available in adequate quantities?
2. Is the available form of energy sustainable?
3. Can I afford to pay for the available energy supplies?

A valuable overview of energy security was published more than a decade ago by the International Institute for Applied Systems Analysis and is still valid today: see Box 1.

This report uses the general term 'energy security' when discussing any or all forms of energy, and the 'security of sustainable energy supplies' when referring to sustainable energies.

[1] The definition in EU Directive states, 'energy from renewable sources' or 'renewable energy' means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas.

Box 1 Energy security highlights from the International Institute for Applied Systems Analysis Global Energy Assessment (Cherp *et al.* 2012)

The relationship between energy security and energy supplies has at least two aspects. One is 'supply security' which involves lowering the risk of disruption of energy services at affordable prices. Another is national security, which typically requires reliable energy supplies. Both aspects can cause significant public concerns and must therefore be given priority on national and international policy agendas. They are also closely interlinked since anxieties about security of energy supply often prompt conventional security responses (political, military, or other) which may, in turn, place additional burdens on energy systems.

Four distinct risks to energy systems can be identified: disruptions in fuel supply, disruptions in energy production, disruptions in affordability, and disruptions in resilience. Each of these dimensions relate to potential disruptions of access to energy sources, energy conversion and distribution systems, or affordability of energy services. Such disruptions may be due to natural, technical, political, and economic causes depending upon the type of energy system in question and the context in which it operates. Political risks can be perceived to be more significant than economic, natural, and technical risks.

Increasing vulnerabilities characterise not only energy sources, but also major components of energy systems. They can result from under-investment and other economic and institutional factors, which frequently lead to energy systems being operated near to their critical loads. Energy systems can also be made more vulnerable by natural factors and climate change which are especially significant for hydro energy production, and more recently also for thermal power generation.

A range of technical and political issues affect major energy systems, including nuclear, fossil, and renewables as well as the reliability of electricity grids. Challenges to energy security are shaped by strategies of exporting and importing nations, international and national energy companies, global and regional markets, and other institutions. Moreover, the responses of these actors to short-term issues do not always reduce the risks for the longer term. Experience shows that neither state-led 'energy nationalism' nor 'free' global markets nor geopolitical manipulations can guarantee global energy security.

The overall concept of energy security includes the availability of energy at an affordable price, but affordability can depend on the consumer; for example high-income households could afford a secure electricity supply for air conditioning, while low-income households in the same region could not afford the same electricity for cooking. Where time-of-use tariffs are applied, then affordability will vary over the day as the mix of generators with different generation costs responds to changes in demand. Similarly, attacks on generators or network infrastructure will typically lead to more expensive generators having to be brought online, with consequent increases in electricity prices and reductions in affordability even if secure supplies of electricity are maintained (Kovács 2024).

When considering energy security policies, two interlinked dimensions are important, the first being energy planning to ensure that secure energy services are supplied for normal operation, and the second being strategic security to ensure that supplies will be available in case of emergencies.

1.3 Historical overview: European energy security policy evolved steadily after the White paper in 2020, but has accelerated since the Russian invasion of Ukraine in 2022

Energy security, sustainability, and affordability (or equity), also known as the energy trilemma (WEC 2024a; WEC 2024b), have been the key priorities of Europe's energy policy for many years.

Since the beginning of the 20th century, Europe and other developed regions across the world have become increasingly dependent on fossil fuels to provide energy for buildings, industry (including agriculture), and transport. Initially, most European countries relied heavily on their own supplies of coal which were a relatively cheap and secure energy supply. Later, coal was complemented and then increasingly replaced by imported oil and gas, as shown in Figure 1, and more recently by the transition from fossil fuels.

The need for policy-makers to address the security of fossil fuel supplies was highlighted in 1956 by the Suez Crisis, and again in the early 1970s with the 'oil shock' (Judah *et al.* 2024), which led to the establishment of the IEA and an agreement to maintain emergency oil reserves of at least 90 days of net oil imports (IEA 2024a).

Studies of the history of energy security in Europe show that, while interest increased after the Russia–Ukraine gas disputes in 2006 and 2009, a coherent approach to energy security has been lacking since that time, and the domination of energy policy by a market logic contributed to partial unpreparedness for the 2022 energy crisis. Indeed, before 2022, geopolitical concerns were not at the top of European energy policy priorities (Kivimaa 2024; Van de Graaf *et al.* 2024).

The EU published a Green Paper on energy security in 2000 (EC 2000), which emphasised that security of supply does not imply seeking to maximise energy self-sufficiency, but it is important to reduce risks linked to dependence. It also emphasised the importance of managing energy demand, ensuring adequate diversity of energy supplies, and maintaining strategic fuel stocks for transitions including EU enlargement, the

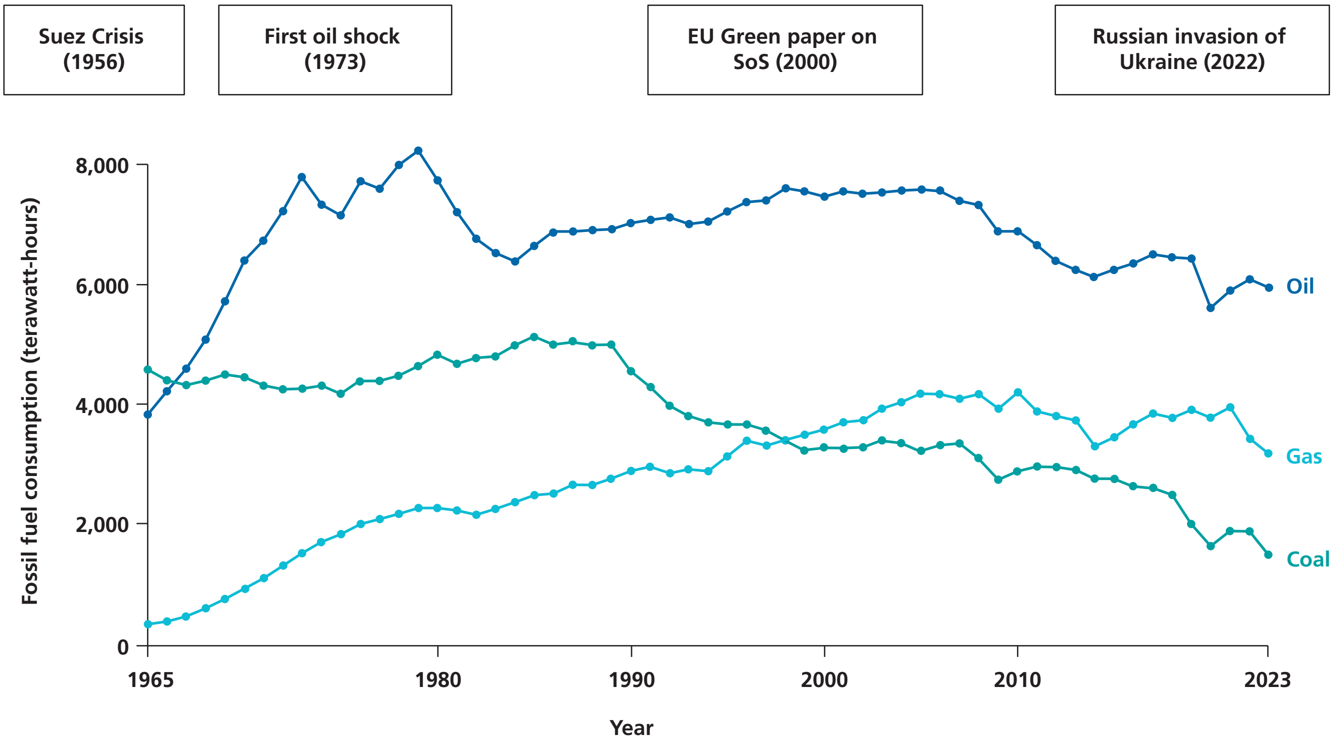

Figure 1 EU 27 fossil fuel consumption and security milestones show that energy security has been a challenge for Europe since the 1950s (Energy Institute 2024).

single energy market, and the 'struggle against climate change'.

Since the Lisbon Treaty on the Functioning of the EU entered into force in 2009 (Official Journal of the European Union 2016), EU energy policy has been legally required by Article 194 to address the security of energy supply in a spirit of solidarity between Member States. The Lisbon Treaty requires energy policy to ensure the functioning of the internal energy market, to improve the environment, and to promote energy efficiency, energy saving, the development of new and renewable forms of energy, and the interconnection of energy networks. It confirms that each Member State has the right to choose its mix of energy supplies, but Member States are interconnected, so problems in one can affect the energy security in others, and energy security policies are needed at both EU and Member State levels. As was seen during the energy shock of 2022, market forces alone are not sufficient to maintain energy security.

Between 2000 and 2020, periodic gas disputes between Russia and Ukraine affected Russian supplies of gas to the EU. Nevertheless, gas storage in the EU was treated for many years largely as a national competence, although provisions for coordination and regional utilisation of existing gas storage with cross-border access were included in the EU regulation on measures to safeguard the security of gas supply (EU 2017). Similarly, ownership unbundling was applied to gas transmission capacity (pipelines) but not to gas storage. As a result, contrary to the policy message in the EU Green Paper (EC 2000) to reduce risks linked to dependences, important gas storage sites in the Netherlands, Germany, and Austria were allowed to be owned by Gazprom, which failed to fill them during the summer of 2021, thereby sowing the seeds of the energy price shock that began in September–October that year. Gas storage capacities varied considerably between Member States, with five countries (Germany, Italy, the Netherlands, France, and Austria) holding 73% of total EU gas storage capacity, and several Member States relying on storage in neighbouring countries because they had no gas storage capacity of their own (EPRS 2022).

In response to the Russian annexation of Crimea in 2014, the European Commission published a new Strategy on Energy Security (EC 2014) in which it pledged to reduce reliance on Russian gas, but it subsequently failed to do so. Instead, European companies and Member States proceeded with agreements to build the Nord Stream 2 pipeline and with deals for further imports and transhipments of liquefied natural gas (Kivimaa and Sivonen 2024). Calls for the EU's Energy Union policy to focus more strongly on energy security were largely ignored at national level, although some eastern Member States became more strongly focused on energy security than on energy sustainability (Berg 2015; Szulecki *et al.* 2016; Münchmeyer 2023).

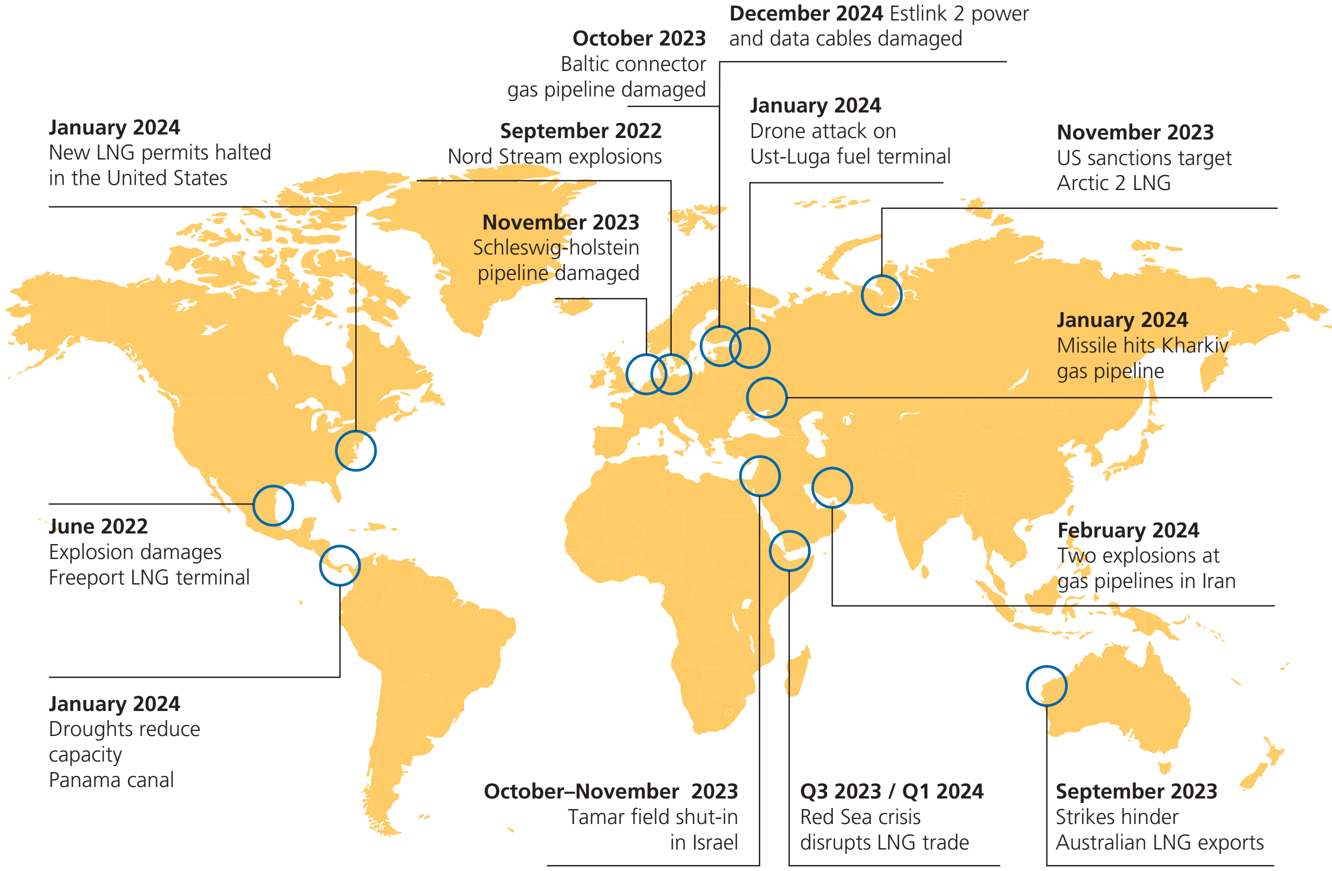

Figure 2 Examples of recent disruptions to potential EU supplies of natural gas, liquefied natural gas, and electricity (IRENA 2024a and ERR 2024).

Consequently, between 2014 and the invasion of Ukraine in 2022, the attention of most European energy policy-makers was not focused on the security of energy supplies.

1.4 Europe is responding to growing numbers of geopolitically motivated attacks on its energy systems and infrastructure

Early in 2022, when Russia invaded Ukraine and then reacted to EU sanctions by cutting most of its pipeline gas exports to Europe, the EU's energy security was quickly put under intense scrutiny. This invasion confirmed the security benefits of renewable energy and energy efficiency but demonstrated that the EU's market-based approach to the purchase of fossil fuels carried high geopolitical and energy security risks. It also highlighted what had been said by some eastern European policy-makers 7 years earlier, namely that the EU must avoid becoming too dependent on a single supplier of fossil fuels (Berg 2015).

Already in February 2022, the EU adopted two energy sanction packages which banned exports of oil refining technologies to Russia. In March 2022, the UK declared it would stop importing Russian oil and coal by the end of 2022. Soon afterwards, Russia halted gas exports to several Member States and introduced a requirement to pay in Russian currency. The EU banned Russian (seaborne) crude oil imports from December 2022, and oil product imports from February 2023 (Bruegel 2024). G7 countries and Australia also agreed to a price cap on Russian oil exports.

In addition to these geopolitical restrictions on energy imports and trade, the numbers of cyberattacks in Europe have been growing (Chapter 5), and a series of malicious attacks and incidents on energy infrastructure and on potential EU supplies of natural gas, liquefied natural gas, and electricity have taken place (Figure 2).

The malicious attacks included damaging the undersea Nord Stream 1 and 2 gas pipelines in 2022, the Baltic undersea gas interconnector and communications cables between Finland and Estonia in 2023 (EC 2023m), and the Estlink 2 power and data cables between Finland, Germany, Lithuania, and Sweden in 2024 (ERR 2024). These attacks, on which investigations are continuing, illustrate the wider risks related to energy security that accompany the growing volatility of geopolitics (IRENA 2024a). They are also having wider impacts on the EU's energy transition. For example, in November 2024 Sweden rejected applications to build 13 offshore wind farms in the Baltic Sea, owing to defence concerns

(Reuters 2024). In summary, geopolitics is being shown to affect not only energy markets and long-term energy supply contracts, but also the security of energy infrastructure and the future deployment potential of sustainable energy systems.

In the immediate aftermath of the invasion of Ukraine, EU and Member State policy-makers were obliged to urgently give a higher priority to energy security (Misik and Nosko 2023). National governments had to react quickly because they are responsible for providing national security which, in today's digitalised world, is heavily reliant on energy security and cyber security. Indeed, as stated in the European Council Versailles declaration in March 2022, '*the current situation calls for a thorough reassessment of how we ensure security of our energy supplies …*' (Consilium 2022).

Member States responded quickly to this call by making collective short-term efforts to fill the available gas storage systems, and some Member States (re-)established gas storage systems that had been lacking. They also took steps to improve energy security by encouraging energy demand reduction and the construction of new renewable energy installations (Kuzemko *et al.* 2022). For example, to facilitate reductions of Russian gas imports, the EC set a target to reduce its consumption of natural gas by 15% in 2022. The result was a reduction of 18%, but it is difficult to identify how much of this was due to high gas prices, how much to lower heating degree days than in the previous year, and how much to collaborative efforts to reduce energy demands across the EU (Eurostat 2023b). Moreover, it was not without problems, as some industries experienced job losses and the high gas prices led to increases in energy poverty. Member States also took urgent national actions to install (floating) regasification plants for importing liquefied natural gas to replace gas supplies from Russia, and to temporarily bring back into service old coal-fired power plants, which had previously been scheduled for decommissioning (Beyond Fossil Fuels 2024).

The EU and its Member States agreed that, in response to the invasion of Ukraine, sanctions should be imposed on Russia, and that these should include stopping EU imports of Russian oil. In addition, in March 2022, the EU committed to reducing its dependence on Russian gas imports by two-thirds within a year, and completely before 2030. However, this created a particular challenge for some Member States, which could not immediately reduce their Russian gas imports to zero, and as a result the EU imported record quantities of Russian liquefied natural gas in 2024 (Financial Times 2024). It also demonstrated that even when the EU agrees on common objectives, Member States have to find their own ways of delivering their contributions because all Member States are different.

Russia's action to halt some of its gas supplies to the EU led to gas and electricity prices becoming more expensive in the EU, and to products manufactured in the EU becoming less competitive in global markets. In addition, temporary interventions were needed in EU energy markets (e.g. price caps) to make the required supplies of gas and electricity more affordable for households and industry (Kuzemko *et al.* 2022; Umar *et al.* 2022).

Once the urgent steps had been taken, EU policy-makers reviewed their energy policy priorities and produced a longer-term response with the aim to deliver secure, sustainable, and affordable energy supplies in the face of the Russian aggression (European Council 2024). This response included more ambitious actions within the EU Green Deal, and funding for a new initiative called the REPowerEU plan (EC 2024k), which maintained EU policy priorities of security, sustainability, and affordability.

The REPowerEU initiative aimed to strengthen policy priorities.

- *Energy security* by establishing a new Energy Purchasing Platform for collaboration across EU borders to purchase energy in global markets (EC 2023d). The aim was not only to secure new gas supply contracts at competitive prices, but also to reduce price volatility within the EU's long-term gas supply contracts, which were largely tied to spot market prices and led to immediate price spikes in Europe following the invasion of Ukraine. In contrast, gas was purchased by most Asian countries based largely on long-term market rates, so their prices were affected less but the supply to some Asian countries such as Bangladesh was also affected as gas supplies were diverted to Europe, which paid higher prices (Kuzemko *et al*. 2022). Nevertheless, following the short-term price spikes in Europe, the gas market worked as expected. Within a few months, prices were smoothed out and the markets for natural gas and liquefied natural gas stabilised (IEA 2024b).

- *Sustainability* by adopting more ambitious targets for renewable energy and energy efficiency, and a more demanding regulatory framework to deliver the EU Climate Law's net zero by 2050.

- *Affordability* by launching investment funds for energy infrastructure, and a Social Climate Fund (EU 2023d) to help vulnerable groups and businesses to pay for the energy they need.

In addition, a Net-Zero Industries Regulation was adopted to support strategically important EU industries (EU 2024f) and to encourage them to remain in the

EU despite initiatives by some third countries to attract them to emigrate, notably the US Inflation Reduction Act (US Government 2022).

At the same time, the EU took steps to encourage more manufacturing of sustainable energy technologies in the EU, and to facilitate the smaller but nevertheless geopolitically influenced EU trade in critical raw materials and in sustainable energy technologies and fuels (EU 2024f). For example, implementation of the Carbon Border Adjustment Mechanism was accelerated. This had been announced in 2019 as part of the Green Deal, to discourage imports of unsustainably manufactured products for sale at prices below those of EU manufacturers (EC 2024o; EC 2022c).

Other energy security-related regulatory steps taken in 2022 included the adoption of a Resilience of Critical Entities Directive (EC 2022a), and updated EU electricity market design, following extensive discussions (EU 2024b).

In addition, an increased focus on open strategic autonomy has meant that production and recycling in the EU of energy and energy-related technologies, systems, components and materials are increasingly encouraged (Miró 2022). Sustainable energy supply must be aligned with the pursuit of open strategic autonomy, for instance, by identifying '*critical sectors, key technologies, needed capabilities, and favourable international relations*', and advancing '*resource and energy demand reduction*' that benefit both sustainability and strategic autonomy (Kivimaa and Rogge 2024).

However, with new suppliers of liquefied natural gas, there is a risk of complacency and too little attention being given to the security of fossil fuel supplies over the next few years while they are still needed. The EU should guard against establishing new dependencies, for example with the USA, which could put the security of its energy supplies at risk.

1.5 Tackling climate change by reducing GHG emissions is improving Europe's energy security

Since 1995, the climate crisis has been discussed by governments and experts from across the world at 29 Conferences of the Parties (COP) to the United Nations Framework Convention on Climate Change. In 2015 at COP 21 in Paris, it was universally agreed that global warming must be addressed by urgent reductions in GHG emissions. This goal was embodied in the Paris Agreement (UNFCCC 2015) to keep the global temperature rise well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature rise even further to 1.5 °C.

The targets agreed under the Paris Agreement later became an integral component of the European Green Deal that was launched in 2019 (EC 2024o), and they underpinned the EU Climate Law that was adopted in 2021 (EU 2021) with a commitment to deliver net-zero GHG emissions by 2050. The Green Deal focused not only on reducing GHG emissions by reducing the use of fossil fuels but also on contributing to 'net-zero' emissions by investing in the development of carbon capture and storage (CCS), carbon capture and utilisation (CCU), and/or carbon sequestration by removing carbon from the atmosphere with negative emission technologies in line with the EU Certification Framework for permanent carbon removals, carbon farming, and carbon storage in products (EU 2025b) and storing it (IPCC 2023).

The Green Deal was reported to have distracted attention from energy security issues (Van de Graaf 2023), and it served as a major driver of the EU strategic agenda from 2019 to 2024 (European Council 2019). Nevertheless, the advancements in renewable energy production and energy efficiency since the 2000s, which were further promoted by the European Green Deal, helped some Member States to better manage the gas shortage during the 2022 energy crisis (EEA 2024a).

Climate change is already starting to make parts of the world uninhabitable and thereby driving migration out of those areas and into habitable countries, such as those in Europe. However, it is unclear how migration into Europe will affect its future energy security, so migration policy is outside the scope of this report.

1.6 A strong legislative framework for European energy security is emerging, but financing and commercialisation of innovations are needed for its implementation

The pushing back of national plans for decarbonisation, which were a justified emergency response to the Russian invasion in 2022, cannot be allowed to continue because global temperature rise is accelerating. Also, provided adequate investments are made in electricity grids and flexibility management measures, including storage, interconnectors, black-start-capable distributed generation, and dispatchable backup generation, European energy security will be stronger when fossil fuel imports have been replaced by sustainable energy sources. This is partly because the more distributed structures of renewable energy systems are less vulnerable to malicious attacks than conventional thermal power generating systems, and partly because renewable energy supplies cannot be disrupted like fossil fuel imports. Yet, the impact of large wind farms on military defence systems has been noted as a specific issue (Auld *et al.* 2014; Kivimaa 2024).

Some European countries with indigenous fossil fuels do not have problems with fuel imports and may therefore choose to invest in CCS or CCU to reduce their carbon emissions. However, this will not reduce the potential for malicious attacks on their energy systems. Unfortunately, no forms of energy supply can be expected to resist all kinds of attack.

The rapidly growing frequency and intensity of extreme weather conditions caused by climate change is leading to floods, drought, fires (EASAC 2023b), and very expensive storm damage. At the same time, malicious attacks as well as climate change impacts are having cascading impacts on Europe's trade, finance, and international relations (Carter *et al.* 2021; Copernicus 2023). A holistic legislative framework that includes crisis response for energy security and creates a supportive backdrop for investments in climate change mitigation and adaptation is therefore required.

Such a legislative framework is already emerging. Regulations and directives have been adopted to address many of the issues that affect energy security, and Member States are required by the EU Energy Governance Regulation (EU 2018) to regularly update their national energy and climate plans, which must address energy security, sustainability, and affordability, and include geopolitical considerations.

Nevertheless, more must be done to develop robust strategies for European industries, including financing and commercialisation of innovations to make Europe more secure and more competitive in global markets, while maintaining the democratic and fundamental priorities of European society and improving the quality of life for all European citizens (Draghi 2024).

1.7 The body of this report contains evidence to support EASAC's conclusions and recommendations for policy-makers

This report reviews the most important energy security risks for Europe and, on the basis of the available scientific evidence, provides independent advice for policy-makers on how these can be addressed. It refers, where appropriate, to some areas of ongoing research, but the focus is on utilising proven policies, systems, and technologies with high technology readiness levels alongside improved foresight activities.

This report begins with a discussion of the energy transition, including what more can be done to improve energy security by reducing energy demands and increasing the sustainability of energy supplies (Chapter 2). This is followed by a review of strategic sustainable energy technologies and fuels (Chapter 3), and of the challenges posed for energy security by the needs for critical raw materials (Chapter 4). Cybersecurity and the growing numbers of cyber-attacks that appear to be driven by geopolitics are discussed in Chapter 5, and aspects of the European electricity system and market design that are strongly related to energy security are discussed in Chapter 6. Against this background, the most important energy security risks for Europe, and how these can be addressed are discussed in Chapter 7, and conclusions are presented in Chapter 8.

Background information on EU energy demands and supplies is presented in Annexes 1 and 2, and a shortlist of uncertainties that have been identified by EASAC during its work on this report and could justify further research is given in Annex 3.

2 The energy transition

How will switching from fossil fuels to sustainable energies affect energy security?

2.1 The transition is being tackled differently in each European country

This chapter addresses the implications for energy security of Europe's commitment to a fair transition from fossil fuels to sustainable energies with the goal of delivering net-zero GHG emissions by 2050 (EU 2021, EP 2023). This commitment will bring energy security benefits to the EU but also risks and costs that must be minimised. It has been agreed at the political level, but the fact that the energy transition will require investment in the short term to reap benefits in the medium to long term, including massive savings from avoiding damage caused by climate change, may not have been adequately explained by policy-makers to their electorates.

The transition will be tackled differently by each European country because they have very different mixes of energy supplies, different energy demands, and different sustainable energy resources. Nevertheless, all EU countries are required by the EU Governance Regulation (EU 2018) to report regularly in their national energy and climate plans on their progress with the energy transition (decarbonisation) and energy security (EC 2023f).

The energy transition will require decarbonisation of buildings, transport, and industry, and much of this will be done through electrification, so a vast increase in the use of electricity is expected. For example, the European Commission's impact assessment for its 2040 energy targets includes scenarios in which electricity supplies will be doubled over the period from 2021 to 2050 (EC 2024a). A strong focus on strengthening electricity infrastructure and on managing electricity supplies will therefore be crucial to EU energy security in the future.

Since the Russian invasion of Ukraine in 2022, the transition plans of European countries have been adjusted to reflect the increased challenge of ensuring secure supplies of energy to their industries and citizens. In the short term, this has resulted in delays to the phasing out of coal in some countries, rapidly made contractual arrangements with new suppliers of gas, increases in liquefied natural gas supplies from Russia, and the establishment of more facilities for importing liquefied natural gas. For example, Austria placed a coal plant into reserve in 2022 delaying its coal phase out until 2023, France delayed coal phase out from 2022 to 2023 and then later until 2027, and Greece reverted to its earlier plan to phase out coal in 2028 (Beyond Fossil Fuels 2024).

