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European Academies
Science Advisory Council

For Further Information:

secretariat@easac.eu
www.easac.eu

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Energy System Integration:

Opportunities, challenges, barriers, and recommendations for policy-makers

Contents

Summary

Integration of the whole European energy system is key to delivering a secure and affordable transition to net zero greenhouse gas emissions by 2050. This commentary highlights the economic, environmental, and energy security benefits and challenges of integrating Europe’s energy supplies, carriers, infrastructures, and demands.

Implementation of the European Union (EU) strategy for energy system integration (2020) will involve expanding electrification, digitalisation, and the use of smart grids and markets for grid flexibility services to balance electricity supplies and demands. At the same time, it will contribute to delivering the Clean Industrial Deal and hence linking climate action with competitiveness.

Opportunities for energy system integration include coupling electricity, heating, cooling, and transport, but these sectors must be supported by secure information and communications technology (ICT) systems, heat and electricity storage, and demand response driven by measures such as time-of-use tariffs. Some significant challenges must be overcome, including grid congestion, risks of cyber-attacks, resistance from existing institutions and fossil-fuel-based industries as these are phased out, and social impacts on households, communities, and small businesses. For this, existing EU energy policies must be fully implemented, and energy markets must be further integrated and harmonised.

Modelling studies confirm that integrated energy systems are more cost-effective and secure than independent sector-specific approaches, but financing is needed for long-term investments in energy system integration and infrastructure. Also, public funding is needed to pay for targeted support to regions affected by the energy transition, and for distributed support to individuals, communities, and small businesses across the EU that need help to adapt and replace skills that are no longer needed, and to reduce the risks of falling into energy poverty.

Stable long-term energy system integration and transition policies with clearly defined targets and goals are needed, together with independent monitoring and progress reporting to build and maintain investor confidence.

Engagement of citizens, local communities, and businesses is crucial to the success of an integrated energy transition, because it reduces the risks of costly delays to permitting for the construction of sustainable energy systems and infrastructure, and it can help to mobilise investments.

Investments in integrated energy infrastructure and markets are investments in energy security

Increasing system efficiency

integrating electricity, heat, green gases and fuels across industry, buildings, and transport with onsite production, storage, and digitalisation

Barriers

Unfair cost–benefit distribution

Resistance from fossil-fuel champions

Policy recommendations

- Focus policies on energy efficiency first
- Enhance cyber security and European information and communication technology (ICT)
- Incentivise heat and electricity storage, and demand response
- Foster interconnections
- Enable time-of-use tariffs and demand response
- Support and engage citizens and communities

Better management of flexibility and congestion

Less cost for electricity grid infrastructure

Less fossil-fuel dependency

Higher industrial competitiveness

1 Introduction and policy background

Integration of the whole European energy system, including its many different energy supplies and sectors of energy consumption, is becoming increasingly important as fossil fuels are being phased out and buildings, industry, and transport are being electrified with the aim of delivering net zero greenhouse gas (GHG) emissions by 2050. In 2023, the two sectors of energy demand with the largest GHG emissions were (1) transport, and (2) electricity and heat producers (IEA 2025a), and the next in line were the industry and residential sectors (see Figure 1). GHG emissions from electricity producers are falling as renewable electricity supplies grow, and the emissions from transport are also expected to fall with the growing use of electric vehicles, provided growth in demand for mobility can be contained.

Within the electricity supply sector, congestion is growing on European electricity grid interconnectors. Congestion occurs when attempts are made to transmit more power (for a given period of time, typically 1 hour or 15 minutes) through an interconnection than the physical limit of the interconnection allows. The reason for transmitting power across an interconnector is predominantly because a price difference makes it profitable, so the price spread is a good indicator of congestion, as shown in Figure 2. It should be noted that the capacity of the interconnection does not, per se, determine whether it will be congested or not. For example, the interconnection between mid-Sweden and mid-Norway is weak, but, as can be seen in Figure 2, there is very seldom any price difference, and it is therefore very rarely congested. In contrast, the interconnections (high-voltage direct current, HVDC) from southern Sweden and Norway to continental Europe have much higher capacity; however, as can be seen in Figure 2, they are highly congested because there is frequently an incentive to transmit cheap Norwegian and Swedish power (hydro, nuclear, wind) to Germany and Poland, which typically have (much) higher generation costs.

Congestion also occurs on distribution grids, where it can be caused by growth in electricity demand from buildings, industry, and transport, and/or by the connection to the grid of many new distributed generators of electricity, notably variable renewable electricity supplies (VRES) from photovoltaic solar and wind generators. The challenge of congestion is being met by a combination of measures, including investments in interconnections and strengthening of the grid together with flexibility measures, including electricity and heat storage, demand response, curtailment, and back-up generation to balance electricity supply and demand.

Energy system integration through such measures has the potential to offer economic, environmental, and energy security benefits to European consumers of electricity, heat, and liquid and gaseous fuels, as has been highlighted by EASAC in its recent reports on the Future of Gas (EASAC 2023) and Security of Sustainable Energy Supplies (EASAC 2025).

In 2020, the European Commission (EC) published an EU Strategy for Energy System Integration (EC 2020), in which it defines energy system integration as ‘the coordinated planning and operation of the energy system “as a whole”, across multiple energy carriers, infrastructures, and consumption sectors’. This definition has been broadly adopted by EASAC in this report but also including energy supplies. The EU strategy aims to promote greater electrification of energy end-use sectors together with key existing and emerging technologies, processes, and business models, such as ICT and digitalisation, smart grids and meters, and flexibility markets. It foresees energy system integration as ‘the pathway towards an effective, affordable, and deep decarbonisation of the European economy in line with the Paris Agreement and the UN’s 2030 Agenda for Sustainable Development’. Since 2020, many of the policy and legislative steps that were laid out in the EU strategy have been adopted by the EU institutions, and work has begun on their implementation (EC 2025b).

Energy system integration is a crucial component of the policies needed to deliver an affordable energy transition to net zero greenhouse gas (GHG) emissions by 2050, and will therefore play a key role in delivering the EU Clean Industrial Deal (EC 2025a), which brings together climate action and competitiveness under one overarching growth strategy in line with the recommendations of the Draghi report (EC 2024).

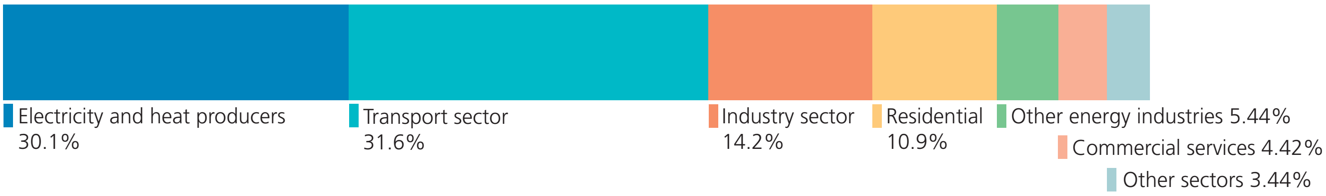

Figure 1 European carbon dioxide emissions by sector in 2023 (IEA 2025a).

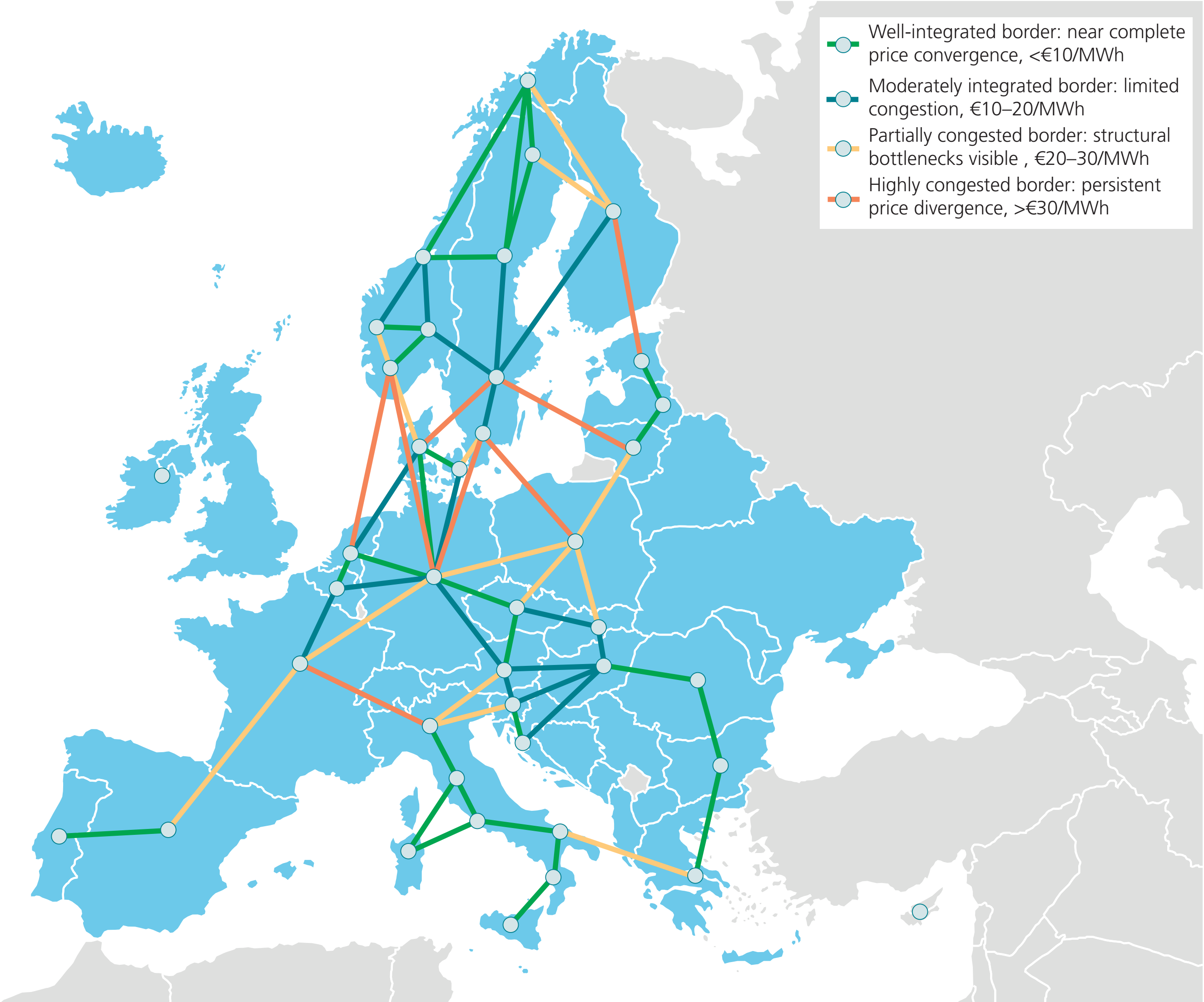

Figure 2 Grid congestion based on electricity price spreads (euros per megawatt-hour) across bidding zones in 2024 (EPRS 2025, based on ACER 2025a).

The International Energy Agency (IEA) has recently reported on integration of the electricity system and has emphasised that increasing VRES will require greater use of grid flexibility management measures (demand response, energy storage, and grid interconnections), as well as novel grid stabilisation systems when conventional electricity supplies are low (IEA 2024a,b). The IEA emphasises the need for international cooperation on cross-border power system integration to improve energy security, decarbonisation, and efficiency. It also concludes that delays in the integration of grid flexibility management measures and appropriate voltage and frequency controls could lead to increased dependency on backup generation from fossil fuels and less efficient utilisation of hydro power plants.

The International Renewable Energy Agency (IRENA) has recently emphasised that, to deliver the pledge made at COP28 to triple renewables and double energy efficiency by 2030, a future power system must integrate not only high shares of VRES but also enhanced and upgraded grid infrastructure to facilitate more electrification in end-use sectors (IRENA 2024b). IRENA notes that, in addition to grid reinforcements, the integration of bigger electricity storage capacities (e.g. batteries) and digitalisation (smart systems) have become crucial to cost-effectively ensuring resilient and secure energy supplies. For example, smart systems are needed to match daytime loads with the available solar photovoltaic generation and to optimise storage for night-time use, thereby reducing the needs for grid reinforcements with their associated costs and permitting delays.