Increased concerns about national security and the security of energy supplies since the invasion of Ukraine have led some European countries to make longer-term changes to their energy policies, with a view to improving energy security (EC 2024v). Examples of steps being taken by European countries to improve their energy security by increasing the self-sufficiency of their energy supplies and reducing their dependence on imported fuels from third countries include the following.

1. Increased investments in offshore renewable energies by five EU countries and their North European neighbours (Ostend Declaration) in May 2022 (Belgium.be 2023).

2. Strong cooperation on key energy research and innovation topics, including renewable energy technologies, batteries, CCS, small modular nuclear reactors, digitalisation of energy systems, and energy efficient end-use technologies (SETIS 2024).

3. Exploring options for expanding the use of nuclear energy. For example, this was foreseen by members of the European Nuclear Alliance: Bulgaria, Croatia, Czechia, Finland, France, Hungary, the Netherlands, Poland, Romania, Slovakia, Slovenia, Sweden (Elysee 2024), and Switzerland (Maihold 2024).

While each EU Member State retains the right through Article 194 and Article 192 of the Lisbon Treaty (Official Journal of the European Union 2016) to decide on its own mix of energy supplies, the benefits of working together for the security of the EU's overall energy supplies were demonstrated in 2022 by the EU's coordinated response to the invasion of Ukraine. Looking to the future, the single energy market across the whole of the EU could offer a unique framework for future cooperation on the security of energy supplies.

2.2 The EU is committed to a 'fair' energy transition with reduced energy poverty

Even though the EU is succeeding in delivering secure supplies of energy to its citizens and industries, the days of living on low-cost fossil fuels have passed. Fossil fuel prices have risen for geopolitical reasons, and major investments are being made in renewable energies and in energy infrastructure, all of which are contributing to higher energy prices than before the war in Ukraine, and a worsening energy poverty challenge.

The European Union reported that, in 2022, 9% of EU citizens (2.2% higher than in 2021) were unable

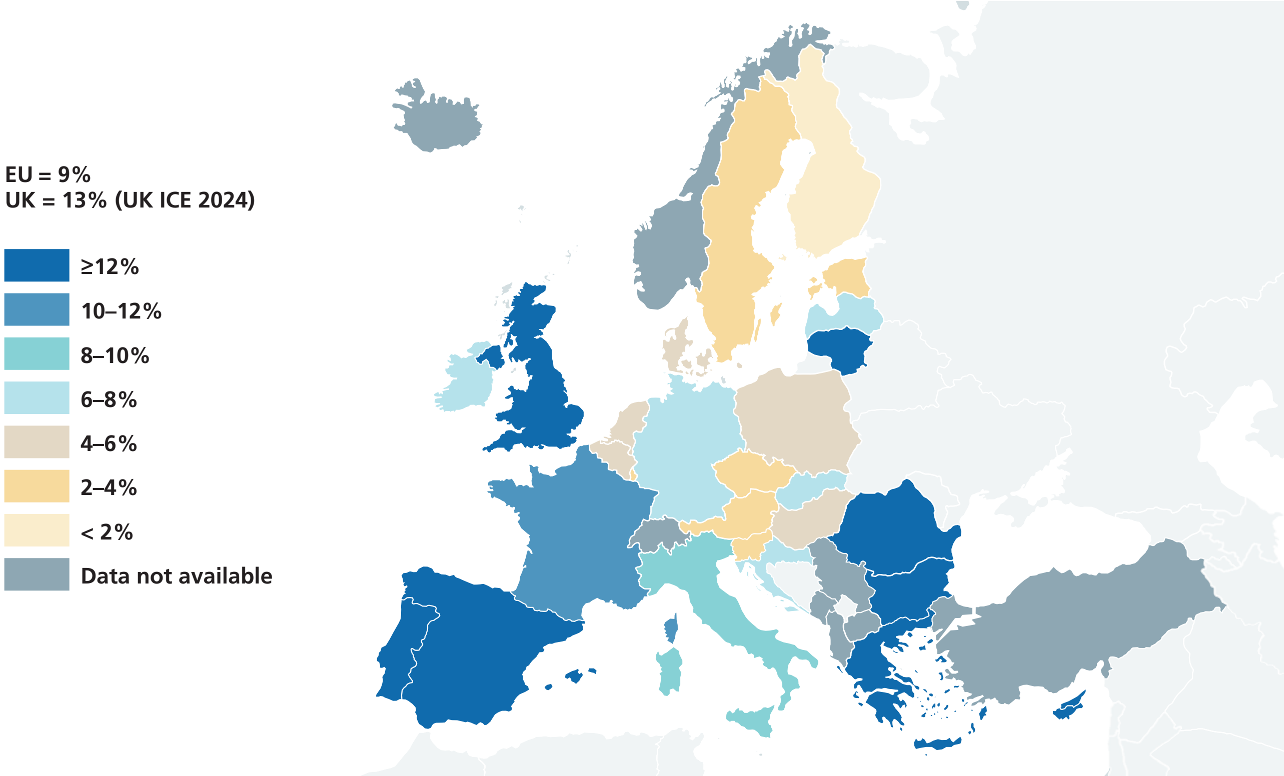

Figure 3 Levels of energy poverty in EU Member States. On average, 9% of the EU population were unable to keep their homes adequately warm in 2020 (Eurostat 2024c); in comparison, the figure for the UK was 13% (UK ICE 2024).

to keep their homes adequately warm and were living in energy poverty. As shown in Figure 3, the levels of energy poverty varied between Member States (Eurostat 2024c). However, these data should be used with caution because the definition of energy poverty, given in the Energy Efficiency Directive (EU 2023c), leaves the door open for Member State interpretation, and the data on keeping homes warm came from surveys that involved subjective interpretation of the question 'can your household afford to keep its home adequately warm?'. The UK was not included in the Eurostat data but is reported to have reduced its level from 22% in 2010 to 13% since 2019 (Hunsaker 2024) and is used below as an example because of the significant energy and transport poverty in the country. Transport poverty, the inability to afford adequate mobility services, is also a growing problem, particularly for low-income and vulnerable groups, so support for these groups is needed to prevent future actions to decarbonise energy systems from worsening rates of energy and transport poverty (Alonso-Epelde *et al.* 2023; Sovacool *et al.* 2023).

To illustrate the day-to-day impacts of the cost-of-living crisis in Europe, it has been reported that it is causing families in UK to visit fast-food restaurants for warmth and hot water, and to wash in their kitchen sinks because they cannot afford a hot shower. Parents are skipping meals to feed their children, pensioners are travelling on a bus all day to avoid a cold home, and people with disabilities are forgoing vital equipment if it costs too much to run it (Sovacool *et al.* 2023). Transport poverty can limit access to employment, education, school, healthcare and leisure, force reliance on expensive cars, decrease well-being, and increase exposure to negative externalities such as transport pollution. As shown in Figure 4, the overlapping nexus of transport and energy poverty can affect minority groups, low-income households, and children, among others (Lowans *et al.* 2021).

The EU and its Member State governments have a responsibility to legislate for the secure delivery of affordable energy to EU citizens and businesses, and to ensure that GHG emissions from the energy sector are reduced to net zero by 2050. In other words, the EU and its Member States are responsible for maintaining energy security, including its affordability dimension as explained in Section 1.2.

One of the tools for managing the upfront costs of the transition to net-zero emissions by 2050 is the EU Emission Trading System (ETS), which already covers thermal power generation and energy-intensive industries and will be expanded in the coming years to cover other fossil fuels for heating and transport (EU 2023b; EC 2024t).

The ETS is designed to minimise the costs of reducing GHG emission reductions. It sets an annually reducing

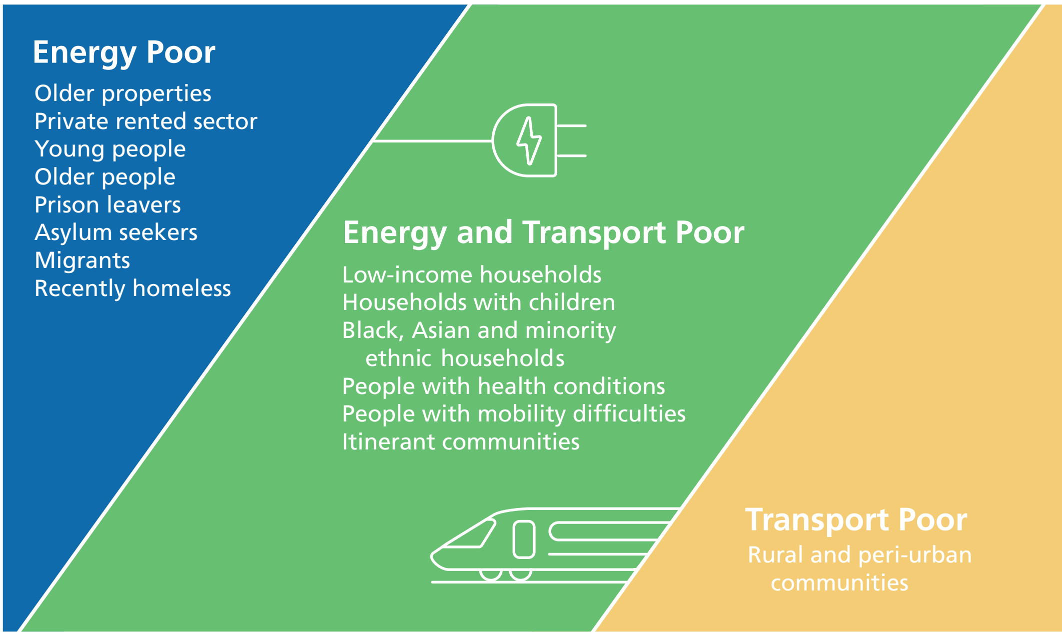

Figure 4 Many different demographic groups were vulnerable to energy and/or transport poverty in the UK in 2021 (Lowans et al. 2021).

cap on emissions, which limits the emissions and allows the market to determine the carbon price (EASAC 2023a). The volatility of global fuel prices, the complexity of the energy market, allocations of free ETS allowances, the trading of ETS allowances, and the market stability reserve all influence how the costs of reducing GHG emissions are passed on to final energy consumers (Cornago 2022).

Another approach for limiting emissions is a carbon tax, which has been used successfully in Sweden since 1991 and sets a price on carbon but leaves open the amount of emissions that are economically possible (EASAC 2023a). A proposal to update the EU Energy Taxation Directive from 2003 and bring it into line with the Fit for 55 package was proposed in 2021. However, to achieve EU-wide agreement on taxation issues is always challenging because it requires unanimity in the European Council, and on this proposal the European Parliament reported at the end of 2024 that '*additional work remains required to reach a unanimous agreement*' (EP 2025).

Renewable electricity generation is in many cases already cheaper than that from fossil fuels when assessed over the long term. However, the low costs of today's renewable energy systems rely heavily on imports of systems and components from China, where production costs have benefitted from very large economies of scale. A fair transition in which more renewable energy systems are manufactured in Europe will therefore need to focus strongly on achieving similarly low production costs. In addition, variable renewable energy sources, notably wind and solar, require flexibility (integration) measures such as storage and backup generation capacity, which increase the overall system costs, so these costs must also be minimised.

Many sustainable end-use energy technologies require high capital investments which may be unaffordable for low-income and vulnerable groups (IEA 2024c). Although some energy savings can be achieved by changing behaviours and habits, these groups cannot invest in energy efficiency and energy saving measures to reduce their overall energy costs without direct subsidies, tax credits, or free advisory services. Support for vulnerable groups therefore forms an integral part of the EU's energy transition strategy (EC 2024r), so that the Member States can deliver a just transition in which no one is left behind and progress is made towards the UN Sustainable Development Goals (UN 2024b).

The need for a just transition is widely accepted, but the Member States have different economies, and they define and manage their support for vulnerable groups in different ways. It is therefore difficult for the EU to put in place a single definition for vulnerable groups or a single approach for supporting them (Crespy and Munta 2023). The EU set up an energy poverty observatory in 2016, and its work was later taken over by a new EU initiative called the Energy Poverty Advisory Hub (EC 2024g), which aims to work with local governments to tackle energy poverty. A definition of energy poverty was included in the recast Energy Efficiency Directive (EU 2023c) and a shorter definition was given in the Social Climate Fund Regulation (EU 2023d), but these are quite generic definitions and leave the door open for national interpretations by Member States. Similarly, Member States are left free to define their own vulnerable groups at a national level and to provide support for reducing energy poverty in ways that fit with their other national schemes for welfare and social protection.

While schemes to subsidise energy efficiency investments and sustainable energy services for vulnerable groups and households are implemented at Member State level, EU funding for this will in future also come from ETS2 revenues (EC 2024t), which will be distributed through the EU's Social Climate Fund (EC 2023i; EU 2023d). Unfortunately, until now many support schemes for promoting energy efficiency and renewable energy have largely benefitted households with higher incomes and have contributed to raising inequalities in society. It is therefore important for future funding schemes to be more strongly focused on low-income households and vulnerable groups and on delivering a just transition (Lekavičius *et al.* 2020). ETS revenues will fall as decarbonisation progresses towards net zero in 2050 so, although much of the upfront costs should have been covered, other sources of funding may still be needed in the future to support some vulnerable groups (EASAC 2023a).

Most ETS revenues are currently distributed through the Innovation and Modernisation Funds. Such funding is needed for decarbonising energy-intensive industries and to support strategic industries that produce technologies and systems for delivering secure supplies of sustainable energy. These industries need support to keep their employees working in the EU and to avoid outsourcing with carbon leakage to third countries that have less ambitious decarbonisation goals, in line with the Net-Zero Industry Regulation (EU 2024f).

The EU has focused its 'just' energy transition on citizens and groups within the EU but, in contrast, global justice emphasises '*the non-discrimination of all people, their equal rights, and their equal responsibilities for the well-being of others*' (Kivimaa *et al*. 2023), and a global perspective forms a key part of the climate and energy policy efforts required by the Paris Agreement. A more global approach to a fair transition would consider, for example, the environmental and social impacts of mining uranium and critical raw materials that are imported to the EU, hazardous waste streams exported by the EU, poor labour conditions related to the manufacture of products used in the EU, and the risks of energy-related accidents in neighbouring countries (Sovacool *et al*. 2019). Fuel imports by the EU, including for example liquefied natural gas and biofuels, can increase energy prices in the countries that supply them and therefore create energy poverty.

In summary, the energy transition offers opportunities to improve European energy security, but actions are required to ensure that it is implemented in 'fair' ways, both within the EU and in neighbouring and partner countries that supply fuels, raw materials, products, and services.

2.3 Engagement with citizens and local communities improves energy security by mobilising support for the energy transition

From an energy security perspective, the EU's response to the invasion of Ukraine was successful in the short term. Lights and heating stayed on in most buildings, EU industries continued working, and motorised vehicles continued to move on roads and rails, on the seas, and in the air (Kuzemko *et al.* 2022; EC 2024k). Nevertheless, despite EU initiatives and market interventions, EU energy costs increased substantially, which increased the costs of food, goods, and services for EU citizens, and reduced the international competitiveness of EU industries. Unsurprisingly, there was a negative public reaction to the energy price rises which led to marches and demonstrations in EU capitals.

Given the growing frequency, severity, and public awareness of social mobilisation and community action on energy and climate issues, researchers have examined more than 90 case studies of opposition to energy infrastructure in Europe in the decade from 2010 to 2020. As can be seen in Figure 5, these case studies included renewable energy, nuclear energy, and fossil fuel infrastructures in multiple regions of Europe (in Norway, Poland, Greece, Germany, and Estonia). The work confirmed that the goals of energy policy on decarbonisation, which depend on the deployment of renewable and nuclear energy technologies, have led to social opposition across the European continent, but it also showed that the outcomes depended on the context and the responses and policies of the leading institutional actors in the countries concerned (Sovacool *et al.* 2022).

In contrast, studies have also analysed the willingness of citizens and households to support and adopt the deployment of renewable energy systems, to accept higher energy prices to pay for measures needed to deliver energy security, and to tackle climate change. This work shows that citizens are more likely to accept and support the deployment of renewable energy if they are satisfied with their lives, whereas their own adoption of sustainable energy solutions is primarily influenced by national environmental and energy policies (Spandagos *et al.* 2022).

Hence, it is important that policy-makers strengthen democratic engagement with citizens to ensure that they understand the transition and how they can benefit from it. In particular, it should be explained that the transition to sustainable energy supplies offers the potential to reduce dependence on imported fossil fuels,

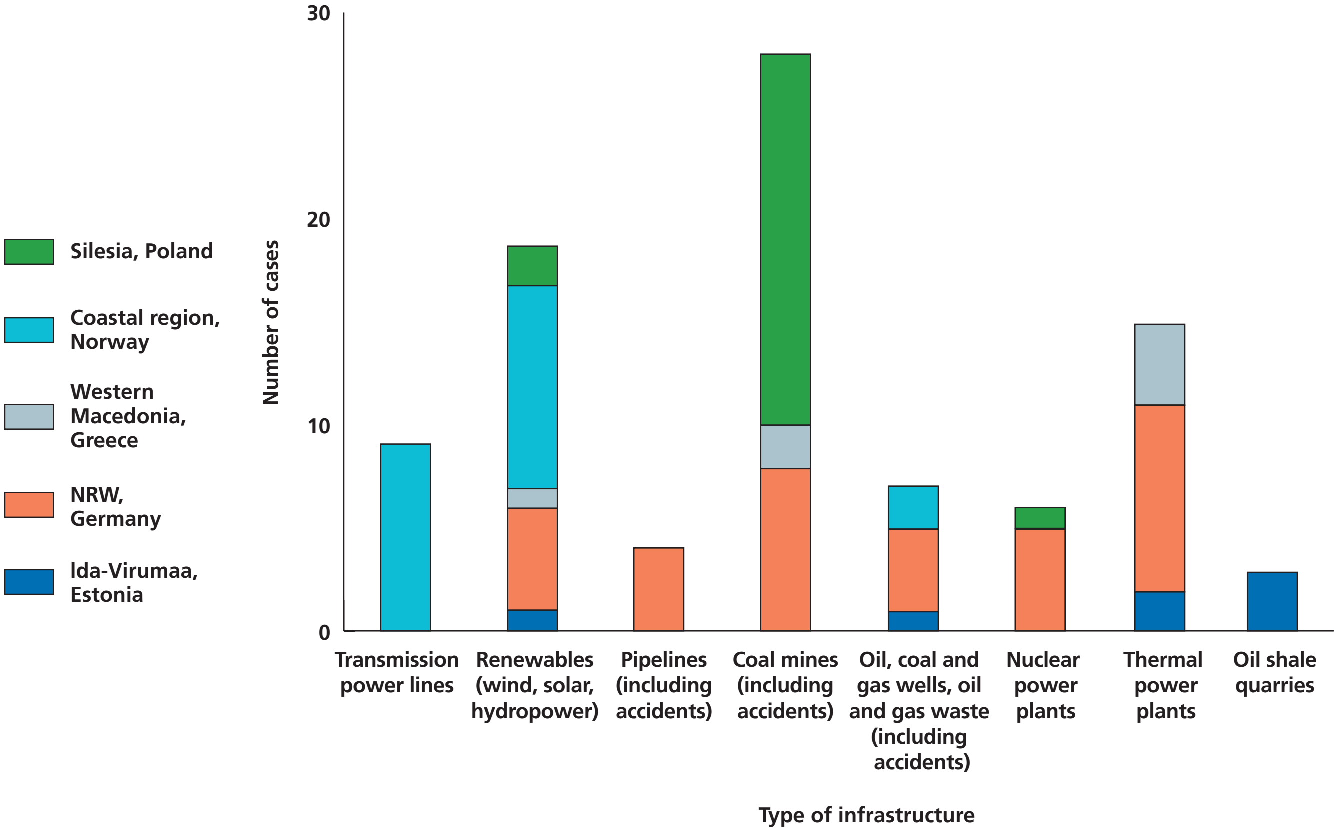

Figure 5 Case studies from across Europe of opposition and community mobilisation against fossil, nuclear, or renewable energy infrastructure were studied by Sovacool et al. (2022).

thereby increasing energy security and reducing global warming. This will help to minimise societal opposition to the systems and infrastructure needed to deliver the transition.

The importance of engaging with renewable energy communities was highlighted and reinforced in the updated Renewable Energy Directive in 2018 and has been strengthened in subsequent revisions of the directive (EC 2024d). A range of tools is available for enhancing citizen engagement, and examples of those that can be used to encourage the participation of communities and individual citizens in decision making are presented in Table 1. Building on citizen engagement work, which has been done in the EU over many years, by European cities, the Covenant of Mayors, renewable energy cooperatives, and others, a Renewable Energy Communities Facility was established in 2024 with EU funding to support such activities (EC 2023n). Other helpful options include online inventories of coping strategies, citizen assemblies, energy biographies, and community or citizen science data collection. In addition, research institutes, universities, local or state planning offices, and community groups can collaborate with trusted government stakeholders to collect and share data related to community concerns and how to resolve them.

To maximise the chances of success, those involved in engaging citizens, communities, business, and industry in the implementation of the energy transition should focus their messages on its benefits (IEA 2019b). Key benefits of the transition include reduced dependency on imported fossil fuels, a shift of decision-making powers from large energy industries to citizens and local communities, and opportunities to invest in energy security, sustainability, and affordability, as well as in potential synergies between them.

2.4 To ensure that energy supplies are secure, their adequacy and flexibility are assessed using energy system modelling

An important role in the assessment of EU energy policies is played by the European Commission, which is responsible for analysing Member State national climate and energy plans, and for working with Member State governments, the European Agency for the Cooperation of Energy Regulators (ACER), and the responsible national organisations to ensure that EU energy supplies are secure, and that EU energy and climate targets are met.

Energy system modelling of different scenarios is used to guide energy policy-making by assessing the adequacy and flexibility of electricity systems. Such

Table 1 Examples of tools for enhancing citizen engagement and participation in the energy transition (based on work of the EFI foundation (EFI 2024), adapted by EASAC)

Tool	Description
Citizen panel	A group of people who represent all the different kinds of people in each community are chosen to discuss an issue and make recommendations on how to proceed
Public hearing	A formal, in-person meeting to record questions from members of the public or give people a set time to speak to voice their opinions
Document co-creation	A process for hub groups and community members to make binding agreements about the benefits that hub groups will provide to the communities
Open house	Often include information or education about a project, where the public can go around and ask questions (such as at a science fair)
Scenario testing	A group of community members identifies a few different hypothetical ways the project could go, including the types of benefit they could get out of it
Community mapping	Community members help hub groups to create a map of the resources and assets that exist in their area
Working group	A group of community leaders and relevant stakeholders who get together regularly to discuss the project
Town hall meeting	More of an open discussion than a formal public hearing
Virtual workshop	Can combine aspects of the above methods (open houses, town hall meetings) but takes place online
Digital story telling	Community members bring their stories to life by creating movies, photographs, and other media

assessments for the EU are managed by the European Commission working with ACER, the transmission system operators (TSOs) (including ENTSO-E and ENTSOG), and independent research institutes and organisations across the EU (Box 2). Energy system modelling is also used for impact assessments of EU energy sector goals and targets, such as the 2040 targets that were set in 2024 (EC 2024a).

Given the substantial differences between the energy economies of the 27 Member States, and the evolving geopolitical context in which the energy transition is taking place, it is important to model a range of possible energy transition scenarios.

A good example of a multiple scenario approach is shown in Figure 6, in which scenarios S1, S2, S3, and LIFE were used for the impact assessment of the EU 2040 targets. These scenarios, which are discussed in detail in the impact assessment report (EC 2024a), include marked reductions in the use of oil and gas together with substantial increases in the use of solar photovoltaics and wind. The gross available energy demand is reduced partly by the switch from fossil fuels to renewables, which avoids fossil fuel combustion and energy system losses, and partly by other energy efficiency improvements.

Energy system models have provided valuable energy scenario assessments to policy-makers for many years (EEA 2021), but models evolve and their use must be adapted to address future energy systems as these deploy more flexibility measures and become smarter. The next steps in the EU's transition to net zero in many Member States will involve phasing out the routine use of fossil fuels, which are dispatchable, and greatly increasing the contribution of variable renewable energy supplies (VRES), mainly wind and solar photovoltaics. The use of hydropower cannot be increased significantly in most European countries because the available resources have already been deployed, but it could be used more as a dispatchable source of generation in some countries. The use of biomass for power generation is also dispatchable, but it is not expected to increase in most European countries because it is a limited resource, and its value, which will be reflected in its price, is significantly higher in other applications. Some existing power plants, such as combined heat and power (cogeneration) plants used for district heating systems, may be retained to provide reserve generation, which will consume little biomass or fossil fuels because it will be used for only a few hours per year (Galinis *et al.* 2020).

In addition to changes in the electricity systems, which will have important energy security implications, the frequency and duration of periods with low wind speeds (dunkelflauten) are changing so the weather data used for electricity system modelling must also be updated. Similarly, the use of flexibility options for electricity grids, which are needed to deliver secure electricity supplies, will increase in the coming years, to accommodate growth in the penetration of VRES, as well as growth in electricity demand.

Box 2 Summary of key messages from EASAC Energy Security Modelling Workshop (October 2024)

To inform this report, a workshop was held with experts from 12 modelling teams working in 11 European countries to discuss the challenges of using energy system models to quantify the energy security costs, risks, and benefits of the transition to sustainable energy supplies. Some of the messages that emerged from discussions at this workshop were directly related to energy system modelling, whereas others were more broadly related to the energy scenarios on which modelling studies are based, as summarised below:

- **There is no universally optimal mix of electricity supplies.** Countries are preparing and implementing national plans for their transition to sustainable energy supplies, but they must each move forward by adapting and building on their existing systems which differ substantially. Some countries consider that the most economic and secure approach for them is to extend the lives of their existing nuclear reactors, possibly build new nuclear reactors, and build more renewable energy generators. For other countries, the option of using their indigenous fossil fuels together with CCS is their preferred option, but most countries are planning also to increase their use of renewable electricity generation.
- **There are still uncertainties relating to the security and costs of transitions to sustainable energy supplies.** Grid networks supplied with high levels of variable renewable energy supplies (VRES) or of nuclear generation will require the deployment of flexibility measures, including interconnectors, storage and flexible generation for balancing supply and demand, and the costs of this will vary significantly between Member States. Computer modelling studies of systems with high levels of VRES frequently include scenarios with fully flexible hydrogen electrolysers, but commercially available electrolysers are not yet fully flexible. One option may be to use clusters of small modular electrolysers that can be switched on and off. Meanwhile, research and development to deliver technological advances and cost reductions for hydrogen electrolysers is continuing. Modelling results are known to be sensitive to the flexibility of the electrolysers used, so further research on how best to deliver electrolyser flexibility is needed.
- **Holistic energy systems modelling is needed for EU adequacy and flexibility assessments.** Modelling electricity systems in isolation can produce potentially misleading outcomes and encourage over-investment. Sector coupling can reduce total system cost, electricity storage needs, and dependence on interconnections.
- **Modelling fully integrated energy systems is computationally costly.** There are many uncertainties when modelling integrated systems that have sector coupling, demand response, storage, and backup generation. Collaboration is helpful, but results depend strongly on technology assumptions and methods used.
- **A mix of flexibility measures is needed to manage electricity systems and markets with high percentage VRES.** This is because not all flexibility measures are effective for all timescales (hourly, daily, weekly, and seasonal). The flexibility measures available include storage, interconnections, and system coordination using smart grid features and smart meters, together with demand response and backup generation.
- **Dunkelflauten (periods of low wind and sun) are a challenge for all VRES-dominated systems**. Short (hourly and daily) dunkelflauten can normally be managed by using a mix of electricity storage (batteries or pumped hydro), demand response, interconnections, and flexible generation. In contrast, long (major) dunkelflauten lasting more than a week occur rarely but are too long to be managed using storage or consumer focused demand response. The impacts of long dunkelflauten may at some time in the future be mitigated by switching off hydrogen electrolysers or using flexible electrolysers if these are developed successfully, but in the meantime long dunkelflauten will need to be managed using strong interconnections to areas outside the influence of the dunkelflauten or dispatchable generation such as hydropower with storage and/or backup generators. In the short term, the backup generators are likely to be fuelled by natural gas, but when it becomes available, they may be supplied with a sustainable fuel such as biomethane or hydrogen.
- **Strong cross-border interconnections provide flexibility to energy systems, but their use must be managed fairly.** They can help to maximise the exploitation of renewable energy sources, which are unevenly distributed across Europe, by facilitating the deployment of technologies where they work best. However, they can cause electricity prices to rise in a country that supplies cheap electricity to its neighbour. Interconnectors therefore need to be managed with close cooperation and clear agreements on how potential dependencies of one country on another for backup supplies will be fairly remunerated so that consumers on both sides of national borders will benefit.
- **Backup dispatchable generating capacity will be needed.** As fossil fuels are phased out, existing gas turbines could be adapted and/or new turbines deployed for use with sustainable fuels to provide backup generation when there is insufficient VRES or in case of other crises. Market incentives (e.g. capacity mechanisms) or government interventions may be needed to secure adequate investments in backup generation in some Member States.

Smart energy systems will be increasingly used during the transition to optimise the use of wind and solar electricity for electrified transport, heating, and industry as well as for producing hydrogen, synthetic fuels, and chemical feedstocks. Smart management of all forms of energy storage (electricity, heat, and liquid and gaseous fuels) will play a greater role in future integrated energy systems and, as a result, dynamic integration of the main sectors of energy demand and supply will become increasingly important (Lund *et al.* 2025). This implies that energy system models must be updated and in some cases several models must be integrated to address more dynamic behaviour of the whole integrated EU energy system than occurred when energy systems were dominated by dispatchable fossil fuels (Gardumi *et al.* 2022). New calibrations of models and sensitivity studies will also be needed to verify results and build confidence in the outcomes produced by updated system models.

Energy security has a higher priority, since the invasion of Ukraine, in the decision making of EU and national policy-makers and investors, because it has become more urgent than sustainability and affordability commitments. Future assessments of energy transition scenarios must therefore take all three priorities, especially energy security, into account (Geelen *et al.* 2023; Van Der Mei *et al.* 2023).

Potential crises or 'worst case scenarios' must also be assessed in future, for example the ability of the whole energy system to withstand extreme weather

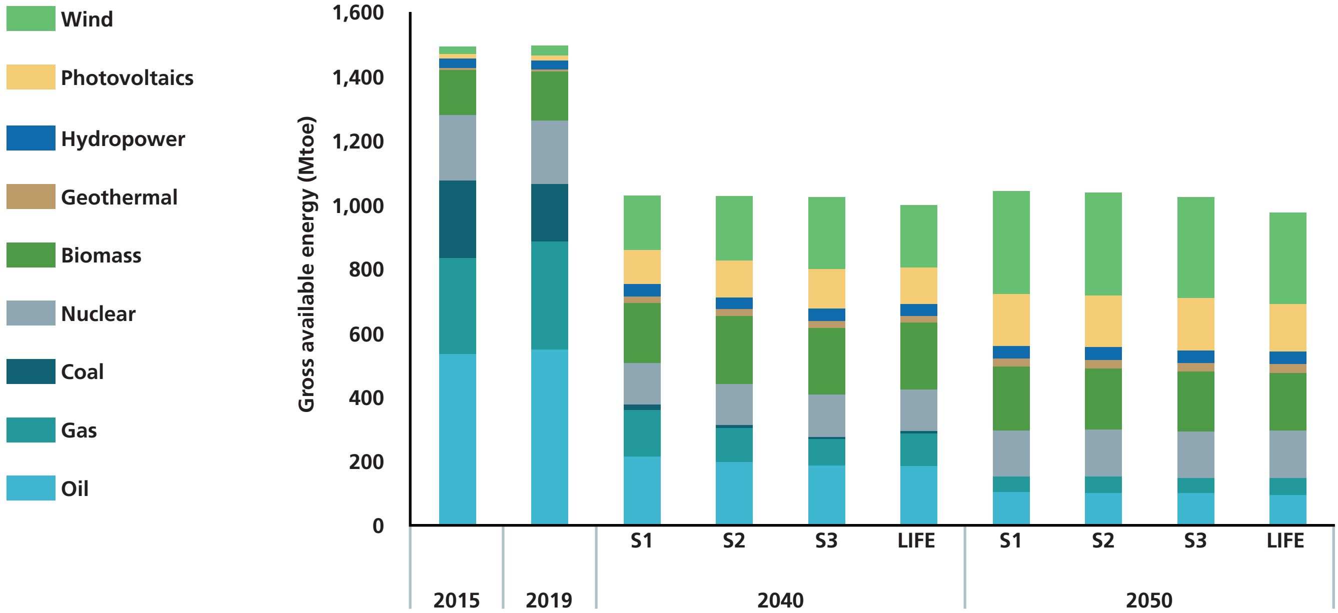

Figure 6 EU gross available energy[2] scenarios (S1, S2, S3, and LIFE) were used in the PRIMES modelling for the impact assessment of EU 2040 targets (EC 2024a). Note: 1 million tonnes of oil equivalent (Mtoe) = 11.63 terawatt-hours (TWh).

conditions (e.g. induced by climate change) and unforeseen breakdowns caused by potential terrorist and cyber-attacks.

2.5 Energy security is being improved by energy efficiency and circular economy measures to reduce final energy demand in buildings, industry, and transport

Final energy demand in the EU is dominated by three main sectors, namely buildings, transport and industry, and this split has hardly changed over the past 20 years (Figure 7). Member States are already working to reduce the energy consumed in these sectors to help them to deliver their commitments to GHG emission reduction as cost effectively as possible.

Increasing energy efficiency can make it easier to deliver and maintain energy security. Simply put, the less energy needed, the easier to meet the energy demand. Energy efficiency is often considered to be straightforward, especially for buildings for which the

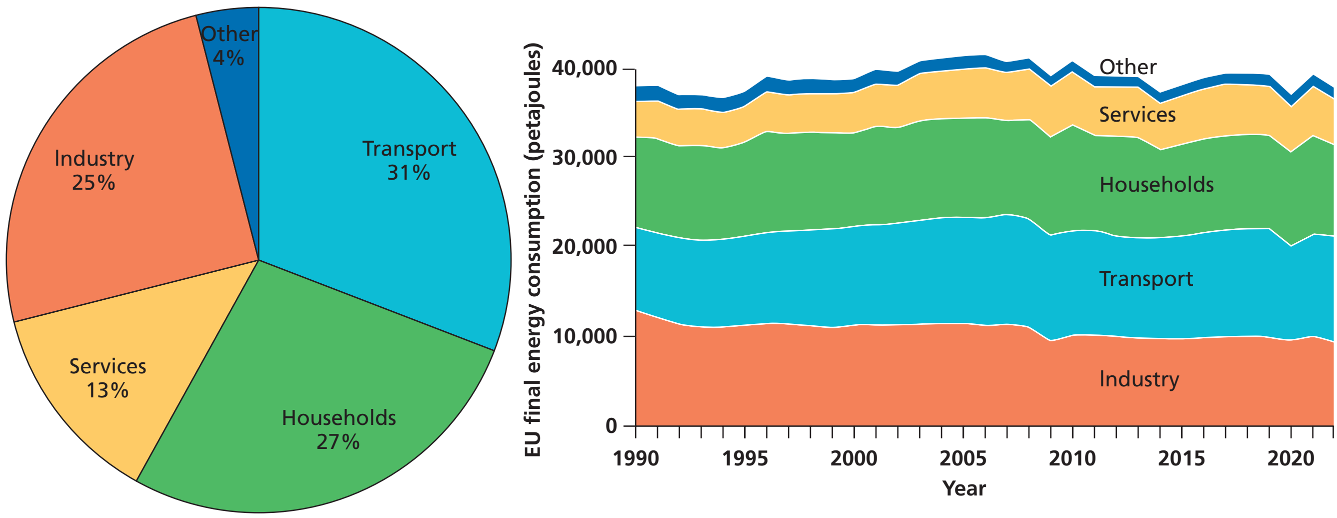

Figure 7 EU final energy consumption was dominated by the transport, household, and industry sectors in 2022, and this sector distribution had hardly changed since 1990 (Eurostat 2024g).

[2] Gross Available Energy refers to the overall supply of energy for all activities. These data include energy for energy transformation, for the energy sector itself, transmission and distribution losses, final energy consumption, and the use of fuels for non-energy purposes. They also include fuel supplied for international aviation and shipping, non-renewable waste, and manufactured gas, but exclude ambient heat from heat pumps.

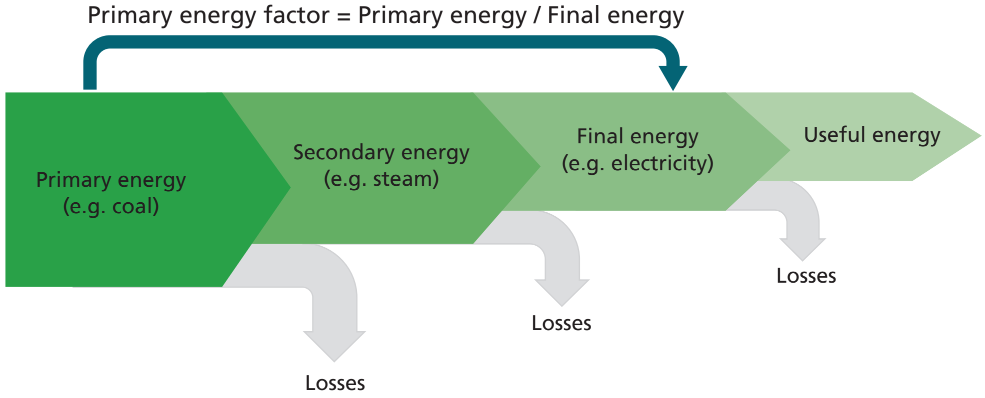

Figure 8 Losses occur at each stage in the process when fuels are converted to useful energy (Hirzel et al. 2023).

EU proposed a renovation wave in 2020 (EC 2020b). However, in many parts of Europe, although existing buildings are in urgent need of renovation, the required financing and skilled workers are lacking (EASAC 2021). In addition, there is an increasing need for cooling which is largely supplied today by chillers powered by electricity but could in future be more sustainably delivered by using active and passive cooling solutions (EC 2023l).

District heating offers an efficient solution for supplying heat in cities where it can capture excess heat, which is currently being wasted, and use it to replace fossil energy sources. It can also be used with heat storage to efficiently distribute sustainable energy sources, such as solar and geothermal heat. Heat mapping studies of urban areas suggest that the use of district heating could be substantially increased in many parts of Europe by 2050 (HRE 2025).

There are many ways to make motorised transport more energy efficient and sustainable, but progress with their delivery is slow (EASAC 2019). Many industries could also be made more energy efficient, but they are not because of the costs and disturbance involved in changing industrial processes.

In summary, while energy efficiency measures might seem to be straightforward, there are still many barriers to be overcome. In addition, studies have shown that direct and indirect rebound effects can cause energy efficiency measures in all sectors to lead to unexpected outcomes, including lower than expected reductions in energy demand (Brockway *et al.* 2021).

The use of fossil fuels involves energy losses in three stages as shown in Figure 8, while renewable electricity produced using wind or solar generators involves energy losses only in the conversion from final energy (electricity) to useful energy. Consequently, as fossil fuels are phased out, not all of their primary energy will be replaced because so much energy is lost when fossil fuels are used.

The ratio of primary energy to final energy is known as the primary energy factor, and this is usually set by convention to be 1 for wind, solar, and hydro-electricity and 3 for nuclear electricity (Hirzel *et al.* 2023). For other fuels, the primary energy factor depends to a large extent on the Carnot efficiencies of the systems involved and no single method for determining the primary energy factor for mixes of electricity supplies has yet been agreed (Bilardo *et al.* 2022). It is therefore important to be clear whether data refer to primary or final energy when comparing fossil and sustainable energy systems.

Changing the energy carrier can offer opportunities to reduce final energy demand and therefore to deliver on all three aspects of the energy trilemma: security, sustainability, and affordability. In practice, switching to sustainable energies will often involve electrification, which is typically more efficient than burning fossil fuels, so it can reduce both primary and final energy demand.

Policies on energy efficiency (EU 2023c) and decarbonisation are already in place in the EU to deliver reductions in energy demand and in GHG emissions. These include regulations on building design (EU 2024a), vehicle performance, and eco-design and energy labelling (EC 2024m). However, although the European Commission is committed to working with Member States to develop and implement the required policies, its assessments of progress through the national energy and climate plans show that policy implementation is slow and challenging in many Member States (EC 2023f).

A circular economy offers many opportunities for reducing energy demands because product and material lifetimes are increased, fewer new products are produced, so energy security is improved. A circular economy is also important for recycling and reusing critical and strategic raw materials (Chapter 4). The EU adopted a circular economy action plan in 2020, which aims to empower consumers and public buyers (EC 2020e). This contains 35 actions which focus on the sectors that use most resources and where the potential for circularity is high such as electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water, and nutrients. The plan also aims to step up the synergies between circularity and reduction of GHG emissions, for example by incentivising the uptake of carbon removal and increased circularity of carbon. The EU has the ambition to take a lead in global efforts to introduce a more circular economy, which would also have the potential to improve the competitiveness of European businesses in global markets for sustainable products and services (Draghi 2024).

Changes to industrial processes and systems can help to phase out fossil fuels and achieve the EU's commitments to reducing GHG emissions. Examples include using engineered wood and timber in the construction industry to replace cement and steel that have high levels of embodied carbon emissions. Negative carbon emissions can be created by wood products, provided their lifetimes are longer than those of the trees from which the wood was taken, because the carbon in the wood is stored in the wood product until the end of the product lifetime. For example, if the wood product is construction timber, then it can store carbon for many decades, and may then be further recycled at the end of its life in construction.

Integration of the energy sectors at EU and Member State levels must form part of the transition, because this can open up new opportunities for reducing energy demands and introducing more sustainable energy supplies (EC 2020d). For example, integration can reduce emissions in hard-to-electrify sectors and make innovative technologies more attractive (Skvorčinskienė *et al.* 2022). Moreover, recent energy systems modelling has shown that integration and sector coupling can reduce total energy system costs, electricity storage requirements, and dependence on interconnections.

In summary, energy and climate policies that drive the energy transition from fossil fuels to sustainable energies will also help to increase energy security. Similarly, research and development in all energy sectors could increase energy security by helping to reduce energy demands and deliver sustainable energy supplies at more affordable prices.

2.6 Switching from fossil fuels to sustainable energies increases the role of electricity, and of biofuels and hydrogen (and its derivatives) for some industry and transport applications

Europe's energy supplies come from indigenous (37% in 2022) and imported (63% in 2022) sources, and include fossil fuels (coal, oil, and gas), imported nuclear fuels, indigenous and imported renewable fuels (wastes, biogas, biomass, and liquid biofuels), and indigenous and imported electricity. An overview of EU final energy consumption is shown in Figure 9a, and recent growth in the renewable share of EU final energy consumtion is shown in Figure 9b. More information on European energy supplies can be found in Annex 2.

Fossil and renewable fuels are energy carriers as well as being energy sources, so they can be distributed by pipelines, ships, and vehicles to their end consumers. Some fuels are burned in boilers or industrial processes to produce heat, some are used as transport fuels,

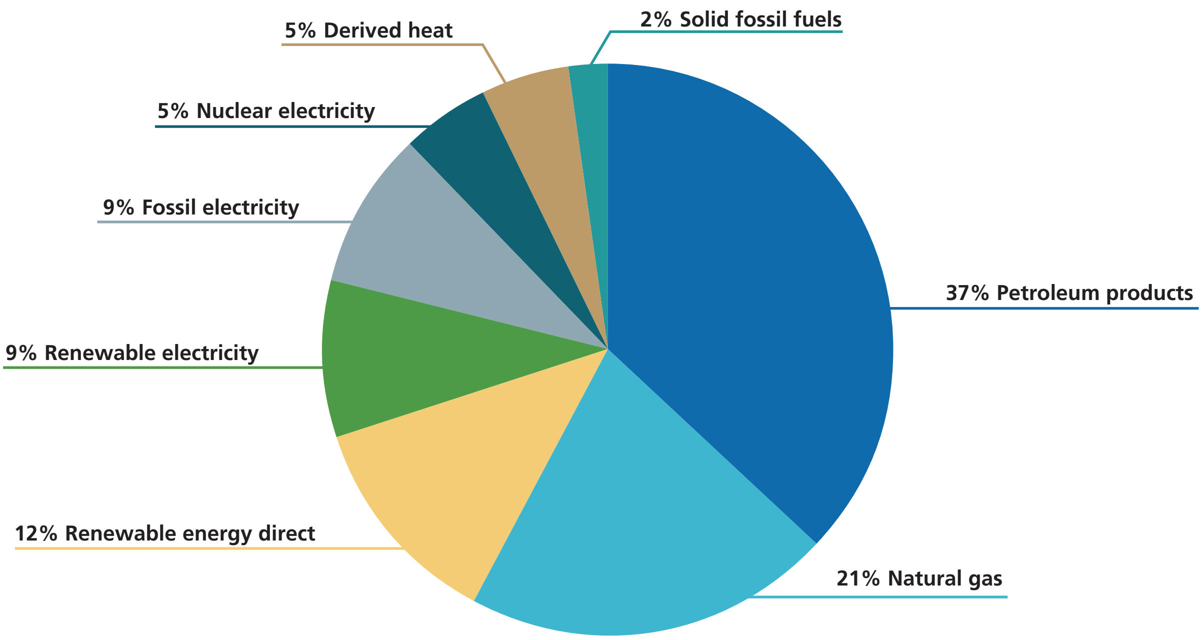

Figure 9a EU 27 final energy consumption 2022 (Eurostat 2024d).

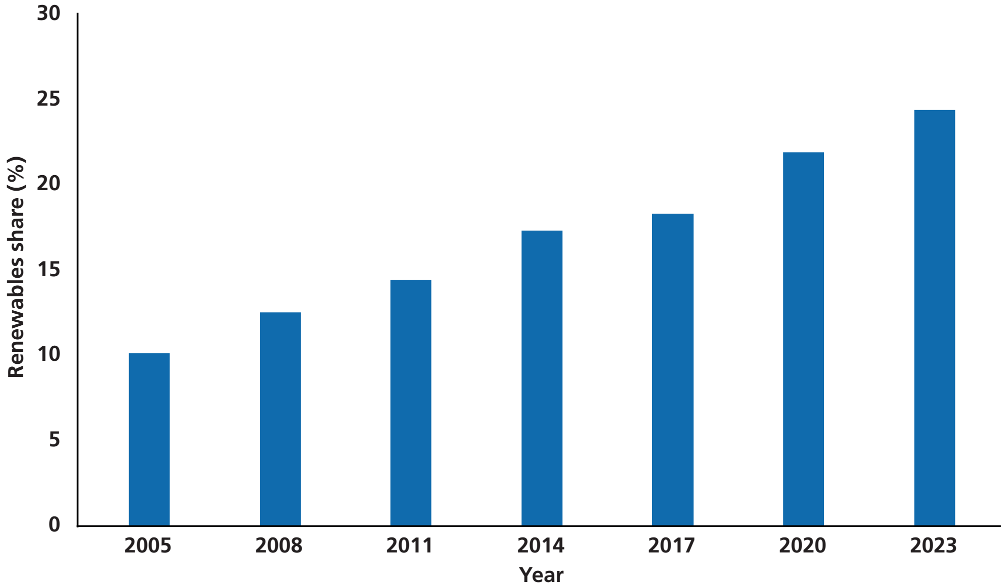

Figure 9b Growth in renewables share (%) of EU final energy consumption (Eurostat 2024f).

and some are used to produce electricity which carries energy to buildings, industry, and transport. However, as fossil fuels are phased out during the transition to net zero by 2050, energy will increasingly be carried by electricity, and to some extent also by biofuels, and hydrogen and its derivatives. The extent to which energy will be carried in the future by hydrogen and biofuels will differ between European countries and be driven largely by their industry and transport sectors.

The mix of energy supplies varies between EU countries, for example in Poland energy supplies were dominated by fossil fuels (87% in 2022), with a share of 42% of coal in its energy mix, which was seen as a cornerstone of energy security because it is an indigenous energy source. In contrast, 66% of Sweden's energy supplies from renewable energies in 2022 (Eurostat 2023c). The mixes of energy supplies will vary between Member States in the coming years and will depend on national resources and policy priorities for energy security and sustainability. Nevertheless, it is already clear that more of Europe's electricity supplies will be produced in future by VRES, namely wind, solar photovoltaics, and hydropower.

Wind energy varies from hour to hour and day to day, and it tends to be higher in winter than in the summer months; so wind electricity supplies follow the same annual pattern as demands for electricity in Member States with high winter heating demands. However, wind electricity supplies are variable throughout the year, so they need to be stored or backed up to match the variable demands of electricity grids.

Solar energy, which can be used for electricity generation (photovoltaics) or for heating, peaks in the middle of the day and falls to zero at night; so it fits well with cooling and other daytime energy demands in southern Europe. However, solar radiation in Europe is much lower in winter than in summer, so solar energy supplies are not well matched with the space heating demands of buildings.

Hydropower has dominated EU supplies of renewable electricity for many years, but most of the potential EU resources are now in use, and some are decreasing owing to reduced rainfall caused by climate change. Unlike wind and solar electricity, some hydropower generators are dispatchable, because their water supplies can be controlled, so hydropower can make valuable contributions to energy security (Aubin *et al.* 2023).

Geothermal energy in the form of low-temperature heat is available in some parts of Europe at competitive costs and is likely to be increasingly used there for space and water heating, notably through district heating systems. To a limited extent, notably in Italy, geothermal heat is available at higher temperatures that can be used for power generation, but only 0.5% of renewable electricity generation in the EU was produced using geothermal heat in 2021 (IRENA 2023).

Electricity networks need flexibility measures, including storage, demand response, interconnections, and dispatchable backup generation, to balance supplies and demands when connected to variable renewable electricity supplies (VRES). In those countries that use nuclear power, flexibility to manage variations in demand can be provided either by the above flexibility measures or in some countries by operating nuclear reactors at part load (RTE 2021). Either option contributes to the capital component of electricity costs.

Frequency and voltage control systems must be fitted to electricity networks to stabilise supplies when traditional generators are replaced by wind and photovoltaic generators, because traditional rotating generators inherently provide synchronous inertia, but wind and photovoltaic generators typically do not (Hartmann *et al.* 2019).

Bioenergy dominates the renewable energies used for heating in the EU today, and much of it is locally sourced. However, the potential for increasing the use of bioenergy is limited by the availability of secure supplies of sustainable biomass (EC 2023j) and by its potential impacts on local ecosystems (Pang *et al.* 2019). Before the invasion of Ukraine, the EU imported forest biomass in different forms of wood from Russia, but this was stopped in 2022, together with oil imports, and replaced by wood pellet imports from the USA (Ireland 2024). In future, instead of importing wood pellets from third countries, which unfortunately involves energy security risks, there is scope for substantially more heating to be supplied by sustainable electricity with heat pumps, as well as more solar and geothermal heating.

3 Sustainable energy technologies, energy carriers, and fuels

What are their strategic roles for delivering Europe's energy security?

3.1 Overview

Sustainable energy technology components and systems, notably solar photovoltaics and wind generators and batteries, have been largely imported into the EU in recent years from China and other parts of Asia, with limited diversity of suppliers. Increasing the manufacture of sustainable energy technology components and systems in Europe would help to improve EU energy security and to create jobs and wealth. However, even after the Carbon Border Adjustment Mechanism is fully operational (EC 2022c), innovative approaches will be needed to reduce EU manufacturing costs before they can compete in European markets with Chinese imports (EC 2024j). Also, for strategically important energy systems, spare parts should be stored in Europe to meet the expected demand for several months, and protection should be provided against cyber-attacks and physical attacks by malicious third parties and terrorists, including attacks by drones.

Sustainable energy carriers and fuels, which will become increasingly important for EU energy security as fossil fuels are phased out, include sustainable hydrogen and its derivatives, alcohols, biodiesel, and biomethane, as well as agricultural and forestry wastes, and solid, liquid, and gaseous biofuels. Some of these will be made in the EU and some will be imported, but schemes for independently certifying their sustainability, such as those that are already recognised as being compliant with the Renewable Energy Directive, will need to be recognised and effectively implemented (EC 2024h).

Potential future energy carriers, which lie outside the scope of this report because of their low technology readiness levels and ongoing needs for research, include the use of powdered metals, notably aluminium and magnesium. These could in future be used as carbon free energy vectors and energy storage media, because they can be burned in air to produce metal oxides which can then be regenerated using renewable electricity. In this way, renewable energy could be carried and stored for later use in a secure and sustainable way, but the technologies required are not yet ready for commercialisation (Halter *et al.* 2023; Wronski and Sciacovelli 2024).

3.2 Manufacturing more strategic energy technologies and systems in the EU would reduce energy security risks

Strategic energy technologies, systems and industries that are critical to energy security have been identified in the EU Net-Zero Industries Act (EU 2024f), which is intended to encourage the manufacture of such technologies and systems to remain in the EU despite the initiatives of some third countries to attract EU industries to move abroad, notably the Inflation Reduction Act in the USA (US Government 2022). The Net Zero Industries Act complements the Critical Raw Materials Act (EU 2024g) by also ensuring adequate diversity in the supplies of strategically important technologies and systems.

An example of concern is the supply of solar photovoltaic cells and modules, of which more than 90% have been imported from China in recent years. However, while supplies of photovoltaic modules will be needed for the EU energy transition, a disruption of the photovoltaic supply chain would create a relatively low energy security risk because it would only impact the construction of new or refurbished photovoltaic energy systems in the country or region concerned (SCNAT 2024). Also included in the Net Zero Industries Act are geothermal and wind technologies, which face significant market and deployment obstacles (McKenna *et al.* 2024).

Energy storage imports (batteries) have grown strongly in recent years. From less than €2 billion per year in 2013–2014, they reached almost €7 billion in 2020 and exceeded €26 billion in 2023. Together with imports of solar energy technologies (almost €20 billion in 2023), they account for a significant share of the total EU imports of energy technologies (Lekavičius *et al.* 2024).

Nuclear energy technologies, including small modular reactors, are listed in the Near Zero Industry Act (EU 2024f) as strategic technologies. However, the capital costs of large-scale nuclear plants are high, they need long-term commitments for financing, security of operations, fuel supply chains, waste management, and decommissioning and are less profitable when operating at part load (NEA 2011). Recent experience in France, Finland, and the UK (Vakarelska 2024; WNA 2024a; WNN 2024) has shown that they can take up to 18 years to build. Meanwhile, research continues on small modular nuclear reactors with support from the EU and the aim to facilitate and accelerate their development, demonstration, and deployment in Europe by the 2030s (EC 2024y). However, none are scheduled for commercial operation in Europe before the 2030s (RTE 2021; IAEA 2024) (see also Annex 2, Section A2.3).

Sustainable end-use energy technologies and systems, including electric vehicles, smart grid technologies together with smart meters, and heat pumps, as well as hydrogen electrolysers, will become increasingly crucial to future EU energy security as fossil fuels are phased out; so, to reduce security risks, a good share of these should be manufactured in the EU.

The EU Carbon Border Adjustment Mechanism will contribute positively to this objective because it will make it more difficult in future for unsustainably manufactured products to be imported into the EU from third countries and sold for low prices with which EU manufacturers cannot compete (EC 2022c). However, as the Carbon Border Adjustment Mechanism is introduced, it may be necessary to provide support for low-income households and vulnerable groups, because the Mechanism will increase the prices of sustainable technologies above those of previously cheap imports. The higher prices may also delay the decarbonisation of buildings, industry, and transport.

Digital controls and computer-based management systems already form an integral part of most energy technologies and systems, including smart grids, so their hardware and software can have strategically important roles. In addition, artificial intelligence will be increasingly used for managing energy technology and system operations, so there are cross organisational systemic cybersecurity risks, which must be regularly analysed and managed by technology producers and users, for example by using cyber protection and independent software backups (Chapter 5).

3.3 Securing supplies of sustainable energy carriers and fuels, including hydrogen, biofuels, and ammonia at affordable prices, will require both production in Europe and diversified imports

Sustainable energy sources and energy carriers will have important roles in the future, but their limited availability will result in increased prices and prioritisation of their use for applications that are 'hard to electrify' (EASAC 2023a).