Coupling end-use sectors through electrification of heating, transport, and industry as well as the integration of thermal energy storage, by using smart energy management systems, can help to decarbonise and reduce the costs of heating, cooling and mobility services, as well as increase the flexibility of the electricity system and facilitate higher penetration of VRES.

Digitalisation is particularly important when integrating decentralised systems with high shares of VRES because it enables the management of data and of interactions between energy systems and their operators. By using real-time data (including weather forecasts) and communication technology, energy supply system operators are better able to manage the grid and to offer flexibility to consumers with lower prices and improved reliability (IRENA 2021). However, increases in digitalisation and the use of ICT will need to be protected from cyberattacks and will also require more training for skilled ICT system operators and cyber protection experts.

Independent studies of the energy transition and its implications for policy-makers have been continuing for many years. Initially such studies expressed concerns about the viability of renewables as technical and economical options, but these concerns have largely been resolved, and renewables are now being increasingly integrated into electricity grids (Brown *et al.* 2018). Nevertheless, they are creating challenges for existing technologies, organisations and infrastructures (Markard 2018). Moreover, the integration of VRES is challenging the overall functioning and performance of the electricity sector by introducing complex interactions between multiple technologies. It is also forcing the decline of established business models and technologies, and it is creating new economic and political struggles for key actors, including utility companies, system operators, regulators, and industry associations. These barriers to integration must therefore be tackled by policy-makers.

Following the Russian invasion of Ukraine in 2022, the EU adopted a REPowerEU plan to phase out EU dependency on Russian energy imports (EC 2022). This plan, which has been further developed since it was launched, is funded with more than €300 billion through the Recovery and Resilience Facility, the Innovation Fund, and the sale of Emissions Trading System allowances. An important element of the plan is to increase the integration of energy systems and energy markets across the EU by boosting industrial decarbonisation, accelerating the deployment of renewables, investing in energy infrastructure and interconnections, and improving energy efficiency.

In March 2024, the EC published a report from a study that had the objective of assessing the progress of energy system integration in the EU (Lise *et al.* 2024). This study investigated many existing barriers to energy system integration, identified solutions, and provided recommendations on how to address the barriers. It analysed three topics in-depth: (1) electrification of end-uses (with a specific focus on transport, industry, buildings) and integration of decentralised renewable energies; (2) uptake of renewable and low-carbon hydrogen (also biogas and biomethane); and (3) utilisation of waste heat. It also covered cross-cutting topics including energy infrastructure, energy storage, and digitalisation. The large number of barriers to energy system integration that were identified in this study confirms that further action is needed by policy-makers, by Member States (through stronger national energy and climate plans EC 2025c), and by other stakeholders that are responsible for energy policy implementation.

In the next IPCC Assessment report AR7, a new chapter 14 on energy system integration is scheduled to be part of the Working Group III report – Mitigation of Climate Change – which is currently being drafted with a view to publication in 2028 (IPCC 2025). It will include for the first time an assessment of the challenges and opportunities associated with integrating different energy systems to achieve a sustainable and low-carbon future. The AR7 synthesis report will be published in 2029.

2 Opportunities for creating a more integrated energy system

To meet international climate and energy commitments, many different energy-supply technologies (that deliver electricity, heat, or gaseous, liquid, or solid fuels), infrastructures, and end-user energy consuming services must be operated together and secure supplies of energy must be delivered with minimum costs and minimum levels of GHG emissions to consumers, who may have rapidly varying levels of demand.

2.1 Integration of electricity supplies

Electricity is increasingly becoming Europe's main energy carrier, but not everything can or should be electrified so an integrated energy system approach, which is adapted to local and regional conditions, should be used to optimise the capital and operating costs, GHG emissions, and security of the energy technologies and systems involved.

Europe is making good progress with the deployment of solar photovoltaic and wind electricity generators, but not enough progress is being made with strengthening the electricity grids and deploying the flexibility management systems that are needed to fully integrate variable renewable electricity generators into the electricity system (see Figure 3). This will require more widespread introduction of measures such as time-of-use tariffs to facilitate demand response, more digitalisation of electricity supplies

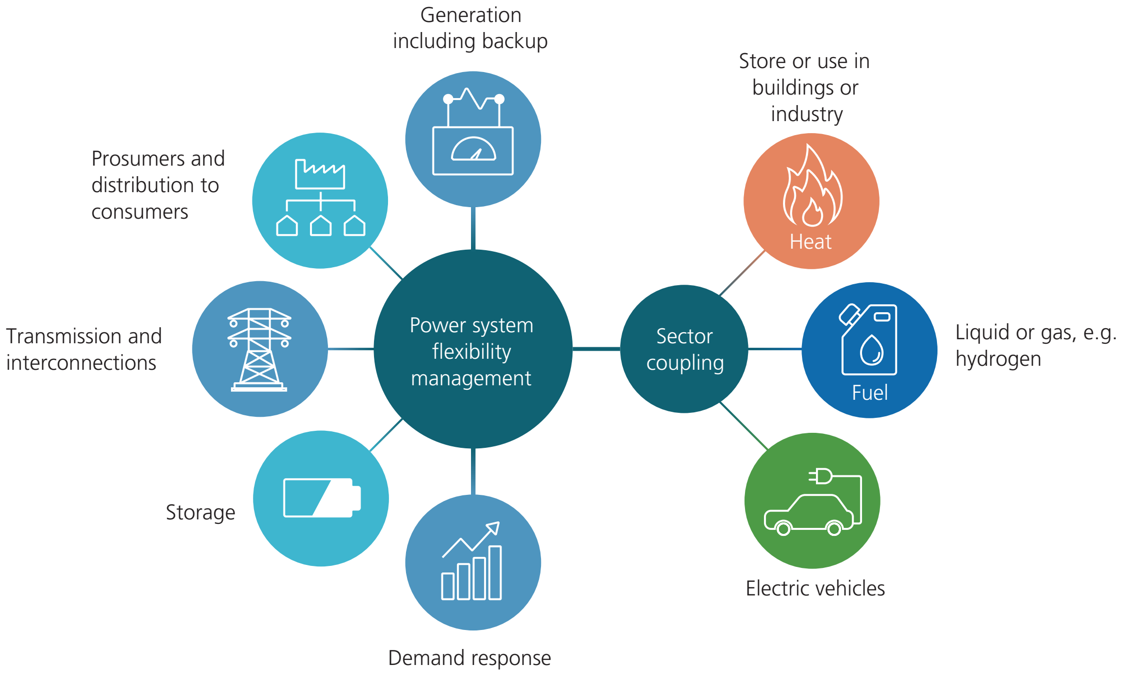

Figure 3 Flexibility management measures for balancing demand and supply on electricity grids (adapted by EASAC, on the basis of IRENA 2024a).

and electricity consuming systems with smart controls and smart meters, and more deployment of heat and electricity storage (e.g. batteries) as well as stronger interconnections, and backup generation.