The EU's Energy Platform (EC 2023d) is being used to purchase secure supplies of natural gas and sustainable hydrogen at affordable costs for the short term, and a similar approach may be used for purchasing secure supplies of a wider range of sustainable energy carriers and fuels in the medium and longer terms (Balachandar 2024).

Hydrogen

Hydrogen and its derivatives (ammonia, etc.), and synthetic fuels (e-fuels) are expected to become part of the future mix of sustainable energy carriers for the EU. In 2023, most of the hydrogen produced in the EU was made from natural gas. Sustainable hydrogen can be produced by electrolysis of water using sustainable electricity or from fossil fuels with CCS (EASAC 2023a), although it is likely to be a more expensive energy carrier than electricity, owing to inefficiencies in these production processes. Sustainable hydrogen can also be produced by methane pyrolysis (from natural gas), which produces solid carbon that can be stored or used in a variety of applications, but this process has yet to be commercialised (Teso *et al.* 2024).

The REPowerEU plan (2022), which built on the EU strategy for hydrogen (2020), set ambitious goals for hydrogen and its derivatives, with the aim of strengthening EU energy security and helping to phase out the EU's dependence on fossil fuels imported from Russia. It set targets of 10 megatonnes (Mt) of domestic renewable hydrogen production and 10 Mt of renewable hydrogen imports by 2030. However, such ambitious goals could bring energy security risks for the businesses involved, especially during the initial years of trading in international hydrogen markets (Dejonghe *et al.* 2023).

Secure supplies of sustainable hydrogen could contribute to EU energy needs by being used in fuel cells for road transport, to decarbonise steel and cement industries, and to produce e-fuels and sustainable aviation fuels. Electrolytic hydrogen could be used as a means of storing electricity for long periods until the hydrogen is used to produce electricity in a fuel cell or burned in a combustion engine connected to a generator, but these would be very inefficient and costly options. An alternative way for sustainable hydrogen to contribute to electricity network management is for hydrogen electrolysers to operate flexibly in a demand response programme (Box 7 on page 46).

Major investments in hydrogen electrolysers would be required to meet the EU's hydrogen targets, so research on reducing their costs is ongoing. Also, the provision of adequate water supplies may pose environmental challenges for electrolysers in some locations. To help with the management of electricity networks with high fractions of VRES, research on hydrogen electrolysers with operational flexibility is ongoing (Nguyen *et al.* 2024).

Hydrogen infrastructure will be needed to transport hydrogen from where it is produced or imported to where it will be used, and studies have already been done by the European gas industries on how existing gas pipelines might be used in future to carry hydrogen (EHB 2024). While it may be feasible to distribute blends of hydrogen with natural gas through small private networks (e.g. in industrial clusters), the widespread distribution of hydrogen blends through the EU's main gas networks is not expected because the costs are high and the maximum acceptable levels of blending (approximately 10%) would deliver negligible (approximately 1%) reductions in GHG emissions (EASAC 2023a).

Hydrogen storage either as a gas or a liquid is more challenging than to store fossil fuels (Alzohbi *et al.* 2023). To store hydrogen as a gas typically requires high-pressure tanks (350–700 bar), and research continues on the potential for storing hydrogen in underground salt caverns (Caglayan *et al.* 2020). To store hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is –252.8 °C. Hydrogen has a low volumetric energy density (in kilowatt-hours per litre), so it requires around four times larger storage volumes than fossil fuels such as gasoline and diesel (EERE 2024). Hydrogen can also be stored in solid metal hydrides using absorption, which offers higher volumetric energy densities and safety advantages. However, research continues to develop a recyclable system for this on a commercial scale (Klopčič *et al.* 2023). Another alternative is chemical storage of hydrogen in the form of methane (by carbon dioxide (CO_2) methanation) or other hydrocarbons, because this can substantially increase its volumetric energy density and hydrogen can be released, albeit at a cost, by subsequent steam reforming or catalytic dehydrogenation. Such hydrogen storage solutions are being studied as possible options for transporting hydrogen from third countries, where it can be produced more cheaply than in Europe (Verpoort *et al.* 2024).

Hydrogen-fuelled boilers are under development and might be used in niche markets at prices that are cheaper than heat pumps in areas where hydrogen is supplied for industry. Hydrogen cannot be used in existing boilers, and it will always be more efficient to use electricity to heat buildings with a heat pump than to use it to produce hydrogen for use in a boiler. The use of hydrogen blended with natural gas in boilers and in gas turbines for power generation has been widely discussed, but these applications are not viable solutions for GHG emission reduction, and they risk creating 'lock-in' for consumers to natural gas supplies that should be phased out by 2050 (EASAC 2023a).

Hydrogen's future: electrolytic hydrogen will always be a more expensive energy carrier than the electricity used to produce it, owing to inefficiencies in its production processes; so, to remain competitive, EU industries are likely to prioritise its use for applications that are hard to electrify. The EU's ambitious hydrogen goals seem unlikely to be delivered on time (ECA 2024).

Biomethane and sustainable aviation fuels

Biomethane is a fuel that can contribute to energy security because it performs like natural gas in networks and boilers, and it could be used to delay capital expenditure on replacing existing boilers. However, its availability will be constrained in the future by the limited availability of sustainable biomass resources (e.g. sewage, agricultural, animal, and food wastes), 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 food processing plants where agricultural or food wastes are digested. It may also be distributed through local gas networks either directly or blended with natural gas and used as a transitional fuel for heating in some areas until sufficient sustainable electricity generation (for heat pumps) has been constructed (EASAC 2023a). The value of the limited supplies of sustainable biofuels, including biomethane, can be expected to rise as fossil fuels are phased out, so they will be prioritised for applications which are hard to electrify, and for use in chemicals industries.

Aircraft need secure fuel supplies and sustainable aviation fuels (SAFs) are the preferred low-carbon footprint options in the short to medium terms (EASA 2024). SAFs typically include blends of fossil kerosine with sustainable biofuels, or e-kerosene, which is made using sustainable hydrogen and sustainable carbon. For e-fuels to be deemed sustainable, the carbon used to make them must come from a sustainable source, such as sustainable biomass.

SAFs, which include sustainable biofuels, must be made using sustainable biomass wastes (municipal wastes, food wastes, animal wastes, agricultural and forest residues) and e-fuels made using sustainable electricity (EASAC 2023a).

SAFs are considered by the aviation industry to be one of the most promising ways to reduce CO_2 emissions from the aviation sector in the near- to mid-term, because they can be used in the existing fleet. Moreover, they are expected to continue to play an important role in the future, after the introduction of alternative clean propulsion technologies (EASA 2024).

The ReFuelEU Aviation Regulation promotes the increased use of SAFs to decrease aviation CO_2 emissions and sets requirements for aviation fuel suppliers to gradually increase the share of SAF blended into the conventional aviation fuel supplied at EU airports (EU 2023a). The Regulation specifies minimum shares of SAF to be supplied to aircraft at EU airports, but there remain significant uncertainties about the future sources of SAFs and the development of SAF markets, both for SAFs made in the EU and those that are imported (EASA 2024).

Ammonia

Ammonia is the foundation of the nitrogen fertiliser industry and can also be used as an energy carrier; so it has the potential to contribute to energy security. It is currently made from atmospheric nitrogen and hydrogen produced by steam reforming of natural gas. Instead, sustainable ammonia can be made by using sustainable hydrogen (Ammonia Europe 2024). In the medium term, as electrolyser prices fall, sustainable ammonia is likely to be made close to where fertilisers are produced.

Sustainable ammonia can also be made by using sustainable hydrogen produced by steam reforming of natural gas with CCS. Its production in the EU will depend on the availability of natural gas and CCS, and on natural gas prices. In the short term, EU produced sustainable ammonia is likely to be prioritised for making fertilisers to support agriculture and food production rather than as an energy carrier, but it may also be imported as foreseen in the REPowerEU plan.

Ammonia can be used as a hydrogen carrier and storage medium because it is easier and can be less costly to transport ammonia at –33 °C and atmospheric pressure (or at 20 °C and 9 bar) than to transport liquid hydrogen. Ammonia is a toxic substance, but it has the advantages that it contains approximately 4.5 times 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 used to carry hydrogen into the EU, for example from Australia (Egerer *et al.* 2022). To recover the hydrogen, ammonia can 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 be used as a transport fuel for ships or heavy-duty road transport (Tavoulareas 2024), or potentially in the power sector as currently envisaged by Japan (Watanabe 2022). However, before it can be deployed on a large scale as a transport fuel, it must be de-risked for use in such applications. Testing and certification companies are already working on this (Bureau Veritas 2024). For ship owners, a key challenge is to prevent accidental ammonia leaks during ship operations and bunkering. Also, measures must be taken to limit nitrogen oxide emissions from ammonia or ammonia/hydrogen combustion in ships (Dinesh and Kumar 2022; EASAC 2023a).

3.4 Carbon capture and storage or carbon capture and utilisation can greatly reduce greenhouse gas emissions from the combustion of fossil fuels

Carbon capture and storage (CCS) has the potential to facilitate the use of fossil fuels with greatly reduced GHG emissions and therefore to supply low-carbon energy for applications that are hard to electrify and are in regions with reliable fossil fuel supplies. However, its wider use would carry the risks of investment lock-in and of extending the period of dependencies on fossil fuel imports.

Carbon capture and utilisation (CCU) offers the potential to use captured carbon as a raw material for carbon-containing products, such as fuels, chemical products, and building materials, but this could only delay the emissions of carbon into the atmosphere unless they were later collected and stored (SAPEA 2018).

The future deployment of CCS will depend strongly on its future costs, and on how these compare with future carbon prices driven by the EU Emission Trading System (ETS) (EASAC 2023a). Given the limited experience with CCS in the EU so far, and the uncertainties about future carbon prices, it is too early to predict a future trajectory for CCS deployment in the EU.

According to the Global CCS Institute, there were 50 CCS facilities in operation in the world in 2023, capturing and storing 51 Mt of CO_2 per year,[3] and 44 CCS facilities under construction (Global CCS Institute 2024).

The EU Net-Zero Industry Act, which sets a target of 50 Mt per year of CO_2 injection capacity by 2030 (EU 2024f), is complemented by the EU Industrial Carbon Management Strategy, the Carbon Capture and Storage Directive, ETS, EU Certification Framework for Carbon Removals (EU 2025b), and support for CO_2 transport infrastructure under the TEN-E Regulation, Innovation Fund, and Connecting Europe Facility (EC 2024s).

Businesses are promoting the idea of using CCS to demonstrate that they are 'green', but progress with CCS deployment in the EU is slow, many projects have been cancelled, and cost reductions have proved to be difficult to achieve. Consequently, technology-based CCS is not yet widely deployed in the EU. In contrast, the most common form of CCS is photosynthesis, by which trees store atmospheric carbon in the soil and in wood, which is then used in long-life wood products, such a construction timber, and can usefully store carbon for decades. This natural form of CCS is proven and has a big untapped potential (Le Pierrès *et al.* 2024).

The competitiveness of technology-based CCS will improve as carbon prices rise, so the Carbon Border Adjustment Mechanism will help EU businesses to justify investments in CCS as the prices of imports are

[3] *51 Mt of CO_2 per year is less than 0.1% of global CO_2 emissions which, in 2023, were the highest ever at 53 $GtCO_2eq$ (excluding land use, land-use change, and forestry). The EU emitted 3.2 $GtCO_2eq$ (excluding land use, land-use change, and forestry) in 2023 (EDGAR 2024).*

Table 2 Potential applications and limitations of CCS and CCU

Potential applications of CCS and CCU	Limitations of CCS and CCU
Cement industry	Lower costs needed to beat competition from (unsustainable) cement imports until Carbon Border Adjustment Mechanism is fully implemented.
New construction materials	Instead of making steel or concrete with CCS, it is well proven and would be cheaper to use timber and engineered wood in buildings.
Hydrogen production	The EU has set ambitious goals for sustainable hydrogen production by 2050, but these appear unlikely to be delivered on time (ECA 2024). Some of this hydrogen will be produced from fossil fuels using CCS, but it will emit much more than the 10 gCO_2eq/kWh emitted when renewable hydrogen is made using wind electricity (EASAC 2020).
Steel production	Steel can be produced using other sources of sustainable hydrogen so CCS will need to compete on price.
Gas fired electricity generation	In most areas, it would not be competitive with VRES in electricity markets, and it would be too costly for backup generation on a few days per year.
Oil and gas industries	Industry would welcome CO_2 injection for enhanced oil and gas recovery, but only until oil and natural gas are phased out.
Chemical industries	CCU could make long-life plastics and other materials sustainable provided their carbon content is captured and stored at the end of their lifetime.
Bioenergy with CCS (BECCS)	BECCS will only reduce global warming if the biomass used has a short carbon payback time, for example less than about 10 years (EASAC 2022).
Timber and engineered wood in new buildings and renovations	Natural CCS (photosynthesis) works well, but it will take time for the building industry to adopt new products on a large scale.

increased to reflect their carbon content (EC 2022c). Some potential applications of CCS and CCU, and their limitations are shown in Table 2.

3.5 Nuclear fuel supplies for Europe's reactors are largely dependent on imports of enriched uranium

Secure supplies of nuclear fuels are needed to maintain secure supplies of sustainable electricity from nuclear power stations. Uranium resources are mined in many different countries and sufficient global uranium resources have been shown to exist to support the projected demand for nuclear electricity and other uses in the long term (NEA 2025).

Nuclear fuels are largely imported into the EU after the natural uranium has been processed to become enriched uranium (WNA 2022). There is also some reprocessing of waste uranium from nuclear reactors. The structure of nuclear fuel assemblies is made to suit the reactors in which they will be used. Approximately 46% of the global uranium enrichment processing capacity today is in Russia (ESA 2023), so the future energy security risks associated with the EU's imported nuclear fuels will depend on the evolution of geopolitical volatility and on diversification to alternative enrichment processing facilities in the EU or in the countries of the EU's allies (Figure 10).

Dependence on Russian fuel supplies for (Russian designed) VVER reactors in the EU has been of particular concern since the invasion of Ukraine. There was a downward trend in the dependence on Russian nuclear fuel imports from 2020, with the share falling to 68% in 2022, but Russia's share of the EU's nuclear fuel imports rose again to 79% in 2023 (Lekavičius *et al.* 2024). In response to the invasion, Member States with VVER reactors doubled their imports of nuclear fuels in 2023, compared with 2022, to build up their stocks in case of future supply disruptions (Bellona 2024). Canada, France, Japan, the UK, and the USA issued a 'Statement on Civil Nuclear Fuel Cooperation' in April 2023, in which they committed to establish a global commercial nuclear fuel market, collaborating on strategic opportunities in the nuclear fuel supply chain. Their aims were to (1) further reduce their countries' reliance on Russia in the nuclear fuel supply chain in the long term; and (2) increase the availability of commercial free-market alternatives in the supply of civil nuclear technologies to other countries (ESA 2023). The EU highlighted the importance of coordinated action to reduce dependence on Russian nuclear materials and fuel cycle services in its REPowerEU plan (EC 2023a), and launched a new initiative in 2024 to diversify nuclear fuel supplies (EC 2024u). The US president signed a law in 2024 to implement an incremental ban on imports of Russian enriched uranium (US Department of Energy 2024).

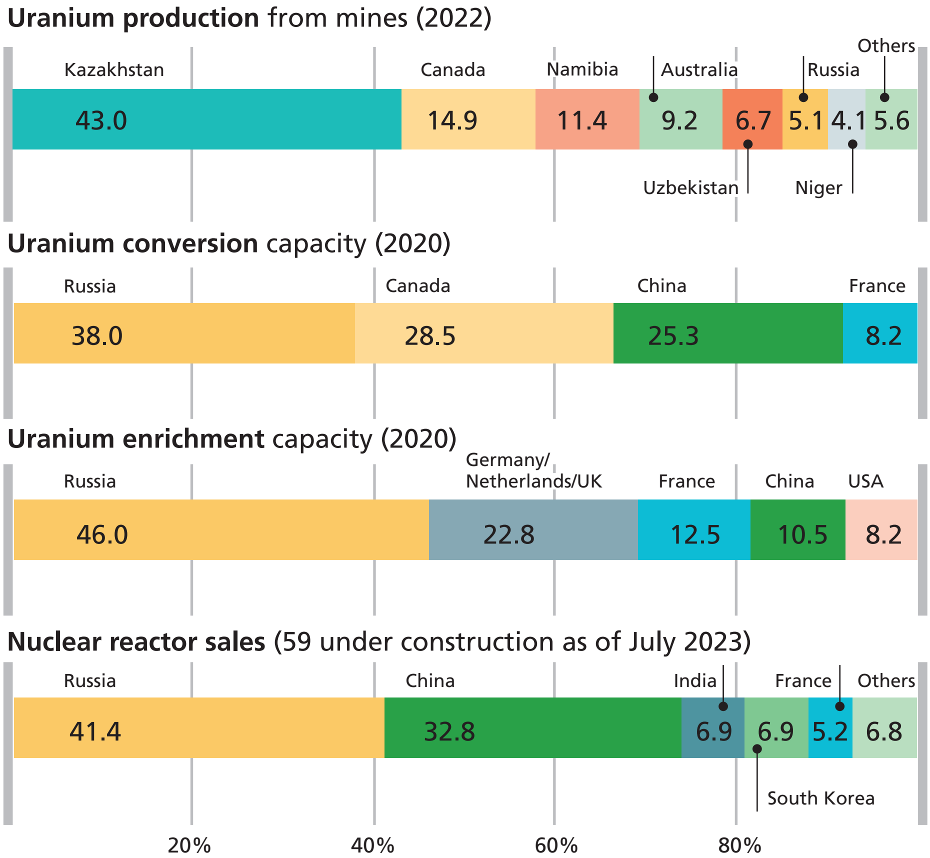

Figure 10 Geographical concentration of the nuclear fuel cycle (percentage of global total): uranium production was dominated by Kazakhstan in 2022, uranium conversion by Russia, Canada, and China in 2020, and uranium enrichment by Russia in 2020 (IRENA 2024a).

Nuclear fuel supplies are highly regulated, but the implementation of such commitments to diversification will be crucial for the future security of sustainable energy supplies in the EU.

Today there is a global overcapacity of uranium enrichment, but if Russian capacity is excluded, there may not be enough to meet global needs by 2040 because demand is expected to increase (ENERDATA 2024). In addition, new reactor models requiring more highly enriched fuels will pose a challenge to the enrichment market, because the infrastructure to support an increased demand for more highly enriched uranium is lacking. Moreover, a lack of international standardisation of uranium fuel assemblies complicates supply chains and can lead to increases in costs (ENERDATA 2024).

From a nuclear safety perspective, unlike intermediate- and high-level nuclear wastes, for which long-term underground storage solutions have still to be confirmed by most Member States that operate nuclear power plants (except Finland, France, and Sweden) (EC 2024z), nuclear fuel assemblies have low radioactivity levels, so radiation shielding is not a problem when they are stored and transported by truck to nuclear power plants. Nuclear fuel assemblies contain fissile material but criticality can be prevented by the design of packaging and by limiting the number of packages carried in one shipment (WNA 2024b).

The security of electricity supplies from nuclear power plants is subject to the risk of major accidents, which occur rarely but can have long-lasting impacts on energy supplies when they do (Annex 2, A2.3).

4 Critical and strategic raw materials

Which metals and rare-earth elements are largely imported into the EU for use in energy technologies and systems?

4.1 Overview

Many raw materials, metals, and rare-earth elements are used in technologies and systems that are needed to deliver secure EU energy supplies (Calderon *et al.* 2020). Those that are economically important and carry high supply risks are classified as critical raw materials (CRM) (EC 2020c), and those that are important for energy supplies are also known as energy transition minerals (Owen *et al.* 2023; IEA 2024d). These have attracted growing attention in recent years, to the extent that the United Nations has set up a UN Secretary-General's Panel on Critical Energy Transition Minerals (UN 2024a). In its Critical Raw Materials Act (EU 2024g), the EU also defined a list of strategic raw materials (SRM).

CRM typically have longer lives (e.g. 20 years) than fuels, so buying them is less time-critical. However, many come from geopolitically volatile regions and/or are imported from geographically concentrated sources, so it is wise to plan ahead, to build supply chain sovereignty (resilience) by purchasing materials from diverse and trusted sources (Schrivers *et al.* 2020 and Maihold 2022), and to store enough in Europe to meet demands for several months. Storing CRM for future use in energy systems is less important for energy security than storing fossil fuels, because a shortage of fuels can quickly have a massive impact on the economy. Nevertheless, the EU's future energy security will depend on a transition to sustainable energies, and CRM at affordable prices will be needed for sustainable energy systems to be manufactured in Europe. Batteries, electric vehicles, and other components of sustainable energy systems need resilient supplies of nickel, cobalt, lithium, graphite, and copper in particular, so it will be important to establish diverse and trusted sources of supply for these critical minerals (Shannak *et al.* 2024).

Significant shares of many metals that are used in energy transition technologies are imported from Russia, including palladium, platinum group metals, and nickel as well as aluminium and copper (Kohnert 2024). These minerals are not only mined in Russia but they are also refined and processed, using specialised processing facilities there. For the EU to reduce its dependence on Russian CRM and SRM, it will therefore need to invest not only in diversifying its supply chains, and possibly in mining its own minerals, but also in finding or establishing new processing facilities. However, even if resources can be found in the EU, challenges can be expected from local communities that may be affected.

Several CRMs (and many energy transition minerals) are imported into the EU from China (Figure 11), a country with which European trading relations are becoming increasingly volatile (EC 2024q). Some come from the Democratic Republic of the Congo where armed conflicts, unsafe/illegal mining, and the use of child labour can be found (Sovacool 2019), and some from areas where mining could put Arctic communities (e.g. Sami communities in Sweden) at risk (Sörlin 2022). Some CRMs can also be found on the ocean floor where deep-sea mining would cause irreversible environmental damage to marine ecosystems (EASAC 2023c). There is also the possibility that CRM deposits are used as 'resource weapons', meaning that a supplier country limits or ends the sale of specific CRMs (Wilson 2018).

Looking at the impacts on society of ensuring adequate supplies of energy transition minerals, a recent global analysis suggests that ramping up the use of energy transition minerals could be more disruptive to the communities involved than ramping down coal. The distribution of risks was found to differ between countries, but for the data studied, a complete phase out of coal was found to disrupt community systems for a minimum of 33.5 million people, while another 115.7 million people would be disrupted if all available energy transition mineral projects were to enter production (Svobodova *et al.* 2022).

European policy-makers must therefore find a compromise. They must balance the need to import CRMs (so that sustainable energy systems can be manufactured in Europe) against the risks of future geopolitical interference in CRM supply chains and Europe's responsibilities to deliver the UN Sustainable Development Goals and to respect human rights in its supply chains from third countries. The policies that have been put in place by the EU to address these challenges are discussed below.

4.2 EU legislation includes lists of critical and strategic raw materials, sets benchmarks for supply chain diversification, and limits impacts on local environments and indigenous livelihoods

An important component of the EU policies for CRMs and SRMs, which is emphasised in the Critical Raw Materials Act (EU 2024g), is their integration into a more circular economy, in which recycling and reuse are maximised.

The Critical Raw Materials Act sets up a joint purchasing system for SRMs (Article 25), and sets the following diversification benchmarks for domestic capacities along the SRM supply chain, namely, to diversify by 2030 at least:

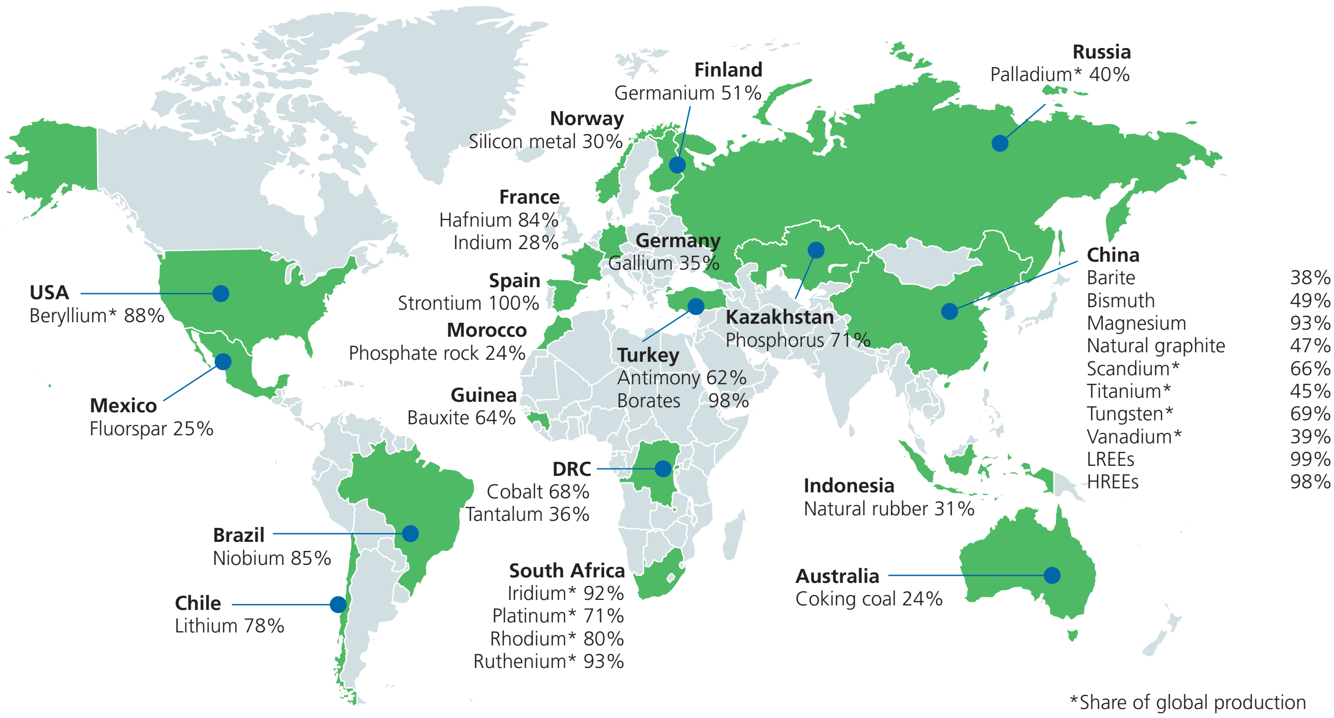

Figure 11 The biggest suppliers of critical raw materials to the EU (percentage of annual EU consumption) in 2020 included Africa, Latin America, China, and the USA (EC 2020c). Abbreviations: HREEs, heavy rare-earth elements; LREEs, light rare-earth elements.

- 10% of the EU's annual CRM consumption for **extraction**,
- 40% of the EU's annual CRM consumption for **processing**,
- 25% of the EU's annual CRM consumption for **recycling**.

It also requires that not more than 65% of the EU's annual consumption of each strategic raw material, at any relevant stage of processing, should come from a single third country.

National exploration programmes for CRMs must be drawn up by Member States and reviewed every 5 years. These must consider the impacts of materials mining on local environments and indigenous livelihoods. A valuable analysis of such impacts was published for the Arctic region (Sörlin *et al.* 2022).

Strategic partnerships will be set up with third countries for supplies of raw materials and to ensure their coordination with other international fora and initiatives. Social justice and a fair transition will be ensured for communities involved in mining and extracting critical materials in third countries.

Lists of materials that are of critical importance for the EU must be expected to evolve over time as new technologies are developed, old technologies are replaced, and recycling schemes, for example for batteries, photovoltaic modules, and wind turbine blades, become more widely established; so the lists published by the European Commission are to be reviewed every 3 years (EC 2020c). The list of 34 CRMs published in Annex II of the Critical Raw Materials Act is shown in Table 3, of which 17 specific materials are listed in Annex I as SRMs (EU 2024g).

Table 3 The 34 critical raw materials that are listed in Annex II to the Critical Raw Materials Act (EU 2024g)

Antimony	Light rare-earth elements
Arsenic	Lithium
Bauxite	Magnesium
Baryte	Manganese
Beryllium	Natural graphite
Bismuth	Nickel – battery grade
Boron	Niobium
Cobalt	Phosphate rock
Coking coal	Phosphorus
Copper	Platinum-group metals
Feldspar	Scandium
Fluorspar	Silicon metal
Gallium	Strontium
Germanium	Tantalum
Hafnium	Titanium metal
Helium	Tungsten
Heavy rare-earth elements	Vanadium

Box 3 Lithium: a critical raw material for use in energy systems

Global lithium resources were estimated at about 98 Mt in 2023 (Jaskula 2023), and recent studies of global and European lithium demand and supply between 2015 and 2050 and beyond (Mellot *et al* 2024) suggest there will be sufficient resources to meet global lithium needs by 2050, even if electric mobility increases significantly.