There is a growing demand for electricity from data centres, which are expected to account for 6% to 10% of the growth in electricity demand in the EU between 2024 and 2030 (IEA 2025d). Many data centres are located near to cities, and rapid growth in their energy demand is driven largely by the use of artificial intelligence (AI), which is being increasingly used by all sectors of European society.

ICT systems that can be used for managing electricity grids are readily available, but their integration will bring increased risks of cyberattacks and of control system failures which can reduce energy security (resilience of the grid). Cyber protection and backup systems (redundancy) must therefore be given high priority as Europe increases the integration of its energy systems in a world with increasingly volatile geopolitics. Cyber-protected ICT systems for energy management must be procured only from trusted suppliers, and system operators must be given regularly updated training in dealing with cyberattacks as well as in ICT system operation (EASAC 2025).

Direct current (DC) technologies, including cabling, switches, and control gear, will play an increasing role in European grid networks. They will be used at high voltage (HVDC) in accordance with the HVDC regulation (EU 2016), at medium voltage (MVDC), and at low voltage (LVDC) levels (JRC 2025a). Advanced DC cabling is typically more efficient than alternating current (AC) cabling for transmitting power over long distances because it uses advanced insulation such as cross-linked polyethylene and mass-impregnated materials to handle high voltages and operating temperatures efficiently (National Grid 2025). HVDC can therefore be used to enhance the resilience of grid networks, for example by acting as a 'firewall' for preventing disturbances such as faults or short circuits from spreading across the grid, by providing interconnections across borders, by transmitting large amounts of renewable electricity over long distances (e.g. from offshore wind farms), by improving transmission terminal stability, and by providing 'black-start' power to restart a grid after a major outage. Work is continuing to optimise voltage source converters which enable substations to be more flexible and compact, and to facilitate the connection of offshore renewable energy sources.

Ways to address the main energy system integration issues for each of the three main sectors of energy demand, namely buildings, transport, and industry (see Figure 4), are discussed below.

2.2 Integration of energy supplies for buildings

Buildings will be an important player in Europe's more integrated future energy system. They can contribute to energy supplies as well as energy demands, and they can also offer flexibility management services to the electricity grid by using their own thermal inertia,

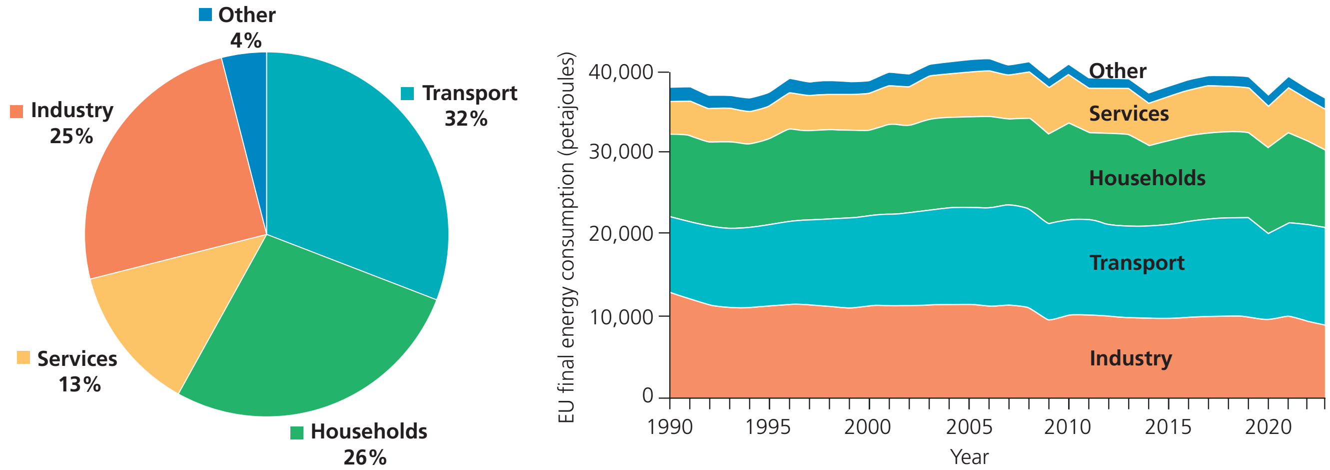

Figure 4 EU Final energy consumption by sector (2023) has hardly changed since 1990 (Eurostat 2025).

and hot water and electricity storage for demand response. Building renovations have the potential to improve energy security by reducing energy demand, but renovations must be done sustainably, for example, by minimising the addition of cement and of virgin (not reused or recycled) steel, which increase a building's embodied carbon emissions during the renovation process.

The decarbonisation of buildings is crucial to delivering the EU commitment to net-zero emissions by 2050 because buildings are responsible for about 40% of EU final energy consumption and for more than a third of EU GHG emissions (EASAC 2021; Gillett *et al.* 2025). Approximately one-third of GHG emissions from buildings are produced by burning fossil fuels for heating and the rest are produced indirectly by consuming heat from district heating systems and grid electricity for lighting, cooling, hot water supply, ventilation, air conditioning, and other appliances. The mix of direct and indirect GHG emissions from buildings varies between European countries, depending on local climatic conditions and on the mix of fuels used for heating, cooling and hot water, the degree of electrification of the building sector, and the degree of decarbonisation of the grid electricity. In addition, embodied GHG emissions are produced when building materials and components are made and transported to site, and from machinery used for building construction and renovation.

Buildings are becoming an increasingly important source of electricity supply, mainly through photovoltaic generators installed on their roofs or in nearby locations. In addition, stationary batteries, thermal mass, and hot water tanks in buildings are being integrated with local electricity systems through demand response. These forms of distributed energy storage not only provide grid flexibility management services to electricity system operators but can also reduce energy costs for consumers.

Energy consumption in buildings is dominated in most European countries by heating and cooling. Around 75% of existing buildings in the EU have poor energy performance (EU 2024c) and they have different designs and access to different energy sources. While buildings can be heated using electric heat pumps, in urban areas they can often be heated reliably and more cheaply by using district heating that can integrate heat from different local sources, including geothermal, solar, and waste heat from industrial processes or other local sources (EASAC 2021). In some parts of Europe, solar heating is the most attractive option. Cooling is a growing challenge as the climate changes and as the European demographic trend continues towards an older population. Existing buildings with large areas of glazing may be fitted with smart glazing systems and/or external shading devices to reduce the risks of overheating on sunny days but increasing numbers of buildings are also being fitted with cooling systems.

Heat pumps offer the advantage of providing both heating in the winter and cooling in the summer. Air-to-air heat pumps are generally cheaper than air-to-water or ground-coupled heat pumps, but many existing buildings were not built to accommodate ductwork for air heating systems and their water-heated radiators are sized to operate at temperatures that are higher than optimal for use with heat pumps. Innovative air handling solutions and large area wet radiator systems are being introduced to facilitate the retrofitting of heat pumps that operate at low temperatures and therefore with high efficiencies and low energy costs (Lämmel *et al.* 2022). However, different ways of delivering low temperature space heating from heat pumps are being used in different countries and regions to suit the local building designs and traditions.

The integration of individual or groups of buildings into local energy systems together with local commercial and industrial operations can benefit from local energy planning in accordance with Article 25 of the Energy Efficiency Directive (EU 2023). Such planning for local heating and cooling can help local energy system operators and building owners, users, and renovators to maximise the benefits of integration in terms of energy security while minimising investment costs, energy costs, and both operating and embodied GHG emissions.

2.3 Integration of energy supplies for transport

Three main options are widely recognised for decarbonising and improving the energy efficiency of transport (EASAC 2019):

- 'avoid' and contain the demand for motorised transport by promoting walking or cycling, etc.;
- 'shift' from private cars to public transport services (trains, buses, trams, etc.), and from planes to high-speed trains;
- 'improve' by reducing the emissions from vehicles (use electric vehicles, sustainable fuels, more efficient power trains, etc.).

Large-scale land-based public transport systems, including trains, trams, and grid-connected (trolley) buses, offer opportunities for integrating energy supplies for transport into grid flexibility management. Research projects such as the European 'Metrology for smart energy management in electric railway systems' directly address enabling smart, energy-efficient operation of railways, viewing the railway itself as a dynamic consumer and potential energy system participant under smart grid principles (Euramet 2025).

Small road transport vehicles, including cars and small vans, are easy to electrify and this is being demonstrated by the rapidly growing use of battery electric vehicles (BEVs). Integration of the battery storage capacity of BEVs with the rest of the energy system is evolving. Time-of-use tariffs and technology can be deployed to encourage (1) the storage of electricity in BEV batteries when electricity supplies are plentiful and therefore cheap, and (2) the transfer of stored electricity from BEVs back to the grid during periods when demand is high and electricity supplies are low and therefore expensive (EASAC 2019). However, more experience is needed to optimise the incentives needed to build public confidence in bi-directional charging and the systems used to manage it (TÜV Rheinland *et al.* 2024), as well as to overcome concerns about the extent to which it will reduce the lifetime of electric vehicle batteries.

Batteries are becoming cheaper, and their performance is being improved, so the markets for BEVs are growing and the need for publicly funded vehicle subsidies is falling. Nevertheless, large amounts of public funding are still needed for strengthening the electricity grid and for installing public charging points to serve the growing fleets of BEVs. Work is continuing on the development and implementation of time-of-use tariffs and incentives for integrating electric vehicles into grid flexibility management, but most distribution system operators in EU Member States have not yet implemented time-of-use tariffs (JRC 2025b).

Many electric vehicles already have the technical capability to support bi-directional charging; however, despite the existence of an ISO standard for the vehicle to grid interface (ISO 15118), the current status of bi-directional charging for BEVs in Europe is still in an early phase. The white paper 'The Integration of V2G in Europe' by the Research Center for Energy Economics (FfE) examined the implementation in 2025 of Vehicle-to-Grid (V2G) in France, the UK, and Germany, and showed varied progress (Zahler *et al.* 2025). Germany lacks supportive regulations and its efforts remain limited to pilot projects; the UK has commercial V2G offers with active market promotion and regulatory support; France's V2G efforts are mainly driven by car manufacturers with no market incentives. The white paper highlights that V2G already adds value in the spot market across all three countries, provided power grids are not overloaded. For scalable, economic implementation, the promotion of standardised technical connections between countries is essential, along with collaborative regulatory and technical frameworks to facilitate interoperability and support V2G integration.

Some transport services are hard-to-electrify and will therefore require supplies of sustainable fuels. Important examples include aviation and long-distance heavy-duty vehicles used for road and maritime transport (EASAC 2019). Sustainable aviation fuels, sustainable hydrogen, e-fuels, and other road transport fuels require electricity for their production and distribution, so to minimise their costs and optimise their use, the production of such electricity-based fuels must be both technologically and economically integrated into the EU energy system (EASAC 2023).

2.4 Integration of energy supplies for industry

Many industries in Europe are still using fossil fuels, notably natural gas which is still subsidised (EEA 2025), and is cheaper than electricity for end-consumers in many European countries. Also, time-of-use electricity pricing is still lacking in many parts of Europe, so this is contributing to limited uptake of demand response. A more integrated approach to energy supplies for industry is needed to encourage investment in the electrification of heating that represents about half of industrial energy demand because industrial processes can typically be made much more energy efficient through electrification, and more sustainable by using sustainable electricity. Improving industrial energy efficiency is a high priority for the EU because of its potential to maintain and improve European competitiveness (IEA 2025b). In particular, European industries have great potential to recover waste heat, which has not been utilised so far (Bianchi *et al.* 2019). High-temperature heat pumps (reaching up to around 200 °C), which can be powered using renewable electricity, also have unexploited potential for decarbonisation in industry (Mateu-Royo *et al.* 2021; Zühlsdorf *et al.* 2024).