Nevertheless, given that electric vehicle battery collection and recycling rates will not reach 100%, the following lithium-related measures will be needed to increase European sovereignty over it (reduce dependency on imports):

- European lithium mining or other forms of extraction (e.g. from brine);
- European lithium processing;
- friendshoring and diversification: sourcing raw and processed lithium supplies from allies, and from several supplier countries, to reduce dependence on any single supplier;
- development of economic circularity through:
  - battery collection and recycling;
  - use of secondary lithium (reincorporation);
- promotion of socio-technological sufficiency;
- research and development on battery technologies, which do not use lithium.

A good example of a CRM is lithium (Box 3), which was added to the EU's list of CRMs in 2020 largely because of its growing role in batteries for electric vehicles and distributed electricity storage (Aguilar Lopez *et al*. 2023).

In summary, the EU has established a strong policy framework for CRMs and SRMs, which includes a demanding set of requirements for action. It will be crucial to Europe's future energy security that these actions are implemented in a timely manner both by Member States and by the industries concerned.

5 Cyber security

How can the EU's increasingly digitalised energy sector be protected against the growing numbers of cyber-attacks by volatile geopolitical forces?

5.1 Overview

Strengthened cybersecurity together with physical security of critical infrastructure have been high on the agenda during the past decade and they have become increasingly pressing since the invasion of Ukraine in 2022. Cyber-attacks and physical attacks are unfortunately growing in number, and all stages of the energy supply chain need to be protected.

Electricity supplies are extremely dependent today on information technology (IT) systems, for transmission and distribution as well as in both fossil-fuelled and sustainable energy generators, so their failure or cyber-attacks on them will very probably lead to disruptions (including brownouts or blackouts) in the energy system. Synchronisation signals for photovoltaic system inverters can be damaged, for example by cyber-attacks, even if the systems are decentralised.

Common practice is to conceptually divide IT systems into two categories:

- operational technology (OT), which is systems close to the physical energy process, such as supervisory control and data acquisition (SCADA) and industrial control systems;
- administrative information technology systems, such as systems for human resources, customer relations, and maintenance.

Organisations in the energy sector typically operate a plethora of systems from both categories, but the consequences of cyber incidents (targeted cyber-attacks or failures) are likely to be most severe for those with key OT roles.

For most organisations in the energy sector, the overall system architecture is extensive and highly complex with large numbers of subcomponents that are interconnected. To just maintain an inventory and to understand the details of exactly how all system components work is a great challenge for IT departments, as they feature many dependencies that are regularly added, removed, and reconfigured.

From an energy sector point of view, regional and national energy supplies involve many organisations with interconnected IT systems. These include distribution system operators (DSOs) and transmission system operators (TSOs) that are close to the physical operations, together with market operators, energy traders, third-party maintainers, and many others. With increasing digitalisation and innovative ideas for sustainable energy management and delivery, the number of organisations and IT systems contributing to energy services in Europe is growing.

Components of IT and OT systems come from an extensive mix of software and hardware supply chains. Typically, any given component is built up with a large share of program code that was not developed by the specific component developer and vendor. So, much of the software is reused and often contains an amalgamation of open source and proprietary software. This means that in addition to the increased complexity and traceability challenges introduced by the supply chain, there are also risks of common points of failure for multiple, seemingly independent components. Hence, a vulnerability in a particular software component in one supply chain can lead to a multitude of vulnerable IT/OT systems in multiple organisations.

Artificial intelligence (AI) will increasingly be introduced in both IT and OT systems, but it is difficult to forecast the exact consequences of this (re)evolution. Nevertheless, it means that there will be more components that need to be protected in the same fundamental way as in any other system. Most likely, AI components will add a new level of complexity because AI models need to be maintained and are increasingly interconnected to form larger networks of AI components serving higher-level functions. Recent studies suggest that a substantial role will be played by major technology conglomerates in the 'industrialisation of AI', as AI technologies shift from research and development to practical, real-world applications across diverse industry sectors. This shift could result in the need to manage new dependencies, for example on cloud platform products and services offered by conglomerates based outside Europe, such as Amazon, Microsoft, and Google (van der Vlist *et al.* 2024).

5.2 Energy systems and infrastructure contain IT components that are vulnerable to cyber-attacks and to unintended software bugs

All components in an IT system infrastructure are at risk of containing vulnerabilities. Even in the world's most well-managed software, vulnerabilities are constantly being discovered (updates containing vulnerability patches are regularly made to operating systems, browsers, and other applications). To reach their targets,

Box 4 Cyber-attack in Lviv, Ukraine, January 2024 (LB 2024)

Hackers used a novel piece of industrial control systems malware to cut the heating and hot water to more than 600 apartment buildings in the city of Lviv, Ukraine. More than 100,000 people were left without heating for almost two days in sub-zero temperatures before service was restored.

The attack used a malware strain named FrostyGoop, according to the industrial security firm Dragos, which believes the hackers broke into the network by exploiting vulnerabilities in its MikroTik routers (Dragos 2024). Dragos says the network was not segmented, and the hackers easily pivoted to compromise the internal network. The hackers compromised a Microsoft Windows system, and the malware sent commands through the internal ethernet network to controllers, which were being used to manage boilers and heating pumps. The malicious commands contained instructions for the Modbus protocol (one of the most popular industrial control protocols used in the world), which the controllers were using to interface with the heating pumps, and caused 'system malfunctions', bringing operations to a halt.

attackers therefore combine multiple vulnerabilities and weak system configurations (such as unnecessarily generous account privileges). Successful cyber-attacks have for quite some time been part of everyday life for organisations, and attacks are now increasingly successful also on OT systems. Eurelectric reports a doubling of cyber-attacks on the energy sector between 2020 and 2022 (Eurelectric 2024a) and, in 2022, it was reported that 15 out of 48 cyber-attacks on European energy and utility companies targeted OT systems (Energicert 2022). An example, illustrating how 100,000 people in Ukraine had their heating disrupted by a cyber-attack on an OT environment is reported in Box 4.

Sector systemic vulnerabilities might also appear because a component, which is found in one IT system, is likely to also be used in others across the energy sector, so a few vulnerable components can create large cyber-attack surfaces that an adversary in principle can exploit simultaneously. From an individual organisation's perspective, a particular vulnerability might rightfully be considered an acceptable risk. However, that risk might only be acceptable if its 'neighbouring' organisations were not susceptible to the same vulnerability in their software products and supply chains.

IT system components are not only used in the energy sector. Many are also used by other types of organisation; so, for example, an attack campaign targeted at the banking sector can also spread to the energy sector if the same (vulnerable) systems and components are used.

Collateral damage can occur as a result of cyber-attacks. For example, German wind turbines suffered collateral damage when Russia attacked the satellite services from Viasat during the invasion of Ukraine (Willuhn 2022).

Unintended software bugs can also lead to interruptions in energy supplies by causing IT systems in energy systems to stop working. A major example of the potential impacts of an unintended software bug occurred in July 2024 when a software bug affected 8.5 million Microsoft Windows devices, and led to widespread disruptions of airlines, banks, broadcasters, healthcare providers, retail payment terminals, and cash machines across the world. The cost of the outage has been estimated at more than €1 billion (Dutton and Rohland 2024).

5.3 Software and hardware supply chains for energy system components may include untrustworthy organisations and countries

Risk analyses should evaluate the trustworthiness of the whole supply chain. When considering vulnerabilities in components, it is often assumed that the vendor and the end-user are in the same boat, fighting against a malicious third-party. However, this is not always the case. Just like other supply chains, those for software may include dependencies on untrustworthy organisations and countries. *Most system operators trust the vendors of software and hardware* because it is practically impossible for them to scrutinise all the code involved (Thompson 1984), but to trust software providers carries a risk.

Geopolitics is increasingly influencing trust in IT systems, and concerns about sovereignty are on the rise in the IT sector in general; for example China recently released a 'delete America' Act (Griffith 2024) and the UK announced malicious cyber activity by Chinese state-affiliated organisations and individuals targeting democratic institutions and parliamentarians (UK Government 2024). The EU depends strongly on China for its photovoltaic cells and modules, and for its photovoltaic inverters which contain increasingly sophisticated IT systems and therefore offer an immense potential cyber-attack surface.

A particular area of interest is open-source software, for which it is sometimes argued that 'many eyes' will detect mischief, but it is not easy to assess code produced by someone else. For example, in 2024 a 'backdoor' was intentionally planted in xz Utils, an open-source data compression utility, which is available on almost all installations of Linux and other Unix-like operating systems (Goodin 2024). It is obviously easier to find flaws in open-source code that is available for scrutiny than in code that is not, but just because it is open-source should not be taken to mean that someone has actually scrutinised it, because much of the open-source software is developed and maintained on a voluntary basis.

5.4 IT and cybersecurity skills are lacking, so more cyber incident response services are needed

A severe shortage of cybersecurity skills has been reported in Europe, and the shortage is particularly important for strategic services (Niinistö 2024).

The management of cybersecurity in the energy sector is challenging because the sector is highly diversified and fragmented, with large numbers of energy producers and distributors. For example, many small DSOs operate power grids in small cities or municipalities with IT departments consisting of very few people, for whom cybersecurity is only one of many IT responsibilities. If small organisations are targeted by highly trained professional cyber-attackers, then they are unlikely to be able to successfully defend themselves. It might be assumed that a problem in a small DSO would have only a small impact on EU energy supplies, but if there were to be a coordinated attack against many small DSOs, then this assumption would not be valid.

Geopolitics is becoming increasingly volatile and the numbers of cyber-attacks are growing, so it is becoming increasingly important to define levels of cyber incident, types of emergency cyber support that these should trigger, and how cyber support should be organised. To staff IT departments of small energy system operators with permanent cybersecurity experts is typically unaffordable, so contracted experts and emergency cyber support services must be used. Good initiatives for organising and coordinating such services are already available through national centres, such as the UK National Cyber Security Centre (NCSC 2024), but broader and deeper support structures are needed.

5.5 Cyber-related legislation is being strengthened but risk analyses must be performed at operational levels where vulnerabilities emerge, as well as at administrative levels

Most organisations in the energy sector are aware of the cybersecurity threat and are working actively to make their IT systems as secure as possible. Nevertheless, to achieve '100%' security in the IT systems that underpin EU energy supplies is impossible. Cybersecurity legislation should therefore guide investments in IT systems for energy supplies by defining responsibilities for risk management, and prioritising risk assessment methodologies that cover the most likely combinations of the cybersecurity threats.

The EU already has several cybersecurity regulations in place, among which Eurelectric highlights six that are serving important purposes (Eurelectric 2024a). The EU Directive on Cybersecurity NIS2 was updated in 2022 to improve cyber resilience (EC 2022b), and the EU Agency for Cybersecurity, ENISA, has a mandate to produce biennial reports for the European Parliament on the state of cybersecurity in the EU (EC 2022b). To comply with the updated Directive and with the EU Network code for cybersecurity of the electricity sector (EC 2024i) (which is a delegated act under the NIS2 Directive), all energy systems and their IT controls should be produced by trusted parties, preferably within the EU. Member States must also include detailed plans for energy security in their national energy and climate plans (EC 2023f).

Making regional, national, or EU-wide risk analyses for the energy sector is an activity that requires clear mandates. The network code makes national authorities, ENTSO-E, and other delegated bodies responsible for inspecting the risk analyses of individual organisations, and for identifying potentially critical infrastructure. Detailed insights into each organisation are needed to do this effectively, but these can be difficult to obtain. Consequently, this work risks becoming costly and bureaucratic.

An EU Cyber Solidarity Act was proposed in 2023, which aims to strengthen capacities to detect, prepare for, and respond to significant and large-scale cybersecurity threats and attacks. A text was provisionally agreed between the European Parliament and Council in March 2024, approved by the Parliament in April 2024, and came into force in February 2025 (EU 2025a). The Act includes a European Cybersecurity Alert System, comprising interconnected Security Operation Centres across the EU, and a comprehensive Cybersecurity Emergency Mechanism to improve preparedness and response to cybersecurity incidents in the EU (Box 5).

Box 5 Action areas of the EU Cyber Solidarity Act (EU 2025a).

1. *Supporting preparedness actions.* Testing entities in crucial sectors such as finance, energy, and healthcare for potential weaknesses that could make them vulnerable to cyber threats. The selection of sectors to be tested will be based on common risk assessments at the EU level.
2. *Creating an EU Cybersecurity Reserve.* This will consist of incident response services from private providers ('trusted providers'), which can be deployed at the request of Member States or EU Institutions, bodies, and agencies to help them to address significant or large-scale cybersecurity incidents.
3. *Ensuring mutual assistance.* The mechanism will support a Member State that offers mutual assistance to another Member State affected by a cybersecurity incident.

The EU Cyber Resilience Act (EC 2024p and EU 2024h) was adopted in 2024. This introduces mandatory cybersecurity requirements for hardware and software products and ensures that manufacturers remain responsible for cybersecurity throughout a product's whole life cycle (EC 2024p). This is expected to improve transparency on the security of hardware and software products, and to bring benefits to business users and consumers.

Organisations must take responsibility for their own cybersecurity and full ownership of it. As these two Acts move to their implementation phase, risk analysis methodologies must be applied at operational levels where vulnerabilities emerge as well as at administrative levels.

6 The European electricity system

How does the way it is managed influence the security of electricity supplies?

6.1 Overview

Europe's electricity system became more resilient on 9 February 2025, when Estonia, Latvia, and Lithuania successfully synchronised their electricity grids with the Continental Europe Synchronous Area (ENTSO-E 2025b). However, each EU Member State retains the right through Article 194 and Article 192 of the Lisbon Treaty on the Functioning of the EU (Official Journal of the European Union 2016) to decide on its own mix of energy supplies; so, although their grids are synchronised, the mix of electricity generators and therefore the challenge of managing the security of electricity supplies is different in each country.

The regulations, directives, and network codes of the EU electricity market design (EMD), which have recently been updated (ENTSO-E 2024a; EU 2024b; EU 2024c; EU 2024d), determine how the electricity system is managed and therefore have an important influence on the attractiveness of investments in the electricity sector and on the security of electricity supplies.

The reformed legislation establishes a new EU DSO Entity that brings together distribution system operators (DSO 2024), and strengthens the energy security mandates of key actors, notably the transmission system operators through ENTSO-E and the energy regulators through ACER (ACER 2024a). The EU has also recently reformed its overarching Directive on resilience of critical entities (EC 2022a), which covers energy supply infrastructure.

Measures to address the affordability of electricity, including protection for vulnerable customers, were included in the EMD, in response to the recent volatility of energy prices. This also gives the EU the power to declare a regional or EU-wide electricity price crisis, which will allow Member States to protect customers and give them access to secure supplies of affordable energy.

6.2 Financing schemes for electricity generation and infrastructure strengthening are needed to deliver the energy transition with high levels of energy security

The size of the investments needed in new sustainable power generation and in strengthening electricity infrastructure is massive and clearly cannot be met by only one financing source. Indeed, there is a need for '*massive mobilisation of both public and private finance*' (Draghi 2024).

Big differences exist between the indigenous energy resources of Member States and between their existing energy system assets, so different technological solutions may be cost-optimal for the short term in different parts of the EU.

However, different potential energy security risks and benefits are offered by different technological solutions, so a 'technology neutral approach' (as proposed by Draghi 2024) could only deliver satisfactory outcomes if all potential risks and benefits of integrating each technology into the local and EU energy systems are taken into account, including short-, medium-, and long-term energy security.

Standardised financing schemes, which are widely recognised and understood by both financiers and project developers, can help to deliver the energy transition as quickly as possible, and there are four main types of these:

(1) *inter-governmental agreements for technology transfer* (e.g. storage, nuclear, smart grid). Generalised agreements, which address risk sharing, can be tailored for specific projects;

(2) *contracts for difference* in which the risks are shared between a public body with a mandate to manage the required funds, and an energy company which is supplying electricity;

(3) *power purchase agreements*, which are commercial contracts between electricity suppliers and consumers, and can be used to guarantee the repayment of debt that has been provided by a financial institution and used to invest in power generation plant;

(4) *financial guarantees* that can be used to cover the project risks and thereby reduce the financing costs (interest rates of debt used to finance the plant).

The EU has set up a wide range of funding schemes (EC 2024x) to deliver the Green Deal by supporting investments in the energy sector. In addition, the recently reformed EMD Regulation and Directive recognise:

- two-way contracts for difference;
- power purchase agreements.

Box 6 Recommendations in EU Action plan for grids (EC 2023g)

- Accelerate the implementation of Projects of Common Interest and develop new projects through political steering, reinforced monitoring, and more proposals.
- Improve long-term planning of grids to accommodate more renewables and electrified demand, including hydrogen, in the energy system by steering the work of system operators as well as national regulators.
- Introduce regulatory incentives through guidance on anticipatory, forward-looking investments and on cross-border cost sharing for offshore projects.
- Incentivise a better use of grids with enhanced transparency and improved network tariffs for smarter grids, efficiency, and innovative technologies and solutions, by supporting cooperation between system operators and recommendations by ACER.
- Improve access to finance for grid projects by increasing visibility of opportunities for EU funding programmes, especially for smart grids and modernisation of distribution grids.
- Stimulate faster permitting for grid deployment by providing technical support for authorities and guidance on better engaging stakeholders and communities.
- Improve and secure grid supply chains, including by harmonising industry manufacturing requirements for generation and demand connection.

Both of these tools can make it easier for developers and investors to deploy large-scale renewable electricity generating plants. Moreover, ways of improving them, for example by adapting the contract to form a financial contract for difference, have recently been proposed by researchers (Schlecht *et al.* 2024).

However, contracts for difference and power purchase agreements do not suit all long-term investments in electricity systems. For example, new nuclear plants may need government interventions, because of the risks of construction delays and cost over-runs, as well as the need for long-term commitments to decommissioning costs. Public sector support can also be helpful for investments in network infrastructure, such as long-distance high-voltage direct-current lines, which need to be built in anticipation of future growth in electricity demand.

Specific EU funding instruments have been put in place to improve energy security by physically reinforcing the electricity transmission and distribution networks, and by strengthening interconnectors between countries and regions. These include the Trans-European Networks for Energy (TEN-E), Connecting Europe Facility (CEF), and Projects of Common Interest (EC 2024b). EU support is also available for energy projects of mutual interest developed together with third countries for electricity, hydrogen, and carbon dioxide transportation networks.

6.3 The EU has proposed an action plan to accelerate the strengthening of electricity transmission and distribution grids

The EU action plan and the EU DSO Entity confirm that EU grids are acting as a bottleneck for implementation of the energy transition because of grid capacity constraints, and therefore that to speed up permitting processes for enhancing EU grid capacity is an urgent priority (EC 2023g). While investments in generating capacity have been progressing well, expanding, digitalising, and better using EU electricity transmission and distribution grids have been lacking investment and suffering from major delays in long-term planning and permitting. Similar messages are supported by the IEA (IEA 2022). EU transmission system operators (TSOs) have been working on these issues with support from EU research programmes in recent years (e.g. through Horizon-funded projects OSMOSE, FARCROSS, TRINITY, and ONENET).

Long-term planning for electricity and gas networks is currently coordinated by ENTSO-E (and ENTSOG). Regulation 2019/943 on the internal market for electricity (EU 2019b) and Regulation (EU) 2022/869 on guidelines for trans-European energy infrastructure (EU 2022) specify that the Ten-Year Network Development Plan should help to identify those infrastructure projects that are key to achieving the EU climate and energy objectives. Such projects, known as European Projects of Common Interest, are selected by the European Commission from the Ten-Year Network Development Plan overall list of transmission and storage projects every two years. Specific recommendations in the EU action plan for grids (EC 2023g) are shown in Box 6.

6.4 Electricity infrastructure, including cross-border interconnections, is digitally managed and must be both physically and cyber protected to deliver secure supplies

The Critical Entities Resilience Directive (EC 2022a) is the overarching legal framework for the security of EU infrastructure, and it specifically includes energy services. On security issues, the EU cooperates closely with NATO, for example through an EU-NATO Task Force on resilience of critical infrastructure (EC 2023k). This is important because offshore and onshore electricity and gas networks, dams, and power plants as well as digital networks may need to be given military protection in times of crisis. Also important to the security of energy infrastructure are the NIS2 Directive on protection against cyber-attacks (EC 2022b), the EU Network code on cybersecurity (EC 2024i), and the Governance Regulation that requires Member States to address energy security in their national energy and climate plans (EU 2018).

Digitalisation of electricity network management systems will increase as the fraction of renewable electricity in the grid grows, and the trend towards smart grids will be accompanied by a wider introduction of time-dependent tariffs and demand response schemes managed using smart meters. As a result, the security of electricity supplies will become increasingly dependent on the internet, high-quality digital systems, and cybersecurity. To demonstrate the EU action plan on digitalising the energy system (EC 2022d), projects have been launched with support from the EU Horizon Europe programme, for example TwinEU 2024.

Stronger cross-border interconnections will help to improve the security of electricity supplies and to integrate more renewables into energy markets. For example, when a power plant fails or during extreme weather conditions (e.g. very high or very low wind speeds), countries can balance supply and demand on their networks by trading electricity with their neighbours. This requires not only physical power lines to carry electricity, but also legislation to ensure smooth trading across borders. The EMD addresses these issues, including the role of ACER in such trading (EU 2024c).

Synchronisation of the networks in the Baltic countries and detaching them from the Russian BRELL ring system to synchronous operation with the rest of the EU countries was crucial for the future security of electricity supplies in the countries concerned (Estonia, Latvia, and Lithuania). Strong interconnections will be needed for the smooth long-term operation of the networks in these countries. Fortunately, the damage caused to the Estlink 2 undersea cable in December 2024 did not delay the transfer. Nevertheless, the damaged cable may affect reserve capacities until it has been repaired (DPA 2025).

Surplus electricity produced in one country can be used in another country through interconnections, thereby reducing the need to build new power plants, and making it easier to manage variable renewable electricity sources. However, for this to work well, close cooperation must be maintained between neighbouring Member States. Dependence of one Member State on another must be closely managed and interconnections between zones should be segmented to minimise load shed, because large networks are susceptible to cascading failures, which can extend the spread of blackouts. Controllable lines, for example high-voltage direct-current lines, can be used to reduce the risks of such blackouts (Gomila *et al.* 2023).

A European supergrid to interconnect all Member States using high-voltage direct-current lines has been proposed for many years, on the grounds that it would facilitate access to offshore renewable generation for all Member States, with high levels of transmission efficiency (Supernode 2023). However, the costs of such infrastructure would be very high, so it is more likely that such lines will be built first between Member States that wish to cooperate, and then others will join later as sustainable electricity supplies and demands increase.

An interconnection target between Member States of at least 15% by 2030 has been set in the EU Governance regulation to encourage Member States to share their electricity production capacity (EU 2018). This means that each country should have in place electricity cables that allow at least 15% of the electricity produced on its territory to be transported across its borders to neighbouring countries. In 2021, 16 countries reported that they were on track to reach that target by 2030 or had already reached it, but stronger interconnections are needed in some regions.

Urgency indicators for use in interconnector analyses are also set in the Governance Regulation because of the significant increase of wind and solar generation capacity, while interconnection capacities have not increased proportionately. These indicators address price differentials in the wholesale market and the nominal transmission capacity of interconnectors in relation to peak load and renewable generation capacity. The Regulation also stipulates that each new interconnector must be subject to a socio-economic and environmental cost-benefit analysis and implemented only if the potential benefits outweigh the costs.

Redundancy in transmission and distribution networks is important for energy security, because it provides for a fault to be circumvented by using alternative cables until it has been rectified. Redundancy is also needed in IT systems, which must be backed up to provide means of restoring operations in the event of software failures or cyber-attacks.

Prosumer (active customer) numbers are growing because photovoltaic systems are becoming cheaper, but significant differences remain in the legislative frameworks for prosumers and their aggregators (Florea *et al.* 2024). Prosumers can strengthen their own energy security by producing all or part of their electricity themselves, by participating in electricity markets (Rodriguez-Vilches *et al.* 2024), or by joining local renewable energy communities (Barabino *et al.* 2023). Growing numbers of prosumers are also installing batteries, which they can use together with their grid system operators to manage grid flexibility and thereby to improve energy security. The potential benefits of this are recognised in the EU Regulation and the EU Directive on the internal market for electricity, which require Member States to ensure that end-users are entitled to act as active customers without being subject to disproportionate requirements, procedures, or charges that are not cost-reflective (EC 2019; EU 2019). Full implementation of this aspect of the directive can therefore be expected to increase the numbers of prosumers who contribute positively to grid flexibility management with their photovoltaic and battery systems and thereby help to improve energy security (Chatzigeorgiou *et al.* 2024).

6.5 Electricity networks need flexibility management measures for balancing electricity supply and demand, especially when handling variable renewable electricity supplies

To deliver secure electricity supplies, electricity transmission and distribution system operators need flexibility measures to achieve a balance at all times between electricity supplies into their grids and changing electricity demands from consumers (Figure 12). This balance has traditionally been achieved by varying the power supplied to the grid from fossil-fuelled, nuclear, or renewable generators, including hydro or bioenergy generation, with some flexible generators used when necessary to provide backup or to operate at part load. The challenge of balancing the grid is higher when large fractions of (variable) wind and solar generation are connected to the grid, so more flexibility management measures, including demand response, storage, and interconnectors are needed where this is the case, as discussed below.

Demand response schemes, driven by time-dependent tariffs and using smart grids and smart meters, allow electricity consumers (e.g. with heat pumps, electric vehicles, or industrial processes) to participate in electricity markets and thereby to help with the management of grid flexibility and the delivery of secure supplies (Box 7). Schemes are being introduced differently in Member States to suit their different resources and demands.

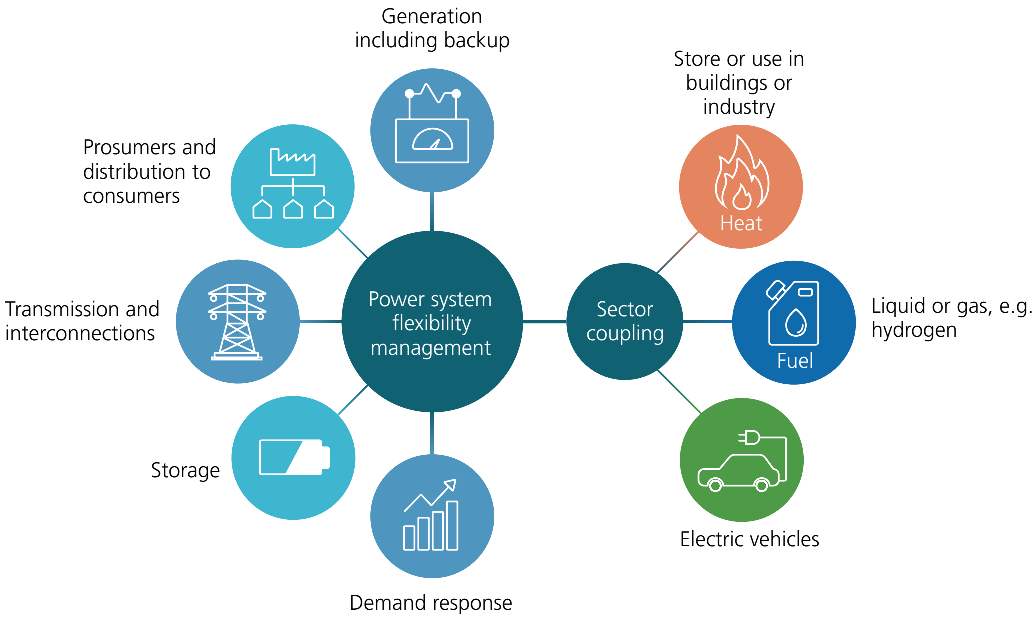

Figure 12 Flexibility management measures for electricity grids include demand response, storage, interconnections, and backup generation, together with sector coupling (adapted by EASAC, on the basis of IRENA 2024a).

Box 7 What is demand response?

Demand response helps network operators to balance supplies and demands on power grids by encouraging customers to shift their electricity demands to times when electricity supplies are more plentiful or other demands are lower. It is typically implemented through prices (tariffs) or other monetary incentives together with smart grid technologies (IEA 2023b).