For those industrial processes that are hard to electrify such as some chemicals and cement, the most sustainable approach to system integration may be to choose an alternative product such as engineered wood to replace concrete and cement for structural applications. Alternatively, fossil fuels may need to be replaced by sustainable liquid or gaseous alternatives, such as biofuels or sustainable hydrogen or fuels derived from it. Renewable hydrogen can be produced by the electrolysis of water using renewable electricity (EC 2025e), or hydrogen with a low carbon footprint (sometimes called blue hydrogen) can be produced by combining carbon capture and storage with the already widely used industrial processes of steam methane reforming or auto-thermal reforming of natural gas (EASAC 2020).

Sustainable hydrogen can be used for ammonia and methanol production, or in other chemical processes, or in the steel industry as a reducing agent for iron ore. Hydrogen can also be used with fuel cells to power heavy duty road transport vehicles (EASAC 2023). The integration of electrolysers to produce hydrogen and fuel cells to use hydrogen for electricity generation is a widely discussed option for delivering long-term (e.g. inter-seasonal) electricity storage, while also offering short-term (e.g. hour by hour) grid flexibility management services.

However, despite the very ambitious goals for producing and using sustainable hydrogen that were set by the EU in its REPowerEU plan (EC 2022), progress has been delayed, and these goals are now unlikely to be achieved. This is largely because the expected cost reductions of electrolysers have not yet been realised, the volatile geopolitics since the invasion of Ukraine have affected the costs and availability of natural gas, and progress with reducing the costs of carbon capture and storage has been slower than predicted (IEA 2025c). Nevertheless, the EU has prepared a legislative framework for integrating hydrogen production and use into the EU energy system and its markets, and this offers a solid basis for future investments in Europe's emerging hydrogen economy (EC 2025e).

2.5 Integration of demand response into electricity markets

Demand response schemes (Box 1), driven by time-of-use 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 (EASAC 2025). Demand response is being introduced differently in European countries to suit their different resources and demands.

Box 1 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 of day when electricity supplies are more plentiful or other demands are lower. It is typically implemented through prices (time-of-use tariffs) or other monetary incentives together with smart grid technologies (IEA 2023).

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

1. consumers are given information on prices and opportunities to switch their equipment on and off (manually or automated);
2. appliances owned by consumers are switched on and off by the electricity utility.

Recent studies of these two approaches have shown that most consumers are too preoccupied by other commitments to devote adequate time to managing 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; Bailey *et al.* 2023; Reguant *et al.* 2025). However, studies have not yet come to clear conclusions for policy-makers about the potential of price incentive schemes for household demand response and the social aspects affecting them (Christensen *et al.* 2020; Barani *et al.* 2024).

A Network Code on Demand Response was submitted to the European Commission in Spring 2025 (ACER 2025b) and will eventually be applicable in all Member States. This will establish harmonised rules to facilitate market access for demand response, including load, storage, and distributed generation (aggregated or not). It will also enable market-based procurement of (demand response) services by distribution system operators and transmission system operators.

As more time-of-use tariffs are introduced in the future, for example to manage the evolving integration of

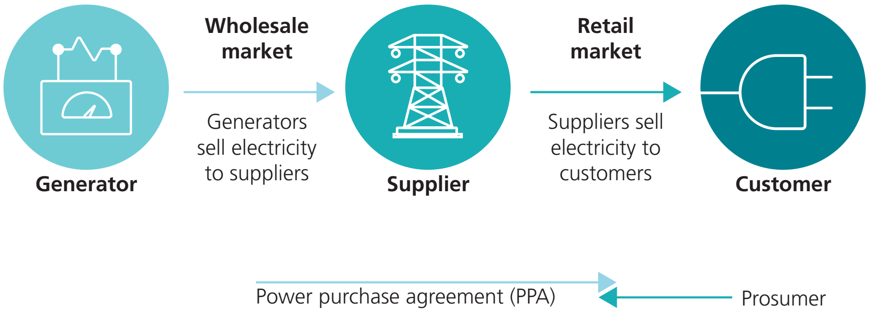

Figure 5 Integrated electricity markets.

electric vehicles into the electricity system, it seems likely that more user-friendly demand response schemes (e.g. with apps for mobile phones) will be offered by electricity suppliers, and more independent companies will enter the market offering demand response aggregator services to consumers. Further developments must therefore be expected as such integration proceeds.

2.6 Integration of energy markets

Energy markets have key roles to play in the integration of the European energy system, and in delivering secure, sustainable, and affordable energy supplies. Marginal markets must allow for the price variations (spreads) that motivate consumers to respond and hence to integrate power, heating, transport, and industry through demand response. A critical element for demand response in electricity markets is time-of-use prices/tariffs, which facilitate the coupling of wholesale and retail power markets. The EU electricity market design was updated in 2024, with the adoption of Directive (EU) 2024/1711 (EU 2024a) and Regulation (EU) 2024/1747 (EU 2024b).

In July 2025, the European Commission provided new guidance on renewables, grids infrastructure and network tariffs to EU countries (EC 2025d), to facilitate the integration of renewable energy sources, to accelerate the rollout of grids and storage infrastructure, and to design future-proof electricity network charges. This guidance was aimed to support the implementation of the revised Renewable Energy Directive and Electricity Market Design, as well as the Action Plan for Affordable Energy which, earlier in 2025, set out to lower energy costs by accelerating the clean energy transition. Member States and national energy regulators were invited to use this guidance when designing national frameworks for their own integrated energy systems.

The Regulation on risk preparedness in the electricity sector (EU 2019) is also part of the EU Electricity Market Design. It requires Member States to prepare plans for potential electricity crises and to put tools in place to prevent, prepare for and manage them. It also requires Member States to identify future electricity crisis scenarios at national and regional levels, to prepare risk preparedness plans, and to cooperate and coordinate their work across borders in a spirit of solidarity.

A key challenge for electricity markets is to build fair and efficient links between wholesale markets in which energy suppliers buy electricity from electricity generators and retail markets in which consumers buy from those energy suppliers (see Figure 5). Energy suppliers typically buy electricity from the wholesale market at prices that fluctuate depending on the mix of generators that are operating at any point in time and then sell it to consumers at prices that are typically fixed for the duration of a contract. Suppliers can also purchase electricity through long-term ‘power purchase agreements’ (PPAs) with generators and can secure electricity purchases for future dates, which help them to offer fixed-rate tariffs to their customers. Power purchase agreements can also be used by large consumers such as data centres.

Retail electricity prices reflect not only the wholesale cost of electricity but also other expenses including network charges, taxes (including environmental charges such as contracts-for-difference levies), and suppliers’ administrative costs and profit margins. Retail pricing of electricity is changing in response to the growing penetration of VRES on the grid, which leads to variable wholesale prices. Time-of-use tariffs need to be made more widely available to encourage more widespread use of demand response by industrial, commercial, and domestic consumers, which can reduce the required generation capacity and therefore the investment costs for power generation.

Other energy markets, notably for heating and cooling must be integrated with electricity markets, especially for European buildings where space and water heating currently dominate energy demands. For example, district heating system operators may buy solar photovoltaic electricity from building owners during very sunny periods and store it as heat which can be sold back to the same or different building owners at a later time, thereby integrating markets for electricity and heating. In urban areas, markets for buying and selling waste heat as well as solar and geothermal heating must be fully integrated so that sustainable heat that is bought and delivered by district heating networks is competitively priced. Such integration can also contribute to reducing energy poverty (ABC 2025). Similarly, isolated or small groups of houses, which use individual heat pumps and contribute to energy security through renovation to reduce their energy demands, should be supplied with competitively priced sustainable electricity (EASAC 2021).

Cooling is largely produced using electricity, so the integration of markets for space cooling is likely to focus mainly on electricity demand response schemes with time-of-use tariffs that match the needs of the electricity system operators with the potential for using thermal mass in buildings to keep them cool.

3 Challenges and barriers to energy system integration

3.1 Unintended consequences of rapidly integrating variable renewable electricity supplies without adequate controls (blackouts and cascading system failures)

The integration of energy demands and supplies, including VRES, typically leads to more complex energy systems that need to be managed by advanced ICT systems, and to risks that are difficult to estimate. However, such risks can be assessed and potentially reduced by investing in pilot and demonstration projects on which studies can be performed (Ornetzeder and Sinozic 2020).

During the transition to a more integrated energy system, electricity system operators must manage their systems in cooperation with new and long-standing energy suppliers within countries and across national borders to minimise the risks of blackouts and cascading system failures. In particular, it is crucial to ensure that appropriate controls of voltage and frequency are put in place when thermal generators with rotating machinery are replaced with wind or solar photovoltaic generators. This is because rotating generators inherently have mechanical inertia and can provide voltage and frequency control at low cost, while solar photovoltaic and wind generators typically do not have these features and may therefore need, at additional cost, to be fitted with grid-forming inverters. Alternatively, synchronous compensators (mechanical rotating stabilisers, some existing rotating generators can be used for this), or power-electronics based compensators, with or without batteries, can be installed to provide voltage and frequency control.

It is also important to provide adequate black-start capability, and short-term dispatchable backup generation to cover longer periods without sunshine or wind. Voltage and frequency control together with black-start capability are often referred to as system services and are crucial for secure and reliable operation of the power system, so their costs must be adequately covered by dedicated financing mechanisms (IEA 2024a).

Technologies other than generators are available to deliver system services, but responsibilities for installing them and mechanisms to pay for their costs must be specified in the relevant legislation. State-aid rules are being adapted to address these issues but work on capacity mechanisms to cover the costs of backup generation and storage, for example by ENTSO-E, is continuing (ENTSO-E 2025).

3.2 Updated remits for institutions and bodies to administer a more integrated energy system

As Europe’s energy system becomes more integrated, the old lines of responsibility are becoming increasingly blurred, and responsibility for oversight of the emerging integrated European energy system must be better defined to make clear who is in charge of what (Büscher *et al.* 2020). New bodies, for example regulatory authorities, may need to be set up or existing bodies with different cultures may need to be merged. This process will naturally be resisted by the existing bodies, so it must be implemented with great care and diplomacy to maintain investor confidence and energy security throughout the transition to a more integrated and decarbonised energy system. New practices and business models will also need to be understood by large numbers of energy consumers (e.g. bi-directional charging of electric cars).

Some changes have already begun in the EU: for example, the mandate for ACER has been updated and the network operators ENTSO-E and ENTSOG have been required to work more closely together. A new EU Distribution System Operator Entity was established in 2021 to bring together all electricity distribution system operators. In addition, an Electricity Coordination Group has been established to monitor the security of energy supplies.

As the European energy transition proceeds and the energy system becomes more integrated, many organisations in the electricity sector will need to work more closely with organisations that deal with other energy carriers and energy sources, including fossil fuels until they have been phased out. Such organisations may deal with solid fuels (coal, lignite, biomass), gaseous fuels (methane, biomethane, hydrogen, ammonia), and/or liquid fuels (fossil oil, biofuels, methanol, sustainable aviation fuels). Even after fossil fuels have been largely phased out, small quantities of natural gas and petroleum fuels are likely to be used for specific applications, such as emergency backup generation, so smaller but active organisations dealing with these fuels will be needed for many years to come.

3.3 Resistance to energy system integration

The fuel suppliers to Europe are dominated by a relatively small number of major energy companies, that have long established fossil-fuel-based business models and must satisfy their shareholders' expectations in terms of profits on a regular basis. They are therefore under financial pressure to keep to their core business, which is strongly based on fossil fuels, and to resist the changes required to deliver a transition to a more integrated and decarbonised energy system.

In contrast, most of the big electricity suppliers in Europe have shifted the focus of their businesses in recent years to work on supplying renewable electricity and have adapted their business models to operate as mainstream actors in Europe's more flexible electricity markets. Nevertheless, these pioneering businesses continue to face resistance from local communities, including delayed permitting for strengthening grid connections and building renewable electricity generators. They also face barriers in their negotiations over the pricing of grid flexibility management measures including storage, demand response, and backup generation. Policy-makers must therefore work with Europe's electricity suppliers, network operators, and local communities to weaken and remove the barriers that are limiting the growth of renewable electricity supplies and therefore delaying the integration of energy systems, reductions in energy costs, and progress towards net-zero GHG emissions by 2050.