There are two main mechanisms for implementing demand response:

- price-based programmes (implicit demand response), which use price signals and tariffs to incentivise consumers to shift consumption;
- incentive-based programmes (explicit demand response), which make direct payments to consumers who shift demand as part of a demand response programme.

There are two main ways in which demand response can be managed:

1. For consumers to be given information on prices and opportunities to switch their equipment on and off.

2. For the appliances owned by consumers to be centrally switched on and off by the supplying electricity utility.

Recent studies of these two approaches have shown that most consumers are too preoccupied by other commitments to devote adequate time to controlling their use of electricity, and therefore the savings that they achieve are substantially less than can be achieved when the switching is performed by the supplying utility (Fabra *et al*. 2021, Cahana *et al.* 2023; Bailey *et al.* 2023). Studies have also shown that price incentive schemes for household demand response are only effective if they also address other social aspects and existing user practices (Christensen *et al*. 2020).

A Network Code on Demand Response was proposed to ACER in May 2024 by the EU DSO Entity and ENTSO-E (ENTSO-E 2024a). This new network code, which ACER is expected to submit to the European Commission in Spring 2025, will be applicable in all Member States, and will do the following:

- establish harmonised rules to facilitate market access for demand response, including load, storage, and distributed generation (aggregated or not);

- enable market-based procurement of (demand response) services by DSOs and TSOs.

Heat and electricity storage will be increasingly used to provide grid flexibility and thereby deliver secure electricity supplies. Electricity storage options include a growing range of battery technologies which are supported by the European Commission and the European Investment Bank through the European Battery Alliance (EC 2024f). Batteries will be increasingly used in stationary applications and/or in electric vehicles with sector coupling, as battery costs fall. Innovative battery designs are expected to emerge in the future with new chemistries to compete with the lithium-ion batteries of today, possibly including flow batteries for stationary applications. Batteries are being increasingly used in combination with photovoltaics on buildings, where they allow prosumers to improve their energy security and to benefit from time-dependent tariffs (Section 6.4).

Pumped hydro storage has been the option with the largest electricity storage capacity until now (EASAC 2017), but the global capacity of battery storage is growing quickly and may soon exceed that of pumped hydro storage (IEA 2023c; Parkinson 2024). However, battery storage and pumped hydro will have different roles in the management of grid flexibility. Batteries offer a very speedy response, while pumped hydro is better suited for storage requirements over longer periods.

Batteries are modular devices that are increasingly being brought together physically to provide grid-scale electricity storage facilities for use by grid system operators. However, smaller batteries that are installed over wide geographical areas by individual prosumers or by local energy communities or businesses can also be brought together and managed by aggregators to provide flexibility services to grid system operators. Work to develop and demonstrate such aggregated virtual power plants for grid flexibility management is ongoing (ENTSO-E 2025c).

Using hydrogen electrolysers to balance the grid by sector coupling to the production and storage of hydrogen for future use by industries and transport is an emerging flexibility measure. However, its potential for grid flexibility management is not yet clear, and this will depend on the future flexibility of hydrogen electrolysers (Section 3.3) (Nguyen *et al.* 2024), and on future investments in hydrogen storage and use (e.g. for steel making or producing methanol, ammonia, and sustainable aviation fuels).

Energy-intensive industries that consume electricity, for example aluminium producers, can similarly help to balance the grid by adjusting their production to suit the availability of variable renewable electricity supplies (demand response). With flexible production, they can benefit from low-cost electricity supplies at times when these are available (Bizjak *et al.* 2024). More industries such as cement producers may participate in demand response schemes in the future (Mossie *et al.* 2025).

Low-temperature heat storage, with sector coupling to buildings, district heating systems, and industry, offers a cost-effective way to store excess electricity for future use in space and water heating (IRENA 2020).

Transmission and distribution grid interconnections can be used to trade electricity across borders and between regions, and this can be a cost-effective way to manage flexibility on grids with high fractions of variable renewable generation. Cross-border interconnections must be strengthened, but cooperation between Member States must also be supported and monitored to maximise energy security. *Mechanisms for managing cross-border trading* of electricity are included in the EMD (EU 2024d), but major investments are needed to strengthen interconnections in many parts of the EU to meet growing flexibility needs and to address problems with grid congestion. As part of its Ten-Year Network Development Plan, ENTSO-E performs studies to identify borders/areas where more electricity trading is needed to deliver secure electricity supplies, reach decarbonisation targets, and keep costs under control (ENTSO-E 2024b).

6.6 Methodologies for electricity resource adequacy assessments and for remunerating backup generation (capacity mechanisms) are still evolving

For a long time, the electricity industry has been responsible for ensuring that it has adequate generating capacity to deliver the peak demands on its systems, and this has been a relatively straightforward task because most of the generating plants were at least partly flexible and dispatchable. However, as fossil-fuelled generating plants are increasingly replaced by variable renewable generators (wind, solar, and hydro), the task of assessing the adequacy of generating systems is becoming more complicated.

The EMD Regulation (EU 2024d) obliges ENTSO-E to carry out resource adequacy assessments for all bidding zones at EU level and the Member States to perform them at national level. The methodology for making them is still evolving under the responsibility of ACER but must take into consideration all the sources of flexibility, including generation, storage, demand response, and interconnections.

Adequacy assessments require close cooperation between neighbouring Member States because of the inclusion of interconnections. Because assessments have to be performed for the different seasons, there are continuing studies to ensure that relevant weather data are used both to address the impacts of the weather on energy demands and its impacts on wind and solar power generation (Harang *et al.* 2020; Dubus *et al.* 2022).

Potentially long periods in winter with very low wind speeds and little sun, known as dunkelflauten, are of particular concern because they have been found to last for up to ~2 weeks in some parts of northern Europe. Moreover, the possible impacts of climate change on the frequency and duration of future dunkelflauten are difficult to predict, but they could obviously have important impacts on the security of energy supplies unless adequate backup generation is available.

Power supply options to mitigate winter electricity deficits can be seen as a significant hurdle in the EU's ambitious goal of achieving a net-zero energy system by 2050. While the widespread adoption of electric vehicles and heating systems promises a cleaner future, it also creates a potential supply and demand mismatch. An important challenge for the energy transition lies in the seasonal nature of electricity production from rooftop photovoltaic installations, which generate a significant amount of electricity during summer months but not during winter's longer nights, when increased heating needs are currently met using fossil fuels.

Wind energy offers a promising solution on a continental scale. However, studies have shown that the abundant resources and geographical diversity of wind energy may nevertheless need to be combined with other electricity sources, such as biomethane, to mitigate the seasonal fluctuations of solar and hydropower in Switzerland (Frank *et al* 2021; Mellot *et al.* 2024). Similarly, the growing use of heat pumps could present a challenge during harsh winters in landlocked nations if they lack access to sufficient sustainable electricity, for example from offshore wind farms. There are several landlocked countries in the EU, including Austria, Czechia, Hungary, and Slovakia, as well as countries interconnected with the EU, such as Switzerland, so for these, the transition to a net-zero may require more than one source of sustainable electricity to bridge the gap during harsh winters.

Analyses of power supply alternatives to mitigate future winter electricity shortfalls in Switzerland, encompassing costs, social acceptance, sector coupling implications, and land and critical raw materials requirements, have identified combined-cycle gas turbines (with CCS if fuelled with natural gas) and high-elevation photovoltaic installations as options for reducing costs (Mellot *et al.* 2024). However, the challenge of meeting winter energy demands in Switzerland remains, and electricity imports will need to continue in winter until more progress has been made with inter-seasonal storage and sustainable fuels for power generation (Rüdisüli *et al.* 2022).

Backup generation and capacity mechanisms have been subjected to hot debate during the revision of the EMD. This is because Member States have adopted different approaches (capacity mechanisms) for remunerating generating capacity that is only needed for limited periods to ensure security of supply but otherwise does not participate in the electricity market. In the past, there has been excess fossil-fuelled generating capacity in most Member States, so resource adequacy has not been a problem. However, as that excess capacity is phased out and variable renewable generation is increased, ensuring energy security at the lowest possible costs for consumers becomes more challenging. Fortunately, many existing fossil-fuelled power plants that are no longer acceptable or competitive in the electricity market could be cost-effectively used for short periods to provide backup or reserves and hence for ensuring energy security while also accelerating the transition to sustainable electricity generation with minimal capital costs. The importance of backup generation, and the need to limit capacity mechanisms

Box 8 Electricity market measures to help maintain secure supplies during the transition

- For wholesale markets, advanced models for long-term contracts, such as Power Purchase Agreements and Contracts for Difference.
- For backup capacity, a balance between flexibility options and regulated capacity mechanisms in wholesale markets, on the basis of pricing models with clear signals for scarcity and excess generation.
- For end-users, including prosumers and energy communities, dynamic (bi-directional) pricing and time-dependent tariff schemes.
- Flexibility measures including storage and strong interconnections, with transparent dynamic pricing signals and price spreads to facilitate demand response and cross-border trading.
- Adequate dispatchable generating capacity (residual load suppliers), so that prosumers and renewable energy communities can maximise their contributions to electricity supplies.

to generators that use sustainable fuels are recognised in the updated EMD Regulation, which requires capacity mechanisms to be compatible with State Aid Rules and open to cross-border participation. As the debate on capacity mechanisms continues, the EMD Regulation requires ACER and the European Commission to simplify the process of assessing them by 2025.

Among scientists, some see capacity mechanisms as the solution, while others prefer market forces (Newbery 2018; Astier and Lambin 2019; Pollitt 2021; Haas *et al*. 2022). Examples of Member States with capacity mechanisms include France (RTE 2024) and the UK (UK Government 2023). Arguments in favour of capacity mechanisms are that they remunerate backup generation and guarantee supply security. Arguments against them are that they distort wholesale markets, leading to wrong price signals for other options, and that they subsidise power generators unfairly (Praktiknjo and Erdmann 2016).

The scope of resource adequacy assessments will need to evolve to address the more integrated energy sector that is expected as the energy transition progresses. They are currently performed only for the electricity system, but backup generators will need to be supplied with sustainable fuels, such as biomethane or in some cases hydrogen or e-fuels, and these will need to be produced and stockpiled for when they are needed. In some locations, backup generation may be provided by natural gas generators that are connected to carbon capture and storage systems. Excess renewable electricity produced from solar generators in the summer may be stored as heat for use in winter (PlanEnergi 2023), and the numbers of prosumers are expected to grow. These evolving components of an integrated energy system will become increasingly important in future resource adequacy assessments.

6.7 Electricity market rules, including bidding zone definitions, use of price signals, and tariffs for managing flexibility measures, and regimes for suppliers of last resort, are evolving

The electricity market rules have been updated in many respects since 2018, in response to the EU's commitment to phasing out fossil fuels and delivering a transition to net-zero GHG emissions by 2050. A summary of market-related measures that would help to maintain the security of electricity supplies during the transition is given in Box 8.

Electricity (market price) bidding zones are the largest geographical areas in which bids and offers from market participants can be matched without the need to attribute cross-zonal capacity. Currently, bidding zones in Europe are mostly defined by national borders. The EMD requires a configuration of bidding zones that aims to maximise economic efficiency and cross-zonal trading opportunities, while ensuring security of supply. To achieve this, a review of the existing bidding zones by TSOs is continuing (at least until the end of 2024) to analyse the different bidding zone configurations and identify structural congestion. Better-defined bidding zone configurations can be expected to bring several benefits, including increased opportunities for cross-zonal trade, more efficient network investments, and more cost-efficient integration of new technologies (ACER 2024b).

Price signals and tariffs are needed for managing flexibility measures, because flexibility measures are only likely to be used if they are triggered by sufficiently high price signals from the electricity markets. Moreover, flexibility measures are less likely to be used if the markets include regulated capacity mechanisms (Halbruegge *et al.* 2024). Energy-only markets can provide the required price signals, for example temporary scarcity prices that are higher than short-term marginal costs when demands exceed supplies, and temporary negative prices during times of excess electricity supply (Seel *et al* 2021; Biber *et al.* 2022). Flexible power plants for providing capacity adequacy will play a role in every system with or without regulated capacity mechanisms, but the required backup capacity must be determined case by case. Few time-of-use tariffs have yet been implemented in the EU, and more work is needed to develop better tariff designs, which should include components that encourage users to limit the maximum power that flows from and to the grid (Haas *et al.* 2023).

The EMD requires Member States to put in place a regime with suppliers of last resort, if they have not already established one, to ensure continuity of supply at least for household customers. Such regimes provide consumers with secure supplies in the event of their first supplier's exit from the market, because all households must be provided with electricity. However, this mechanism does not protect consumers from facing higher costs after the transfer, except in the case of energy poor and vulnerable households, as was demonstrated during the crisis that followed the invasion of Ukraine. In response to this, ACER now underlines that a minimum level of financial robustness should be expected from energy suppliers (ACER 2022b), but discussions are continuing on the best ways of achieving this, for example a financial guarantee or a consumer levy mechanism.

7 Energy security risks, benefits, and threats

Most energy security threats are addressed in EU policies and legislation, so what more needs to be done?

7.1 Overview of energy security risks and benefits

The energy transition is expected to reduce the risks of international energy-related crises and conflicts, but these could be replaced by similar crises related to supplies of technologies and critical materials for sustainable energy systems unless these are produced domestically or in partnership with trusted suppliers. As discussed in earlier chapters, sustainable energy supplies reduce greenhouse gas (GHG) emissions, are less vulnerable to physical attacks, and empower local energy communities and prosumers to act and make decisions locally.

However, in recent years, Europe has become heavily dependent on imported sustainable energy technologies, because these have been cheaper than those produced in the EU. Hence, before the supply security and affordability benefits of the energy transition can both be fully realised, steps must be taken to reduce the costs of domestically produced sustainable energy technologies.

Member States must report on energy security in national energy and climate plans (EU 2018; EU Monitor 2023), but their reporting lacks a common structure, so assessing progress at EU level is difficult. If Member States were to report on their progress towards agreed energy security targets using specific criteria, then their implementation of energy security policies would be more visible. For example, they could report on the criteria and benchmarks contained in the Net Zero Industries Act (EU manufacturing capacity of strategic net-zero technologies), and in the Critical Raw Materials Act (extraction capacity, processing capacity and recycling capacity of SRMs), as well as on the diversity of fuel and technology suppliers, and storage capacities for sustainable fuels.

While carbon dioxide (CO_2) emissions from the EU amounted to only 6.1% of global CO_2 emissions in 2023 (EDGAR 2024), the EU has played a leading role in promoting GHG emission reduction in recent years, and it is committed to encouraging other countries and regions to reduce their emissions and thereby to mitigate global warming and climate change. In addition, the energy transition offers valuable energy security benefits to the EU (Box 9), including opportunities for European industries to export sustainable energy technologies and services that have been proven in European markets.

The EU's commitment to net zero by 2050 is a long-term policy objective, which is needed to boost investor confidence in long-term investments in sustainable energy technologies and systems. However, it must be recognised that many businesses and investors are focused on achieving returns on their investments in the short term, and that the capital costs required to deliver the last few per cent of CO_2 emission reductions will inevitably be higher than those in earlier years. Hence, policies and regulations for the short and medium terms are also needed to guide investors and stakeholders through an energy secure transition to 2050. For example, using very small amounts of fossil fuels in existing or new backup generators, which are needed for only a few hours per year and therefore produce very few GHG emissions, may be justified—especially if progress is made in the future with innovative solutions involving negative emission technologies for capturing and storing CO_2 from the atmosphere in line with the EU Certification Framework for permanent carbon removals, carbon farming, and carbon storage in products (EU 2025b).

Box 9 Energy security benefits of EU transition to sustainable energy supplies

1. Reduced EU dependency on fossil fuel imports, which can be insecure, and reduced volatility of fuel prices that can weigh heavily on the trade balance of large importers such as the EU. In contrast, sustainable sources of energy are often available locally and have become more affordable.
2. Reduced GHG emissions which helps to mitigate climate change and hence to avoid adverse:
   (a) cascading impacts of climate change on trade, finance, and infrastructure;
   (b) impacts of climate change on human health;
   (c) impacts of climate change on biodiversity.
3. Decentralised energy systems and infrastructure, that are less vulnerable to damage from extreme weather, and to malicious attacks, but not necessarily to cyber-attacks.
4. Increased opportunities for decision making by local communities and citizens.
5. Opportunities for European industries to export sustainable energy technologies and services that have been proven in European markets.

The transition from fossil fuels to sustainable energy supplies carries, financial, regional, temporal, and geopolitical risks. Massive investments are needed in sustainable electricity generation and in strengthening electricity infrastructure, including storage, interconnections, and related measures for managing grids that are supplied with variable renewable electricity. At a local level, some negative impacts on land use have been reported where solar photovoltaic farms were built in valuable natural environments or on high-quality agricultural land. However, there are potential synergies when land is used for both solar photovoltaic panels and agriculture, and further developments with 'agrivoltaics' can be expected as pressures on land use increase (Widmer *et al.* 2024). Also, the EU energy transition could be delayed by geopolitical attacks on imports and trade until most new sustainable energy technologies are made in the EU.

Table 4 Security risks for fossil-fuelled, renewable, and nuclear electricity generation

Security risk	Fossil fuels	Renewable energies	Nuclear energy
Resource availability	Finite resources, subject to depletion (stocks).	Abundant resources, subject to variability (flows).	Finite resources, but these are projected to be sufficient for long term (NEA 2025). Also, potential for reprocessing.
Vulnerability to supply disruption	Vulnerable to supply cut-offs caused by physical disruptions and geopolitical tensions, leading to energy shortages and/or price spikes, depending on availability of stored fuels.	Wind, water, and solar resources are variable but predictable and distributed. Supply chains for renewable technologies and materials are vulnerable to cut-offs, but do not pose immediate risks to energy supply.	Vulnerable to cut-offs of nuclear fuel and uranium enrichment supplies, caused by geopolitical tensions, but low risks to short-term energy supply because stocks are held in EU.
Infrastructure resilience	Vulnerable to disruptions due to centralised infrastructure. Burning fossil fuels without CCS or CCU creates negative climate impacts on energy systems.	Decentralised infrastructure increases resilience to disruptions.	Vulnerable to disruptions due to centralised infrastructure. Large power plants can cause substantial falls in electricity supplies if disruptions occur without enough backup generation.
Affordability Notes: 1. Electricity prices vary with demand and mix of supply. 2. Electricity cost comparisons must include capacity factors and system operating costs (IEA 2020).	Susceptible to fuel price fluctuations and fuel market volatility. Comparatively low capital costs for power plants (notably gas turbines).	No fuel costs, apart from biomass. Upfront capital costs for renewable technologies have been falling. Substantial system costs for grid reinforcement and flexibility management (storage, demand response, backup generation, etc.).	Nuclear fuel costs are a minor part of total generating costs. Upfront capital costs for nuclear power plants tend to be underestimated. System costs (for grid reinforcement and flexibility management) are typically less than for variable renewables.
Sustainability Note: comments based on life cycle GHG emissions (NREL 2021).	Fossil fuels are not sustainable. EU is committed to transition away from fossil fuels.	Renewable energies have low-carbon footprints and are deemed to be sustainable, but have potential impacts on nature depending on location and indirectly through mining of CRM and SRM.	Nuclear power is deemed to be sustainable because life cycle emissions of plant and fuel supplies are much lower than those of fossil fuels, but there are small risks of nuclear accidents (radiation) or spills during fuel transportation.
Storability Note: storage should be in EU and not dependent on owners in third countries.	Physical storage of solid, liquid and gaseous fuels is well known, and greatly reduces the need for electricity storage.	Biofuels and e-fuels can be stored, but may degrade over time. To store hydrogen is challenging. Falling battery costs are improving the viability of renewable electricity storage.	Enriched uranium is storable. Operators usually store it locally so that they can continue operating in case of supply disruption.
Intermittency	Electricity produced using fossil fuels is dispatchable.	Electricity produced by wind and solar is variable, so flexibility management measures are needed. Hydro may change with the seasons.	Nuclear power can be dispatchable.

Many of the energy security risks and challenges that are expected to arise during the energy transition were quantified by the IEA in its 2024 World Energy Outlook and discussed in a report on geopolitics by IRENA (IEA 2024e; IRENA 2024a). Key energy security risks related to the use of fossil fuels are compared with those for renewable and nuclear electricity generation in Table 4, which is based on IRENA's work, but adapted by EASAC.

7.2 Threats to energy security and how to address them

There are many potential threats to energy security (Cherp *et al.* 2012; Kivimaa and Sivonen 2023), of which most are already being largely addressed by EU policies and legislation. However, EASAC has identified 10 key threats that justify special attention by policy-makers (Box 10).

These key threats are discussed below, together with summaries of options and measures that can be used to address them.

Box 10 Key energy security threats

1. Malicious physical attacks
2. Malicious damage to supply chains, commerce, and trade
3. Cyber-attacks
4. Natural disasters, pandemics, and extreme weather
5. Societal tensions
6. Accidental or systemic failures of energy systems or infrastructure
7. Energy system and market integration
8. Electricity generation and network current carrying capacities
9. Electricity grid flexibility management
10. Inadequate skills in the workforce

Threat 1 Malicious physical attacks on energy infrastructure

With or without a formal declaration of war, terrorists and/or national governments in third countries are carrying out physical attacks on energy infrastructure in EU and neighbouring countries (Siddi 2023).

Attacks on large-scale energy installations can cause greater disruption than on small-scale and distributed power plants. Recent examples include a ransomware attack on Norsk Hydro in 2019, explosions in the Nord Stream gas pipelines in 2022, damage to the Baltic undersea gas interconnector and communications cables between Finland and Estonia in 2023, and damage to the EstLink undersea cable between Finland and Estonia in 2024 (Section 1.4).

Threat 1 How to address threats of malicious physical attacks on energy infrastructure

Preparing for a more dangerous world is necessary (Niinistö 2024) because attacks and terrorism cannot be avoided. This includes diplomacy, building partnerships with third countries, and stockpiling energy resources for military use. (Note: European Defence Fund supports research on greening energy supplies for military use (NOMAD 2024). Military defence policies lie outside the scope of this report.)

Sustainable energy diplomacy can help to reduce geopolitical tensions and peace building. It can also help to build stronger links across Europe between teams working on energy security, counter terrorism, and military defence.

Member State cooperation to protect energy infrastructure must cover electricity and gas grids (offshore and onshore), dams, power plants and digital networks (Section 6.4).

Threat 2 Malicious damage to energy supply chains, commerce, and trade

Geopolitical risks increase market uncertainty, which dampens investments in innovation and growth (Draghi 2024).

Malevolent actors are weaponising energy supplies and energy costs, and this risk has been increasing in the EU and across the world since the invasion of Ukraine.

In 2022, Russia attacked EU supplies of natural gas. Future threats to European energy security could involve attacks on international trading of both fossil and sustainable fuels (including hydrogen, ammonia, and e-fuels), critical raw materials (including enriched uranium), and strategic components, systems, and spare parts for renewable energy technologies. Russia could also restrict exports of enriched uranium for nuclear power generation, which have already been blocked to the USA, and for which the EU is heavily dependent on Russia.

Strategic energy technology manufacturing and its supply chains, including supplies of critical raw materials, and international energy and energy technology markets may all be subjected to malicious attacks and the use of energy and other resources as geopolitical tools.

Threat 2 How to address threats of malicious damage to energy supply chains, commerce, and trade

Diversification of fuel and technology suppliers is crucial for energy security and is already being implemented with coordinated purchasing through the EU energy platform (EC 2023d). This platform could be used in future for sustainable fuels, such as hydrogen, ammonia and biofuels, and for building international partnerships to strengthen the resilience of supply chains. In line with the EU Green Deal Industrial Plan (EC 2023h), future trade agreements should fully reflect the energy transition, and combat unfair trade policies, practices, and subsidies in third countries.

Energy technology manufacture in the EU could be expanded and protected to improve energy security. This will permit imports to be replaced by energy technologies and spare parts made in the EU (industrial policy), with innovative designs to reduce the use of critical raw materials (research and innovation policy).

Sustainable fuels for backup generation, industry, and transport, including hydrogen, e-fuels, and SAFs can be produced in the EU with protected production facilities.

A circular economy is less vulnerable to malicious attacks and contributes to energy security by reducing energy demand in cost-effective ways. It reduces the need to mine and refine raw materials and focuses on reusing or recycling components, for example those made of steel, aluminium, copper, and cement, instead of making new ones.

Knowledge and information sharing on geopolitical threats can help energy system operators and security organisations to prepare for malicious attacks on energy systems and infrastructure. International science, technology and innovation networks and partnerships with third countries can help to build mutual understanding and cooperation for addressing threats to supply chains, commerce, and trade.

Threat 3 Cyber-attacks

Cyber-attacks are growing in number as energy supply and energy consuming systems become increasingly dependent on information technology (IT) components and systems, so all stages of the energy supply chain must be protected (Chapter 5). The need for cyber security has been recognised for many years, but the need to strengthen it has become more urgent since the invasion of Ukraine.

IT systems typically include large numbers of pieces of software (known as dependencies) that rely on third-party program code to function properly and can be challenging to understand. These typically pose three main threats:

1) components contain bugs which could lead to system failure;
2) components can be controlled directly or indirectly by a third-party. [USA, China, and Russia are banning each other's software for fear of this];
3) components offer a potential attack surface for malicious actors.

Software that enables remote and on-site gathering of data from energy supply and consuming equipment is particularly vulnerable to cyber-attacks.

Threat 3 How to address cyber-attacks

IT systems used for energy supplies can be manufactured and installed by trusted organisations within the EU to improve energy security. This is a requirement of the updated cybersecurity directive NIS2 and network code (EC 2022b; EC 2024i), but its implementation in Member States will need to be closely monitored.

The new EU Cybersecurity Reserve (Box 4) will offer incident response services by trusted providers to organisations that have few in-house IT staff with cyber security experience. This could also build up a coordinated knowledge base of shared experiences that would help IT system operators across the EU to strengthen energy security by working together.

Cyber risk analyses made by network operators in line with the NIS2 Cybersecurity Directive will strengthen EU energy security, and their scope should include all likely combinations of the cybersecurity threats involved.

Threat 4 Natural disasters, pandemics, and extreme weather

Natural disasters, including earthquakes, volcano eruptions, wildfires, plant diseases, and human pandemics can disrupt supplies of electricity and heat from fossil and sustainable energy sources.

Greenhouse gas emissions from the use of fossil fuels are the main source of anthropogenic global warming, which is leading to climate change and causing more frequent and more extreme droughts, wildfires, storms, and floods (Caudron 2024; IPCC 2023).

Secure water supplies are important not only for human health and agriculture, but also for cooling thermal power generators, including nuclear reactors, and for hydropower generation and pumped hydro-electricity storage (RTE 2021). Droughts in summer can therefore lead to energy supply shortages (Gjorgiev and Sansavini 2017).

Severe storms, wildfires, and extreme heat are causing damage and disruption to urban, rural, and offshore infrastructure.

Extreme heat reduces the performance of wind and photovoltaic generators, and increases energy demands for cooling (IRENA 2024a; EEA 2024b).

Threat 4 How to address the threats of natural disasters, pandemics, and extreme weather

Phasing out fossil fuels to reduce the emissions of carbon dioxide and methane is the most powerful option for mitigating climate change in the short to medium terms. Options that may become more competitive in the longer term include CCS, CCU, and capturing and storing carbon from the atmosphere using negative emission technologies in line with the EU Certification Framework for permanent carbon removals, carbon farming, and carbon storage in products (EU 2025b).

Strategic energy reserves, including backup generation, are needed for crisis management following natural disasters, and Member States have a responsibility under the Critical Entities Resilience Directive (EC 2022a) to provide essential services. As sustainable energies replace fossil fuels, the resilience of electricity supplies will grow, and the need for strategic energy reserves will fall. Nevertheless, sharing strategic energy reserves between Member States will strengthen energy security and benefit from economies of scale.

Disaster response plans for electricity supplies will require dispatchable electricity generation. In addition, they may include raising public awareness and promoting temporary energy saving measures, for example lower temperatures in buildings, less motorised travel, and temporary reductions of industrial production.

Secure energy supplies rely on secure water supplies in many parts of Europe, and climate change is causing increasingly serious damage to the security of water supplies. Plans to address the collection, storage, conservation, and management of water supplies for use with energy systems are outside the scope of this report, but they clearly deserve close attention by policy-makers.

Threat 5 Societal tensions

Societal tensions affect energy security in different ways. Some groups of people respond by refusing to adopt policies, such as phasing out fossil fuels, which could improve energy security for everyone (by reducing dependence on fossil fuel imports). Other groups delay and increase the costs of the energy transition by protesting against the construction of wind or solar generators, or electricity pylons or other grid reinforcements near where they live. Populist politicians and movements encourage such protests (Vihma *et al*. 2021; Yazar and Haarstad 2023).

Energy-related reasons for increased tensions in society include the following:

- Energy prices have been rising, owing to gas supply disruptions, government measures such as levies for grid reinforcement, and inflation. This has increased the cost of living because many goods rely on energy for their manufacture and distribution. In addition, the polluter pays principle and the ETS increase the prices for fossil fuels.
- Job losses among workers in the fossil fuel industries are being caused by the transition to sustainable energy sources. Although monetary compensation has been offered, historical traditions and cultures associated with fossil-fuel-based employment are so strong in some communities that there is a backlash against the energy transition (McNeal and Beauman 2022).
- Energy transition has more severe impacts on low-income households than on wealthy ones. For example, wealthy households can afford to invest in solar panels and heat pumps, and in energy efficiency measures to reduce their energy consumption. They can also buy low emission cars which are permitted to enter city centres. In contrast, poor households cannot afford to invest in energy efficiency measures or renewable energies, or to replace their cars.
- Sustainable energy generation is competing with agriculture and forestry for land use. Farmers are finding it more profitable to use their agricultural land for solar farms than for food production, and foresters are felling their trees to sell for bioenergy. In addition, developers are building wind farms and hydro plants, or mining for raw materials in areas of outstanding natural beauty and environmental interest.
- Homes and communities in rural and urban areas, as well as forests, farms, and critical infrastructure are being destroyed by wildfires, floods, and rises in sea water levels, caused by climate change. Such impacts of climate change create societal tensions in the communities involved, and the numbers of such communities are growing (EEA 2024b).

Threat 5 How to address the threats of societal tensions

Engagement with citizens on the security benefits and opportunities offered by the energy transition is key to limiting the impacts of energy policies on societal tensions. Misinformation can be tackled and citizen engagement in the transition increased in many ways. Some strategies for citizen engagement are given below:

- Positive opportunities for action should be emphasised, not messages of doom, because negative messages are typically ignored (Cotteleer and Murphy 2015). Messages should be concise, memorable, and link behaviour and actions with hope for the future. Media should be selected to suit the target audience.
- Independent advice on energy security issues can be provided to citizens and households through local one-stop-shop energy centres, for example on the following:
  - how to become a prosumer or to set up a local energy community;
  - how energy bills can go down when the unit price of energy goes up if energy efficiency measures are used to reduce consumption;
  - the difference between final energy and primary energy consumption (important for assessing energy options: see Section 2.5 and Figure 8).
- Training schemes can repurpose and adapt the skills of workers whose skills are no longer needed. Compensation schemes can support communities that experience employment loss, not only with money for livelihoods and training, but also with dialogue that acknowledges cultural aspects of their livelihoods.
- Support for energy services can be given to vulnerable households and groups, thereby offering energy justice and reducing energy poverty.
- Financing and subsidy schemes can be provided for working households and strategic industries to buy sustainable energy systems that have high capital costs. Financing intermediaries and schemes such as mortgages can help households, local energy communities and strategic industries (Brown 2018; Brown *et al*. 2019).
- Potential synergies when land is used for both solar photovoltaic panels and agriculture, 'agrivoltaics', have been studied for more than 40 years. Photovoltaic module mounting systems have been developed for different crops and livestock, and further developments can be expected as pressures on land use increase (Widmer *et al.* 2024).
- Sustainable forest management to produce timber for construction and long-life wood products helps jobs in rural areas, and reduces forest fires. It also improves energy security by reducing energy demand for making steel and cement.
- 'Energy efficiency first' can be discussed with businesses and industries in local 'energy cafes' (Martiskainen and Speciale 2017). Businesses rely on supplies of affordable energy, and workers rely on businesses for jobs and incomes, so improving energy efficiency can reduce tensions among businesses and workers.
- Energy 'sufficiency' improves energy security by deliberate behaviour change to reduce energy consumption, for example switching off lights when not in use, walking instead of driving, or heating only occupied rooms. Sufficiency has no agreed definition, and its impacts can be reduced by rebound effects (Brockway *et al.* 2021), for example sufficient energy for a household can mean more energy use (Gynther 2021).

Threat 6 Accidental or systemic failures of energy systems or infrastructure

Innovative technologies and systems can experience failures in the early stages of commercialisation despite careful testing and maintenance, and correcting problems (including human errors) that occur when the production of new technologies is rapidly increased, can incur high costs (Draghi 2024).

The energy transition will substantially increase the demand for electricity and so it will put stress onto the whole electricity supply system. In contrast, gas networks will deliver less gas and produce less income for the businesses that own them, so they risk becoming less well maintained.

Modern technologies rely increasingly on IT systems, which can experience hardware or software failures caused by misuse, imperfect software updates or cyber-attacks (Threat 3).

Threat 6 How to address accidental or systemic failures of energy systems or infrastructure

Certification of the performance and reliability of energy systems, before they are put into the market, is crucial for energy security, but it takes time and can be costly, so support for it can help the EU to compete in global markets. Many energy systems are already covered by the EU eco-design and labelling Regulation (EC 2024m).

Monitoring the performance of energy networks and systems during operation can provide advanced notice before failures occur. In addition, analysis and reporting on the findings to other actors with similar equipment can help to prevent more failures.

IT systems for energy supply must be professionally managed using documented programmes of checks and updates, with secure backups. They must also be made cybersecure (Threat 3). Close cooperation on IT issues and cybersecurity between transmission system operators, distribution system operators, and power suppliers is particularly important.

Threat 7 Energy system and market integration

1. A fully integrated energy system and market that is designed to deliver secure energy supplies to all consumers (buildings, industry, transport, etc) in the EU is still 'work-in-progress'. The updated regulation and directive on electricity market design (EMD) (EU 2024c; EU 2024d) focus almost entirely on the electricity supply system, so there is a risk that their future implementation will fail to fully integrate electricity with other energy supply systems, such as district heating, hydrogen, and biofuels as well as with end-users in industry, transport, and buildings. Similarly, the electricity risk preparedness regulation (EU 2019a) focuses on the electricity system (ACER 2025). A more integrated EU energy system and market would help to limit the costs of the energy transition and could improve energy security by using the available energy resources more efficiently (EC 2024e).
2. Energy markets alone typically fail to mobilise private funding for long-term investments over periods of 20 to 30 years in sustainable energy plant and infrastructure, including smart grids and upgrading of existing grids, which are needed to strengthen energy security.
3. Markets tend not to adequately price risks that have high impacts but little chance of occurring. Member States may therefore lack mechanisms and energy systems that permit them to respond efficiently to natural disasters, extreme weather, unforeseen breakdowns, terrorist attacks or geopolitical interference with their IT systems (cyber-attacks).
4. Public confidence in the energy transition will be put at risk unless the costs of deploying security measures in energy supply networks and systems are set and managed independently.

Threat 7 How to address threats related to energy system and market integration

1. The EU energy system integration strategy (EC 2020d) highlights steps to improve energy security as fossil fuels are phased out and electrification increases. Progress was reviewed in 2024 (EC 2024e), and five steps are summarised below:
   (a) Hydrogen markets and infrastructure (electrolysers, network and storage) can support electricity grid flexibility management (ACER 2024c), and supply industry and transport. Research is needed on electrolysers (Annex 3);
   (b) Building renovations contribute to energy markets and improve energy security by reducing demand for electricity, heat, and fuels. Buildings should be renovated, not demolished and use materials with low embodied energy. Renovations offer health benefits and add value to buildings (EASAC 2021);
   (c) Sustainable district heating and cooling offer demand response and low-temperature heat storage to energy markets. For space heating, heat pumps with sustainable electricity, geothermal, and solar energy will be prioritised over bioenergy, which has more valuable uses (EASAC 2021). Local heat planning helps to prioritise the use of waste heat from industries, data centres, and other sources, for example shopping malls or nuclear reactors;
   (d) Transport is being increasingly integrated with electricity markets, and its energy use can be reduced (EASAC 2019), offering higher energy security by:
      - facilities that encourage people to avoid motorised transport, for example by walking, cycling, video conferencing, and working from home;
      - shifting people to attractive, competitive, and less energy-intensive transport services, such as buses, trams, trains, and ships;
      - improving efficiency of vehicle power trains (e.g. electrification), and reducing vehicle weight, drag and rolling resistance;

   (e) Industrial processes can participate in electricity markets through demand response schemes and typically consume less energy if electrified. Heat pumps can supply industrial process heat up to about 200 °C (JRC 2023).
2. Member States can support investments in sustainable energy systems and infrastructure, to reduce the risks within State Aid Rules. For example, subsidies may be justified where delaying action will be more costly (Alberti 2024), although subsidies can be expected soon to be replaced by tailored long-term financing.
3. Capacity mechanisms fund backup generation in some Member States for natural disasters, extreme weather (including long dunkelflauten), breakdowns, terrorist attacks or geopolitical interference (e.g. cyber-attacks), and when supplies from the market are insufficient. Until now, backup has been provided by fossil-fuelled generators, but these are being replaced by wind and solar generation. The EMD Regulation requires ACER and the European Commission to simplify the assessment of capacity mechanisms in this evolving context by 2025 (Section 6.5).
4. ACER has a key role in making the risk assessments, on which energy security costs are based, because energy security, like national and cyber security, is a public service to be managed outside energy markets and paid for transparently.

Threat 8 Electricity generation and network current carrying capacities

A secure supply of electricity means that the electricity system can always meet the agreed national loss of load expectation, which varies across Europe from approximately one hour per year in Sweden to 15 hours per year in Czechia, with most Member States having agreed values of between 2 and 5 hours per year (ACER 2022a). So, as fossil fuels are phased out and more buildings, industries, and transport systems are electrified, more sustainable generating systems must be built to ensure sufficient generating capacity, and grids must be strengthened to ensure sufficient current carrying capacity.

To minimise the overall costs of electricity, which will eventually be passed on to consumers, the combination of investments in reducing electricity demand, in generating plants, and in electricity infrastructure must be minimised.

The electricity resource adequacy assessment methodology in the updated EMD focuses on assets that participate in electricity markets, but it leaves Member States to choose how to provide backup generation in the event of a crisis (ACER 2024d). This approach will need to evolve as the energy transition progresses.

Inadequate current carrying capacities in networks are already reducing energy security by causing delays to the connection of renewable electricity generators, and by increasing grid congestion. Grids must be reinforced so that more generation can be installed.

Innovative electricity supplies can be expected to enter the market in future, so the existing methodologies for assessing resource adequacy and security risks may need to be adapted. For example, the feasibility of using CCS is being explored by countries with indigenous oil and/or gas supplies, with a view to continuing the use of some fossil fuels for electricity generation while also delivering commitments to GHG emission reductions.

Threat 8 How to address threats to electricity generation and network current carrying capacities

Electricity demands can be reduced by doing the following:

1. ‘Energy efficiency first’: typically a no regrets option in buildings, industry, and transport. It reduces energy demand without reducing the services delivered.
2. ‘Sufficiency’, for example flying less, buying smaller cars, or consuming less. This can be encouraged by institutions, businesses, administrations, and local leaders.
3. Building renovations that reduce the need to heat and cool buildings. These can reduce the electricity used in individual buildings and in district heating systems.
4. Expanding the use of efficient district heating in urban areas, using waste heat, cogeneration, solar and geothermal energies, and sustainable bioenergy.
5. Constructing facilities for people to avoid using motorised transport, or shifting to less energy-intensive transport modes, and improving vehicle performance.

Electricity supplies can be increased by doing the following:

1. Deploying more sustainable electricity generators (IEA 2024c).
2. Mobilising public and private financing for electricity infrastructure, to increase the capacity and flexibility of networks, including interconnectors, storage, backup generation, and smart technologies for demand response schemes. Where feasible, dynamic line rating technologies may be used to temporarily increase the ampacity[4] of existing overhead lines by up to 200% (ENTSO-E 2024c).
3. Accelerating permitting processes for the construction of sustainable generators and electricity infrastructure. This was addressed in the revised Renewable Energy Directive in 2023, but implementation by Member States is slow and some have reported skills shortages in permitting processes related to VRES (Draghi 2024).
4. Deploying CCS or CCU with power generation in areas where they can also be used by industry. Note: it is too early to assess the competitiveness of these options (Section 3.4).
5. Deploying more nuclear electricity (listed in Near Zero Industry Act (EU 2024f) as a strategic technology). Large-scale nuclear plants have high capital costs, need long-term commitments for financing, security of operations, fuel supply chains, waste management, and decommissioning (Sections 3.2 and A2.3).

[4] Ampacity is the term used for the maximum current carrying capacity, in amps, of a particular device.

Threat 9 Electricity grid flexibility management

Variable renewable generation and bi-directional exchanges with local energy communities and prosumers are growing and leading to grid congestion. Meanwhile, dispatchable fossil-fuelled generation is being decommissioned, thereby increasing the risks of brownouts or blackouts.

Dunkelflauten (low levels of wind and solar energy) are a growing threat to energy security. Until now, they have typically occurred for a few days per year in Europe, and longer dunkelflauten over large areas and lasting for more than a week have occurred about once in 20 years. However, it is unclear how the frequency and duration of future dunkelflauten will be affected by climate change.

Energy security mandates for transmission system operators and distribution system operators may need to be updated to accommodate the growing challenges of grid flexibility management.

Threat 9 How to address threats related to electricity grid flexibility management

The EU action plan for grids must be given a high priority (Box 6)

Public and private financing are needed for investments in grid infrastructure and in grid flexibility management measures (Sections 6.2 and 6.5), including the following:

1. Electricity storage, including pumped hydro, compressed air, and systems to exchange electricity with stationary and/or electric vehicle batteries.
2. Heat storage, including low-temperature heat stores in buildings and district heating systems, as well as high-temperature heat stores in industry.
3. Cross-border interconnections (with redundancies and reserve power carrying capacity). Interconnections require close cooperation between neighbours to avoid free riding (i.e. delegating responsibility for security of supply).
4. Backup generation (Threat 4 above).
5. Curtailment of variable renewable generation during periods of excess wind or solar supplies, when neither storage nor demand response can meet the needs.
6. Electrolysers for producing sustainable hydrogen (Section 3.3).
7. Demand response schemes with smart grids, time-of-use tariffs, batteries, and smart meters for managing demand (Section 6.5 and Box 5). Smart charging points for electric vehicles are already behind schedule in many parts of the EU.
8. Grid frequency and voltage stabilisation systems, for example high-inertia stabilisers or power electronic systems for absorbing reactive power. These and black start capability will be needed as rotating generators are replaced by wind and photovoltaics.

Mandates for transmission system operators and distribution system operators can be updated through ACER to cover evolving issues, including capacity reserves and backup generation (capacity mechanisms), electricity and heat storage, grid reinforcement and interconnections to mitigate congestion, and cyber risk analyses and cyber protection for digital network management.

Threat 10 Inadequate skills in the workforce

One of the biggest risks to the security of sustainable energy supplies in the EU is a lack of knowledge and skills in the workforce (Eurelectric 2024b).

In contrast to the situation some years ago, there is now an urgent need to increase the number of workers with skills in computers, IT, and artificial intelligence. In particular, there is a need to increase the number of experts working in energy supplying and consuming industries who have high levels of knowledge about how to defend the EU's energy infrastructure and systems from software failures and cyber-attacks.

There is a need to increase the numbers of workers with knowledge and experience of manufacturing, installing, and operating sustainable energy technologies, including wind and solar technologies, batteries and battery chargers, hydrogen, and electricity network management. The deployment of heat pumps is reported to need more skilled installers (IEA 2024e).

There is a particular need to maintain sufficient workers with knowledge and skills in nuclear energy because many of those who built the existing systems are approaching or have already reached retirement age, and workers will be needed for many years to decommission the existing systems as well as to build and operate new systems in those countries that plan to invest in them.

Skills and expertise in foresight and analysis of potential geopolitical and other security risks are needed as well as in security policy coordination.

These needs must be addressed urgently and managed for the long term.

Threat 10 How to address inadequate skills in the workforce

Existing education and training programmes can be reinforced and where appropriate expanded to focus more strongly on energy security in the following fields:

- Information technologies, artificial intelligence and computer skills for operating and managing digitalised energy and supervisory control and data acquisition (SCADA) systems.
- Cybersecurity and protecting systems from cyber-attacks and software failures.
- Renewable energy technologies and systems, including the manufacture, installation, and operation of wind, solar photovoltaics, hydropower, solar heating, and geothermal electricity and heating.
- Efficient end-use energy technologies and systems, including manufacture, installation and operation of heat pumps, batteries, battery chargers, electric vehicles, hydrogen electrolysers, and fuel cells.
- Electricity network flexibility management, including time-of-use pricing, demand response, curtailment, electricity and heat storage, backup generation, and interconnections.
- Nuclear energy technologies and systems, including construction and operation of large reactors, small modular nuclear reactors, and management of supply/disposal chains for nuclear fuels and wastes.
- Holistic and system-wide foresight and understanding of the energy sector, market operation, energy policy, and its links to other sectors and policy domains.

8 Conclusions

This report has shown that security aspects of the transition to sustainable energy supplies are diverse and interconnected with developments in other sectors, such as information technology, buildings, transport, and industry. Hence, policies, governance arrangements, and actions for ensuring European energy security must be coordinated with those in other sectors.

Most of the fundamental policies and governance legislation needed to deliver European energy security during the transition to sustainable energy supplies have already been adopted or are under discussion at EU level. Nevertheless, updates will be needed to address the evolving geopolitical context and the technological developments that must be expected in the coming years.

Implementation of energy security policies and legislation, together with phasing out fossil fuels and the transition to sustainable energies, are now the crucial next steps for all European countries. The future mix of sustainable energy technologies will differ between countries, but 'energy efficiency first' to reduce energy demand will typically be a no regrets option. A more circular economy will also improve energy security by reducing energy demand. Financing will be needed, especially for strengthening electricity infrastructure and for building more sustainable electricity generation.

Also important for delivering secure supplies of sustainable energy in the future will be citizen engagement in the energy transition and increasing the production of both sustainable fuels and energy technologies in Europe, as well as the diversification of imports.

Recommendations for policy-makers and energy sector stakeholders are summarised in the Executive Summary to this report on page 9.

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(Note: throughout the reference list, all hyperlinks were working on 31 March 2025.)

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Abbreviations

ACER	European Agency for the Cooperation of Energy Regulators
AI	Artificial intelligence
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
COP	Conference of the Parties
CRM	Critical raw material
DSO	Distribution system operator
EASAC	European Academies Science Advisory Council
EC	European Commission
EMD	Electricity market design
ETS	Emission Trading System (EU)
ETS 2	Amended Emission Trading System Directive, provisionally agreed in December 2022
EU	European Union
GHG	Greenhouse gas
IEA	International Energy Agency
IT	Information technology
OT	Operational technology
SAF	Sustainable aviation fuel
SMR	Small modular nuclear reactor
SRM	Strategic raw material
TSO	Transmission system operator
UN	United Nations
VRES	Variable renewable energy supplies

Contributors

Working Group composition and timetable

The project was approved by EASAC's council in December 2022, and EASAC's member academies nominated experts to form a Working Group in the last quarter of 2023. The work was done from winter 2024 to winter 2025, and the report was finalised in late winter 2025.

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A project kick-off workshop and first meeting were held back-to-back in person at the Palais des Academies in Brussels in February 2024, after which Working Group meetings were held by Zoom.

A draft working document was produced in spring 2024, and most of the work was then done by e-mail together with Working Group meetings by Zoom on 3 April, 29 May, 17 September, and 21 November 2024.

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Annex 1 European energy demand

A1.1 Buildings

Energy consumption in European Union (EU) buildings for space heating and cooling, domestic hot water, lighting, and appliances is around 40% of the EU total. The operation of buildings is responsible for about 36% of GHG emissions and their energy demands for cooling are increasing because of climate change (EASAC 2021). In addition, about 10% of EU emissions come from embodied emissions produced during building construction, making the building sector responsible for approximately 46% of GHG emissions. To reduce these numbers, the EU adopted a strategy for a Renovation Wave for Europe (EC 2020b), and more recently revised its Construction Products Regulation to strengthen requirements for the energy and emissions (including embodied emissions) performance of construction products and construction works (EU 2024i). Both of these steps can be expected to contribute positively to future EU energy security.

The Energy Performance of Buildings Directive is the main regulation for energy use in buildings. It was recently updated and requires Member States to decarbonise buildings through renovation and replacing fossil fuels with sustainable energies (EU 2024a). These steps reduce energy security risks because they reduce the EU's overall demand for energy and its dependency on imported fossil fuels. In addition, the recast Renewable Energy Directive requires EU countries to increase their annual share of renewables in heating and cooling by at least 0.8% from 2021 to 2025 and by at least 1.1% from 2026 to 2030 (EC 2024d).

Coal was used to heat buildings, but this has already been phased out in most European countries, and is only expected to continue after 2030 in a small number of Member States (Beyond fossil fuels 2024).

Natural gas boilers are widely used today to provide hot water and space heating in domestic, commercial, and industrial buildings. The Joint Research Centre of the European Commission estimated that there were around 65 million gas boilers in residential buildings in the EU in 2019 (EC 2021c). Today, the natural gas used in most domestic boilers is not covered by the Emission Trading System because the boilers are too small, but this will soon be addressed under the revised Emission Trading System Directive (ETS 2). Gas boilers must soon be replaced by sustainable alternatives, such as active and passive solar heating, solar water heating, solar photovoltaics, geothermal, heat pumps powered by sustainable electricity, sustainable solid, liquid, and gaseous biofuels, and sustainable wastes in highly efficient district heating systems. Neither biomethane nor hydrogen will be widely used to replace natural gas for heating because they will be more highly valued (and highly priced) for applications in industry or transport that are 'hard to electrify' (EASAC 2023a).

The cost-of-living crisis, which has been exacerbated by the war in Ukraine, has resulted in growing numbers of households living in energy poverty (ENPOR 2024). This has also led to more research on how to find a balance between the costs of investments in building renovations and those in sustainable energy systems (Eyre *et al.* 2023).

Renovations can improve the energy security of buildings by reducing their operating energy needs, but to deliver energy security at national, European, or global levels, the greenhouse gas (GHG) emissions embodied in the building fabric must not be significantly increased by renovations. This wider goal can be achieved by renovating without disturbing the steel and concrete structural elements of the buildings or by using timber or engineered wood to replace the cement and steel, which are currently produced mainly using fossil fuels.

Decentralised renewable energy can be produced on or near to individual buildings, thereby contributing to the EU Target of net-zero emissions by 2050 and the target in the EU Renewable Energy Directive of at least a 49% share of energy from renewable sources in the EU's final energy consumption in buildings by 2030 (EC 2024d).

The building decarbonisation plans of EU Member States will typically result in reductions in the consumption of natural gas and coal and increases in the consumption of electricity for heating and domestic hot water, thereby improving energy security. The thermal mass in buildings provides a valuable source of thermal storage, which can be used together with heat pumps to deliver demand response services to electricity networks.

Cities and urban areas are responsible for more than 70% of GHG emissions which still come mainly from burning fossil fuels. In modern cities, the amount of heat generated as a result of human activity, including in factories, sewage treatment plants, computer data centres, and metros, can be sufficient to cover the basic heating and cooling needs of residents. Recovering this energy, which currently is largely wasted, would significantly reduce urban energy demand.

District heating networks typically offer the most sustainable supplies of heating and cooling for urban areas with high population densities, because networks can be supplied not only with sustainable energy sources (solar, geothermal, and biomass), but also with waste heat from industry, data centres, shopping malls, sports centres, and other sources (Volkova *et al.* 2022). Moreover, district networks can not only use low-temperature waste heat together with renewable energies for heating, but also cold water supplies from rivers or aquifers for natural cooling (HRE 2025).

District heating and cooling systems are quite resilient because most of their infrastructure is underground, so they are less susceptible to weather induced operational risks. If they are built to include large hot-water storage systems, and to use locally available solar or geothermal heat sources, they can be largely independent of centralised supplies of electricity and fuels. However, electricity storage (e.g. batteries) or backup generators fuelled by biofuels or natural gas may be needed to power their distribution pumps in case of interruptions to centralised electricity supplies.

Existing district heating systems face significant challenges in responding to the energy transition (IEA 2019a). The heat demand in buildings is being reduced by renovation, and the existing district heating systems need to be decarbonised and modernised to operate in a more integrated overall energy system. They can therefore include flexibility services for electricity networks in their future business models. However, this requires specialised expertise together with substantial investments in new equipment and materials. To give confidence to investors and improve the probability of success, national, regional, and local plans are needed with well-defined long- and medium-term goals. This should include accessing support mechanisms and public aid for increasing the use of renewable and waste energy for heat production and improving energy efficiency.

An efficient district heating and cooling system is defined by the Energy Efficiency Directive (EED recast) (EU 2023c) as one that meets specific GHG emission criteria, which are more demanding each year from January 2026 to January 2050. It also requires each country to ensure the renovation of at least 3% of the total area of heated or cooled buildings belonging to public bodies each year, and to produce local heating and cooling plans in municipalities where the population exceeds 45,000. The recast Energy Efficiency Directive requires operators of heating and cooling systems rated at more than 5 MW to implement a plan to reduce distribution losses and increase the share of renewable energy, waste heat recovery, or cogeneration. These requirements of the Directive can generally be expected to lead to improved levels of energy security.

A1.2 Transport

Europe uses energy for five main modes of transport: road, rail, air, maritime, and inland waterways.

The EU sustainable transport policy framework is summarised in its Sustainable and Smart Mobility Strategy (EC 2020a). Energy consumption in the EU transport sector was dominated by road transport (more than 94%) in 2021, which was largely powered by diesel and gasoline, produced from fossil oil.

EASAC published a report on the decarbonisation of transport in 2019 (EASAC 2019), in which it provided messages for policy-makers on *avoiding* motorised transport, *shifting* to more energy efficient transport modes, and *improving* the energy performance of transport vehicles.

From an energy security perspective, the EU was more than 97% dependent on imports for its oil supplies in 2022 (Eurostat 2022), so it was dependent on global oil prices, which can be strongly influenced by supplier cartels. In contrast, access to oil supplies is not a major energy security problem for the EU because crude oil is fungible and available from a good number of different suppliers in global markets. For example, in the aftermath of 2022, Norwegian oil production has become more important to European energy security.

The share of renewable energies in the EU transport sector was just over 10% in 2020, but it has since fallen to about 8%. Renewable energies used in road transport include renewable electricity and biofuels through blending biodiesel with fossil diesel and bio-alcohols with gasoline. Battery electric vehicles are increasingly replacing passenger cars and light duty vans and trucks powered by internal combustion engines. Heavy-duty road vehicles for carrying freight are being decarbonised through the use of biofuels in conventional combustion engines, or hydrogen with fuel cells.

The decarbonisation of air transport is expected to be achieved by using sustainable aircraft fuels based on sustainable resources including biofuels, and maritime transport is beginning to switch from fossil fuels to more sustainable fuels, including ammonia and methanol (IEA 2023a).

From an energy security perspective, the short-term challenges for the transport sector will be dominated by its needs for fossil oil because it is expected to take up to 15 to 20 years to replace the existing fleet of road vehicles. However, the EU transport sector will become increasingly dependent on electricity supplies in the future as the numbers of electric vehicles grow, and as the demand for electrolytic hydrogen grows. This transition will create new challenges related to the availability of critical minerals, metals, and technology components.

A1.3 Industry

Final energy consumption by industries in the EU in 2021 was dominated by electricity (more than 33%) and natural gas (more than 32%), but also includes the use of fossil oil, renewable electricity, biofuels, solid fossil fuels, and wastes (EC 2023e).

The decarbonisation of the electricity sector and energy-intensive EU industries was foreseen to be driven by the Emission Trading System (ETS) but, while progress has been made in the energy sector, the impact of the ETS on the heavy industries has suffered from many challenges since its inception, notably from too many free allowances being awarded to the big industries.

The ETS operates through a cap on carbon emissions set by policy-makers. The aim is for the planned levels of emission reductions to be delivered securely and as cost effectively as possible by encouraging the cheapest options to be implemented first. As a result, the ETS tends to encourage incremental emission reductions but other policy tools such as product standards, mandates for the production of clean technologies, and procurement policies such as contracts for difference are needed to provide targeted support for breakthrough technologies and innovative production processes (Lehne *et al.* 2021). Many of the small and low-energy-intensity industries will decarbonise through electrification, but some may replace fossil fuels with hydrogen or its derivatives, or with biofuels, so infrastructure, standards, and regulations will be needed for these fuels.

From an energy security perspective, the biggest challenges for industry in the short to medium term are expected to be related to the continued supplies of fossil fuels and to the growing use of electricity, both for direct electrification and for the production of electrolytic hydrogen, notably for the energy-intensive industries that produce steel and other widely used metals, and cement.

Annex 2 European energy supplies

A2.1 Fossil fuels

In line with the agreement at COP 28, all Member States are committed to transition away from the use of fossil fuels in energy systems and to increase their supplies of sustainable energies (UNFCCC 2023). However, in 2022, some countries announced delays to their plans for phasing out fossil fuels, following the invasion of Ukraine. These delays were largely caused by the need to maintain secure supplies of energy for their industries and households.

The transition to net zero by 2050 by phasing out fossil fuels and introducing more sustainable energy supplies must be carefully managed by European Union (EU) and national policy-makers to deliver their decarbonisation commitments without compromising the security of their energy supplies.

Coal: coal consumption for energy in the EU is higher in winter than in summer and steps are therefore needed to address the security of supplies through storage of imported coal. This is particularly important in the short term because more than half of the EU's imported hard coal came from Russia in 2021. Before the invasion of Ukraine, most Member States were planning to stop using coal for power generation by 2030, in line with their commitment to the Paris Agreement, but some are finding this more difficult without Russian gas, namely Romania (now planning for 2032), Croatia, Czechia, and Slovenia (now planning for 2033), and Bulgaria and Germany (now planning for 2038), and Poland (no date yet agreed) (Beyond Fossil Fuels 2024). Coal is also used to chemically reduce metal ores, notably iron ore, for making steel, although hydrogen is expected to be increasingly used for this in the future (Chapter 3).

Burning all forms of coal has a strong negative impact on the climate, but coal is available in many parts of Europe and can therefore offer secure supplies (EC 2000; Euracoal 2024). Locally produced coal is still competitive but, for environmental reasons, it should be used for energy only transitionally (or as last resort) and not beyond 2030, as agreed under the REPowerEU initiative (EC 2023a).

In 2021, Russia supplied more than half (53.6%) of the EU's hard coal imports, followed by Australia (17.5%) and the USA (15.7%) (Eurostat 2023). The EU's dependency on imported solid fuels has increased in recent years (Eurostat 2023a).

Oil: crude oil is imported into the EU from more than a dozen countries, refined and supplied primarily (almost 50%) for road transport in the EU, with 13% for industry (non-energy uses), 9% for transport by waterways, and 8% for air transport. Refined oil products are also imported for use in transport and industry (Eurostat 2024a).

Oil consumption in the EU shows little seasonal variation so, in line with other IEA member countries, Member States are required to keep strategic petroleum reserves, equal to 90 days of the previous year's net oil imports, at all times. The overall size of the strategic petroleum reserves can therefore be expected to fall as demands for oil decrease, but the 90-day rule will need to be retained for the foreseeable future.

The EU has very little of its own oil resources left in the ground and has therefore shifted to other forms of energy for most applications other than transport, for which it relies heavily on imports. Russian oil imports coming directly to the EU have dropped substantially since 2022, but they have come instead indirectly through other countries, notably India and China (Transport & Environment 2023).

Natural gas: the EU has confirmed that natural gas will continue to provide a substantial contribution to the EU energy economy in the short term, at least until 2030, because it cannot be replaced overnight. However, following the invasion of Ukraine, the EU responded with major changes to its energy legislation and its targets for decarbonising the EU energy sector (EC 2023b). These are summarised in the REPowerEU initiative (EC 2023a) and include the diversification of suppliers of natural gas (and liquefied natural gas) and coordination of the purchasing of natural gas through the EU's energy platform. While these steps are crucial to the future security of gas supplies, the energy transition also alleviates this challenge by gradually reducing the EU's dependence on gas.

The EU is now committed to limiting its natural gas consumption and imports (including liquefied natural gas) to gas with low methane leakage along the supply chain (EC 2024n). This is very important from a global warming perspective, but the impact of this constraint on energy security over the next few years (short term) must be monitored and managed.

EASAC's report on the Future of Gas (EASAC 2023a) highlighted the risks of methane leakage along natural gas supply chains and emphasised the need to ban the use of gas boilers for heating buildings as soon as possible because of their negative impact on global warming. However, this policy objective can only be achieved if building owners have or can be given access to adequate financing for investments in more sustainable energy supplies for space and water heating, and if the transition is managed without reducing the security of energy supplies to the buildings concerned. For example, local electricity distribution grids as well as electricity transmission grids will need to be strengthened to supply sufficient electricity if gas boilers are replaced by electric heat pumps. Reducing GHG emissions from gas boilers by blending natural gas with hydrogen is unlikely to be a viable option because of the increased technological risks involved and the limited GHG emission reductions that could be achieved (EASAC 2023a).

Natural gas consumption in the EU is substantially higher in winter than in summer so, since the invasion of Ukraine, major steps have been taken to ensure that the EU's gas storage facilities are filled before the beginning of each winter season. As the future demand for gas decreases, it will make economic sense for the overall capacity of the gas storage facilities in the EU to be reduced (in line with the reduced winter demands). This process will be managed in accordance with the EU's gas security of supply regulation and solidarity mechanism (EC 2024l).

A2.2 Sustainable fuels

Sustainable fuels will be increasingly used as fossil fuels are phased out and will therefore contribute to EU energy security. Those that are available in the EU and imported, include wastes, and solid, liquid, and gaseous biofuels, notably agricultural and forestry wastes, sustainable hydrogen, alcohols, biodiesel, and biomethane. They are discussed in Chapter 3.

A2.3 Electricity

In 2023, the EU produced approximately 2,400 TWh of electricity, of which fossil fuels were used to generate around 32% and nuclear electricity around 25%. Gas was the main fossil fuel used in the EU to generate electricity (15%), followed by coal (13%), and around 44% of the electricity generated came from renewable sources. Electricity production in the EU is expected to increase by about one-third between 2021 and 2050, to supply the transport, industry, and buildings sectors (EC 2024a).

The costs of supplying electricity are influenced by the energy system in which generators operate because this can affect their capacity factor, and the system costs associated with their operation, including those of the flexibility management measures used. There is therefore no simple way to compare the overall costs of electricity from different energy sources (IEA 2020).

There will be adequate electricity generating capacity in the EU at least until 2030, because there is a higher installed electricity generating capacity (about 1 TW) than peak electricity demand (approximately 500 GW), new renewable electricity generation is being built, and it will take time both for the existing reserve capacity of (largely fossil-fuelled) generators to be decommissioned and for the expected growth in electricity demands to occur. Electricity generation using coal should be phased out in all EU Member States by 2030 (although this is likely to be delayed in some Member States), but power generation using gas or sustainable fuels (e.g. biomethane) is likely to continue for longer in some Member States for mainstream supplies and in others mainly for backup generation when wind and solar radiation levels and/or when hydro resources are low.

The expected growth in electricity supplies will be generated largely using wind, solar (photovoltaic), and hydro technologies, which can be produced in the EU or imported (IEA 2024e). A small amount will also come from geothermal power generation, mainly in Italy, but other EU countries are exploring potential opportunities for geothermal power (IRENA 2023). The costs of photovoltaic and wind technologies have fallen substantially in recent years, largely owing to economies of scale, but they have increasingly been imported (primarily from China), thereby introducing new risks of security of energy technology supplies.

Major investments in grid flexibility management measures, including storage, network reinforcements and interconnectors, backup generation, and demand response, will be needed to accommodate the growing use of variable renewable energy sources. Such measures are already deployed in EU electricity networks, but their deployment will need to be substantially increased to ensure the future security of the EU's sustainable electricity supplies.

Large nuclear reactors *(typically greater than 1,000 megawatt electric):* the EU had 100 nuclear reactors in 2023, which were located in 12 of the 27 EU Member States (Belgium, Bulgaria, Czechia, Finland, France, Hungary, the Netherlands, Romania, Slovakia, Slovenia, Spain, and Sweden). Other Member States (Austria, Croatia, Cyprus, Denmark, Estonia, Ireland, Greece, Italy, Latvia, Lithuania, Luxembourg, Malta, Poland, and Portugal) do not have nuclear power, and Germany is phasing out the use of nuclear power. In 2021, nuclear energy produced 25% of EU electricity (EPRS 2023).

Several European countries are considering the construction of new nuclear reactors, to deliver their GHG emission reduction commitments and some, including the UK and Slovakia, are already constructing new reactors. However, the costs of recent nuclear projects in Europe have far exceeded initial expectations and there have been long delays in the construction process (Vakarelska 2024; WNA 2024a; WNN 2024). The long time taken to build new nuclear power plants delays the phasing out of fossil fuels, because investments in renewable generation tend to be crowded out by those in nuclear generation (Sovacool *et al* 2020).

The costs of nuclear electricity depend not only on the construction costs of the plant but also on how these are financed, because the costs of financing depend on the risks perceived by investors, and these risks can be reduced by government involvement (RTE 2021).

Flexible nuclear generation: most of the existing nuclear reactors can be operated at part load and can therefore be used to help with the management of flexibility on the grid (NEA 2011). However, nuclear reactors (large and small) typically have high capital costs and low fuel costs, so it is usually more profitable for them to operate at their rated power than at part load. Like other thermal power generators, nuclear plants use rotating generators with inertia that smooths out short-term variations in grid frequency and voltage, but their response times for load following are typically longer than those of gas turbine generators.

The choice of the nuclear plant supplier can bring potential energy security risks if it involves a future dependency on the supplier for technology support and fuel supplies, which are not the same for all reactor designs. Similarly, there are financial risks if plants are (part) financed by third countries. As for all energy technologies, manufacture within the EU would benefit energy security.

Public acceptance of nuclear power is a key issue in some European countries but less in others. For example, in France, nuclear power is widely accepted while in Germany nuclear power has been phased out. How each European country will proceed is often hotly debated at a national level, but the EU does not take a position because the Lisbon Treaty on the Functioning of the EU gives individual Member States the right to choose their own national mixes of energy supplies.

The risks of incidents or major accidents at nuclear power plants, such as those that occurred at Three Mile Island (USA) (1979), Chernobyl (Ukraine) (1986), or Fukushima (Japan) (2011), must be managed to deliver both nuclear safety and energy security. Since the early days of nuclear power generation in the late 1950s, many studies have been published on the safety of nuclear power, and international organisations have been established to manage it. Nuclear safety is an EU priority, which is managed largely through the Euratom Treaty that established the European Atomic Energy Community. Organisations that are responsible for managing nuclear safety have concluded that lessons have been learned from incidents and accidents that have occurred in the past, and that the safety of the nuclear fleet has been steadily improved (WNA 2024c). In contrast, some peer-reviewed papers have concluded from statistical analyses that while nuclear incidents have decreased in frequency following actions taken by the industry, more major accidents may be expected (Wheatley *et al.* 2016). These and other studies do not provide a single view of the likelihood of future nuclear incidents and accidents. However, the available evidence suggests that the impacts of future incidents and accidents on energy supplies will depend largely on how they affect public opinion on nuclear safety.

Small modular (nuclear) reactors *(SMRs, typically less than 300 megawatt electric)*: work is continuing across the world, including in the EU on the development of SMRs. The European Commission launched a European SMR Industrial Alliance in February 2024 (EC 2024y) and has identified SMRs as a strategic low-carbon technology. The Commission is supporting ongoing research on SMRs (EC 2024c), which includes work on passive safety systems such as natural circulation for cooling, and cost reduction through mass production in factories instead of construction on site like the big reactors. The International Atomic Energy Agency reports that more than 80 SMR designs are under development or deployed at different stages in 18 countries (IAEA 2024). However, their performance and costs have not yet been demonstrated, and some long-term operational and management issues have yet to be resolved. Therefore, members of the SMR industrial alliance continue to work with support from the European Commission and with the stated aim to accelerate the development, demonstration, and deployment of SMRs in Europe by the 2030s (EC 2024y). Meanwhile, a growing number of Member States are studying potential applications of SMRs while a strong debate on the opportunities and challenges of nuclear energy continues between two groups of Member States, namely the nuclear alliance and the friends of renewables (EPRS 2023). Nevertheless, no SMRs are scheduled for commercial operation in Europe before the 2030s (RTE 2021; IAEA 2024).

Skills to support nuclear power generation: the lack of investment in new nuclear plants in Europe, over the past decade (only three have been commissioned since 2014), has led to an ageing nuclear fleet and an ageing workforce. To continue with the operation and eventual decommissioning of the existing fleet, and to prepare for the introduction of new plants, more efforts are needed to address skills shortages in the nuclear workforce (ENS 2024; Nuclear Europe 2024).

Variable renewable electricity generation: of the 44% of electricity generated from renewable sources in the EU in 2023, wind and hydropower accounted for more than two-thirds and the remainder was from solar power, solid biofuels, and other renewable sources

(EC 2023c; Energy Charts 2023; Eurostat 2024f). However, the mix of electricity generation differs between countries and is evolving fast, partly in response to the REPowerEU policy initiative (EC 2023a), but also because the costs of wind and solar generation have been falling, natural gas prices have become more volatile, and gas supplies have become more difficult to obtain following the invasion of Ukraine.

The fraction of wind and solar electricity in networks will increase in the future, to meet the EU's agreed decarbonisation targets while, at the same time, the dispatchable generating capacity will fall as the existing coal and gas fired generators are decommissioned. Consequently, the threats of interruptions in supplies, caused by variations in renewable electricity generation, will grow and must be managed by network operators as more buildings, industries, and transport are electrified.

***Wind electricity generation**:* wind turbines generally exhibit good levels of operational reliability, and are typically installed in clusters, which reduces the impact on security of supply when one turbine stops generating. Nevertheless, they require regular repairs and maintenance (Mishnaevsky 2023). Most of the materials in wind turbines can be readily recycled, but WindEurope and others are calling for a Europe-wide landfill ban on wind turbine blades from 2025 onwards, to encourage the wind industry to commit to 100% recycling or recovery of out-of-service blades. Several recycling technologies are being developed for wind turbine blade recycling (WindEurope 2020).

*Wind speeds vary substantially over the yea*r, and there are periods of time with very low wind speeds (dunkelflauten) during which wind turbines deliver near to zero output. There is also a growing frequency of extreme weather conditions (storms) during which wind speeds may be too high for wind turbines to operate safely. More spatial and temporal analyses of wind data are needed, but initial analyses suggest that long dunkelflauten over large areas and lasting for more than a week have occurred once in about 20 years (Royal Society 2023), and the length and frequency of future dunkelflauten may be affected by climate change.

Experience with electricity grids that have a high fraction of wind power generation shows that they can be managed successfully by using good-quality weather forecasting, time-dependent tariffs, storage and demand response schemes, together with dispatchable backup generation.

The availability of more onshore sites for large wind farms with good wind resources is limited in some Member States, especially in more densely populated areas of Europe. Some European countries are therefore developing offshore wind power, which offer the additional advantages that offshore wind speeds are generally higher and more consistent than onshore wind speeds, and offshore wind turbines are typically larger and have higher efficiencies. The costs of offshore wind turbines are typically higher than onshore, but offshore costs are falling because of economies of scale, so offshore wind generating capacities in Europe are expected to grow quite rapidly. The impact of large wind farms on military defence systems must be taken into account in some areas (Auld *et al.* 2014; Kivimaa 2024).

Potential environmental concerns about wind power include noise, visual impact, and impacts on migratory species (such as birds and bats) from collisions during operation. Engagement with the local community is crucial for addressing such concerns, together with detailed environmental impact assessments. Recent turbine designs with improved efficiencies have reduced operational noise, and careful siting and layouts of wind farms can minimise visual impacts as well as potential impacts on migratory species, such as birds and bats, from collisions during operation (IRENA 2016).

***Solar (photovoltaic) electricity generation**:* solar photovoltaic (photovoltaic) modules typically exhibit high levels of reliability and are supplied with a warranty for 25 years, during which their output can be expected to drop by less than 20%. They typically need to be cleaned annually, but otherwise require little maintenance, so they offer very good energy security. Less reliable are the inverters that are used to convert the photovoltaic electricity from direct current to alternating current. For example, a recent survey in Switzerland found that 34% of inverters experienced their first failures after 15 years (Bellini 2023).

The Waste Electrical and Electronic Equipment Directive (EU 2024e) includes targets for the recovery and recycling/preparing for reuse for photovoltaic panels (85% of the collected photovoltaic panel waste to be recovered and 80% of it to be reused/recycled from 2018 onwards). However, Member States have transposed this directive in different ways, the industry has struggled to follow it, and work is continuing to improve it (IEA PVPS 2024; EEA 2024c).

Photovoltaic generation can be installed close to the energy demand, which is a big advantage; for example, photovoltaic panels can be installed on the roof of the building in which its electricity will be used.

Photovoltaic solar farms with capacities of up to about 1 GW are also being built in Europe and up to about 5 GW in China. These have the advantage that economies of scale reduce the costs, but they can create resistance from local communities and farmers because the land is typically covered with photovoltaic modules using simple low-level mountings which prevent it also being used for traditional agricultural food production purposes. However, agrivoltaic solutions are being developed to avoid this problem (Widmer *et al* 2024).

There is growing interest in floating photovoltaic systems, which can be installed on lakes and reservoirs and in maritime locations, where they operate more efficiently because the water keeps them cool, and they can bring added benefits such as reducing evaporation from inland lakes (Ramanan *et al* 2024).

Photovoltaic generators produce more electricity in the middle of the day than at other times, more in summer than in winter, and no electricity at night. They can feed electricity directly into the grid for immediate use or into a battery for later use. They can also be connected to heat pumps to store their energy as hot water, for use later to heat buildings or as domestic hot water.

Many photovoltaic generators are connected to low-voltage distribution grids and are managed locally, so they pose little threat to the security of energy supply at EU level. Alternatively, stand-alone photovoltaic systems combined with battery storage can offer electricity supplies with a higher level of security than centralised grids in war torn areas (Rettig 2023).

Concentrating solar power generators: these can produce electricity by using mirrors to focus solar radiation onto a receiver through which a fluid is passed and heated. The hot fluid is then used to generate electricity, and the waste heat can be used for industrial processes. Concentrating solar power systems can only focus direct solar radiation, so their use is limited to very sunny locations in the south of Europe. They have moving parts which require maintenance, and they are not yet cost competitive with photovoltaic generators in most locations, but their costs came down by almost 40% in the period from 2010 to 2023. Nevertheless, very few systems are being built worldwide (only one in 2023), so the technology is not fully commercialised. Work continues to demonstrate their use and potentially increased competitiveness when combined with high-temperature molten salt heat storage, which can extend their operating hours into the evening, after sunset (IRENA 2024b).

Hydro-electricity generation*:* until recently, hydropower dominated EU supplies of renewable electricity, but its leading role has recently been taken over by wind power, which is growing quickly. In 2023, hydropower generated 13% of EU electricity and wind 19% (WindEurope 2024). Unlike wind and solar, hydropower generation is largely dispatchable, which permits it to make valuable contributions to energy security. However, most of the hydro resources in the EU have already been exploited, and in some areas the available resources are falling because of decreasing levels of rainfall caused by climate change. Its contribution to future energy security will therefore be limited in many parts of the EU.

Ocean energy for electricity generation*:* renewable electricity can be generated by using waves, tides, marine currents, salinity gradients, or temperature gradients. These ocean energy sources have the advantage that they are more predictable than wind or solar energy resources. Tidal stream and wave energy technologies are the most advanced and have been tested and demonstrated in European waters. However, there are still very few systems in operation, and their costs are still high. Work continues with support from EU research and demonstration programmes to deliver solutions that will make ocean energy cost competitive with other sustainable energy technologies, and the European Commission estimates that there is potential for ocean energy to contribute up to 10% of EU electricity demand by 2050 (EC 2024w).

Bioenergy for electricity generation*:* biomass from forests, agriculture, and municipal wastes is used for power generation. However, it is widely recognised that biomass should only be burned for energy if it has a short carbon payback time (time to offset the emissions from burning biomass by reabsorption of carbon dioxide through regrowth of the harvested trees). Agricultural and genuine forest wastes do have short carbon payback times, but most trees have a carbon payback time of several decades, so the emissions from burning them cannot be reabsorbed from the atmosphere in time to contribute positively to delivering the EU Climate Law requirements of net zero by 2050 (EASAC 2022). Most trees should therefore not be harvested to produce bioenergy.

EU forest biomass resources are limited and should be used for purposes with much higher environmental and economic values than unsubsidised bioenergy. They should be used first for long-life wood products, which can then be reused and recycled before eventually being burned for energy, in accordance with the biomass cascade of the EU forest strategy, which emphasises that whole trees should not be burned for energy (EC 2021a; EC 2021b). Wider use of Europe's woody biomass resources as a long-life construction material is both environmentally and economically attractive (Hurmekoski E 2017). It is attractive to the forestry industry because it provides jobs and it incentivises sustainable forest management (adding value to forests). It is attractive to the building sector because wooden buildings typically have good thermal performance and require less energy to provide good comfort conditions for their occupants. Using structural wood in buildings is also good for energy security because it reduces the energy needed to make cement and steel.

A2.4 Heating

In 2022, the EU produced approximately 589 TWh of derived heat, of which fossil fuels were used to produce around 55%, and renewable energies and wastes around 40%. Gas was the main fossil fuel used in the EU to produce heating (32%), followed by coal (21%) (Eurostat 2024b). Secure supplies of heating are crucial for both buildings and industry.

Heating is typically supplied to the building sector at 'low' temperatures below 100 °C, and to the industry sector at low (less than 100 °C), medium (100–400 °C) and high temperature (greater than 400 °C). The evolution of energy supplies for heating is slow, especially in the building sector, because it takes time for changes to be made. However, scenarios for the future have been developed for the impact assessment used to support the European Commission's proposal for new targets for 2040 (EC 2024a).

Gas boilers currently produce most of the space heating for buildings in the EU, but they must be phased out as soon as possible (Section A1.1). However, they can be replaced by one or more of the sustainable heating systems discussed below.

Heat pumps supplied with sustainable electricity are well suited for heating buildings, and they can be used with demand response schemes to strengthen energy security by facilitating the management of flexibility on electricity grids.

Biomass can be used in individual boilers or in district heating systems to deliver heat to buildings or industry, and it is a secure source of heating. Examples of its use are given in Box A1. Revisions to the Renewable Energy Directive (EC 2024d) have led to more ambitious national renewable energy targets, but at the same time to more demanding sustainability criteria for the use of biomass. The future for biomass heating in the EU is therefore still evolving, and its links to energy security are likely to remain high in some countries, especially in the Nordic countries. An initial overview might have been expected in the European Commission's analysis of the recently updated national energy and climate plan (EC 2023f), but the Commission reports that most of the updated plans lack detailed plans for the future of the bioenergy sector.

Active solar heating can be provided by panels that are installed on the roof of a building or nearby. The most common systems use solar panels that are connected by water pipes to a hot-water storage tank, which can be used to supply domestic hot water or space heating. Alternatively, the solar panels can be connected using air ducts, which carry the heat from the sun into the house to provide warm air space heating. Both options provide independent supplies of heating during sunny conditions but they typically need a large heat store or a backup energy supply during periods of inclement weather.

Passive solar heating can be provided by integrating solar energy collecting devices into the building envelope in ways that allow heat from the sun to be transferred into the house using natural convection. Like active solar systems, these may also need a large heat store or a backup energy supply during periods of inclement weather.

Geothermal heating is normally supplied through district heating systems, where it can be professionally managed, and it benefits from economies of scale.

District heating networks offer an efficient, sustainable, and relatively secure means of supplying heat to buildings and industry. They can be fuelled by biomass, solar, and geothermal energy sources as well as by waste heat from diverse sources including sports centres, data centres, shopping malls, and industry including thermal power generators. Like electricity networks, district heating networks are operated using computer systems, which can fail for physical reasons (hardware failures) but may also experience software failures as a result of misuse, imperfect software updates, software hacking, or cyber-attacks. They also need to have built-in redundancy and to be fitted with

Box A1 Examples of biomass use for heating (Brack *et al.* 2018)

Denmark produced 10% of its electricity and 31% of its heat from solid biomass in 2016. This was increasingly used to replace coal and gas in Denmark's extensive network of combined heat and power stations and district heating systems. Wood pellets and chips were the main feedstock for large-scale plants. Straw, wood fuel, and wood chips were used in private boilers, district heating, combined heat and power and power-only plants, but several of these plants have now switched to wood pellets. Most wood fuel, wood chips, wood residues, and straw were sourced domestically, but pellets were mainly imported.

Finland's largest energy source in 2016 was biomass, generating 12% of its electricity and 49% of its heat. Woody biomass comprised about 80% of the bioenergy consumed and was often co-fired with coal or peat. Industry, particularly producers of pulp and paper, was the largest consuming sector. The country's sizeable timber industry generated large volumes of wastes and residues (and black liquor from the pulp and paper industry) that could be used for bioenergy, but there were also imports of wood chips.

backup protection which will restore operations in the event of software failures or cyber-attacks.

High-temperature heating can be produced sustainably by electrical resistance heaters powered by sustainable electricity, biomass combustion, or concentrating solar power. Such systems have been demonstrated for providing industrial process heating. However, concentrating solar power is a technology that requires high levels of direct solar radiation and can therefore be used only in southern Europe.

High-temperature heat storage in molten salts has been demonstrated together with concentrated solar power systems, where the stored heat can be used during the night for power generation. Instead of using batteries to store excess renewable electricity, high-temperature heat storage systems can be used to store excess electricity from photovoltaics or wind generation as heat, which can then be used directly and very efficiently for industrial process heating (IRENA 2020).

Heating from nuclear power plants: these power plants are typically located away from urban areas because of safety concerns, but they produce large quantities of waste heat that can be used for district heating or other low-temperature heating applications, such as horticulture and fish farming. The possibility that heat could be provided to district heating systems by locally installed SMRs has been highlighted by the Nuclear Energy Agency of the OECD. While SMRs are still in the research and development stage, it is too early to judge the business case and economics of their use for heating applications, but an appropriate regulatory framework should be prepared for this potential application.

A2.5 Cooling

Cooling is largely supplied using chillers (heat pumps) powered by electricity, and most of the waste heat is discharged into the air. Buildings can be designed to minimise the need for cooling, by limiting the amounts of glazing on south-facing surfaces, integrating thermal storage, and installing appropriate shading systems. In dense urban areas, there is a growing use of cool underground water to reduce the temperatures of buildings and other occupied spaces such as underground train networks (Rowe and Paul 2022).

Annex 3 Uncertainties that justify further research

The aim of this report is primarily to focus on using the results from research, development, and innovation that have already been completed, namely 'science for policy'.

Nevertheless, it must be emphasised that continuing research, development, and innovation programmes will be crucial to the European Union's future energy security, the success of the Union's energy transition, and to its future 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 European Union energy supplies.

Substantial risks and uncertainties related to Europe's future energy security have been identified in this report, and some of these could be reduced by further research on the performance and costs of the following topics (listed in alphabetical, not priority, order):

1. Cyber protection of sustainable energy systems.
2. Electricity storage, including innovative battery chemistries, flow batteries, pumped hydropower, and recyclable metal fuels (e.g. aluminium or magnesium).
3. Energy market integration (electricity, heat, and fuels).
4. Energy security modelling – technology assumptions, optimisation studies, adequacy assessment.
5. Flexible hydrogen electrolysers.
6. Foresight and analysis of potential geopolitical and other energy security risks.
7. Geothermal heating and power generation.
8. Hydrogen storage, including in salt caverns.
9. Impacts of climate change on variable renewable electricity generation, including its impacts on the frequency and duration of future dunkelflauten.
10. Low- and high-temperature heat storage.
11. Potential for extracting critical and strategic raw materials in Europe.
12. Security of sustainable energy supplies, including network and system operations.
13. Small modular nuclear reactors.
14. Sustainable transport fuels, including hydrogen, e-fuels, sustainable aircraft fuels, and biofuels.

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