3.4 Impacts of energy system integration and decarbonisation on local communities and small businesses

The integration of more renewable electricity into the European energy system will be accompanied by the phasing out of fossil fuels, notably coal, lignite, oil, and gas. The use of coal has been substantially reduced in Europe in recent years, and this has had major impacts on local communities where it was mined and used. Communities that have been built to support the oil and gas industries in Europe have also begun to experience decline as local supplies of these fuels have dried up or become less competitive in global markets. The EU and national and regional governments must therefore provide targeted support to such communities with initiatives and funding that will facilitate the creation of new job opportunities for their populations and minimise the numbers of households, especially low-income households and vulnerable groups, and small businesses falling into energy poverty.

While major impacts on communities and businesses, for example where mines or oil or gas wells or refineries are closed, may be visible to policy-makers at all levels, energy system integration and the energy transition will require many thousands of people to change their jobs in communities and small businesses that are widely distributed across the EU. For example, fewer technicians to install and maintain gas boilers will be needed as boilers are replaced by heat pumps, and fewer mechanics with skills to maintain and repair internal combustion engines will be needed as vehicles with these engines are replaced by electric vehicles. Distributed support schemes for tackling such distributed needs must be put in place not only to compensate for the decline of fossil-fuel-based employment but also to minimise resistance to the energy transition. Distributed support should include retraining, new jobs, and transitional funding for people with redundant skills in a wide range of small and medium-sized enterprises.

3.5 Investor confidence is needed to deliver energy system integration

Major long-term investments are needed to build an integrated European energy system for delivering sustainable, secure, and affordable energy to European citizens in the future. Investors typically feel more confident about making long-term investment decisions if these can be made in the context of long-term policy frameworks and credible targets, so Europe's Energy Union, Climate Law (net zero by 2050), Green Deal, REPowerEU, Clean Industrial Deal, and related initiatives and legislation are important foundations on which to build investor confidence.

However, like all policy frameworks, they must be defended and lobbies by industrial or political groups with vested interests to weaken them must be strongly resisted by policy-makers at all levels.

3.6 Modelling of integrated energy systems confirms that they are cheaper and more secure

Recent modelling studies on the transition to integrated energy systems have reaffirmed that the integration of VRES enhances energy security while lowering system-wide energy costs. This was explained in peer-reviewed papers by researchers more than 10 years ago (Lund *et al.* 2014; Bogdanov *et al.* 2021; Meschede *et al.* 2024). However, recent exchanges between European modelling groups have found that electricity sector-only models, which do not fully address interactions (integration) with the wider energy system, can produce misleading outcomes of the energy transition, and lead to artificial concerns and inappropriate negativity about the security of energy supplies (EASAC 2025).

The concept of an energy hub has been introduced to model the interaction between different energy carriers in a systematic way (Krause *et al.* 2011), but modelling of integrated energy systems can also be done using other approaches. In both cases, electricity is the central energy system, and heating/cooling, transport and industry can be modelled with lower temporal granularity.

4 Discussion and conclusions

Energy system integration is a policy option that has the potential not only to improve the sustainability of energy supplies, but also to improve their affordability (lower energy prices) and energy security. Integration is therefore an important step in the transition to net zero by 2050.

It is important to address the potential risks and unintended consequences of increased energy system integration. This commentary aims to contribute to the continuing discussion on this.

Several barriers to the implementation of energy system integration still have to be overcome, but these are not insurmountable and should be addressed as soon as possible by European policy-makers working together with the responsible national authorities, the energy industry, and most importantly with citizens, local communities, and businesses.

As shown by the recent study (Lise *et al.* 2024), monitoring progress with energy system integration is not easy, but it is important that it be done independently as well as by Member States in their National Energy and Climate Plans.

5 Key recommendations on energy system integration for policy-makers

Note: energy system integration can be defined as the coordinated planning and operation of the energy system 'as a whole', across multiple energy supplies, carriers, infrastructures, and consumption sectors.

Energy system integration will reduce energy costs and improve energy security. In the context of growing concerns about energy security, the cost of living, the competitiveness of European industries, and the impacts of climate change, EASAC reiterates the importance of moving ahead as quickly as possible with the implementation of the EU strategy for energy system integration (2020), with particular emphasis on the seven points listed below.

1. Integration will require an increase in digitalisation and use of ICT, which will need to be protected from cyberattacks. It will also require more training for skilled ICT system operators and cyber protection experts.

2. Integration should include not only energy supplies but also energy demands with energy efficiency (first) in buildings, industry, and transport.

3. Integration policies and legislation should address not only electrification but also fuel supplies for heating and transport, including fossil fuels while these are being phased out.

4. Integration should include not only technologies and physical systems but also energy markets, in which time-of-use tariffs and demand response can help to reduce the needs and costs for strengthening energy infrastructure with more cabling (including HVDC, MVDC, and LVDC systems), heat and electricity storage (batteries), interconnections, and back-up generation.

5. Integration policies and legislation are key to delivering the transition to net zero by 2050. However, they will create challenges not only for existing technologies, but also for incumbent organisations, management infrastructures, and business models that will need to be revised and updated to accommodate the new integrated energy systems.

6. Energy system integration will involve systemic innovation, which can bring both unknown risks and unintended consequences that must be identified and addressed as early as possible in the transition process.

7. To address the impacts of energy system integration and the transition to sustainable energies, targeted support will be needed in specific regions and communities that are directly affected by the decline of old fossil-fuel-based industries, and distributed support will be needed by small and medium-sized enterprises and citizens all over Europe with skills that are no longer needed. Both targeted and distributed support should include retraining, facilitating new job opportunities, and transitional funding to minimise the numbers of households and small businesses falling into energy poverty.

Abbreviations

ACER	EU Agency for the Cooperation of Energy Regulators
BEV	Battery electric vehicle
COP	Conference of the Parties
EASAC	European Academies Science Advisory Council
EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSOG	European Network of Transmission System Operators for Gas
EU	European Union
GHG	Greenhouse gas
HVDC	High-voltage direct current
ICT	Information and communications technology
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LVDC	Low voltage direct current
MVDC	Medium voltage direct current
UN	United Nations
VRES	Variable renewable electricity supplies
V2G	Vehicle to grid

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(Note: throughout the reference list, all hyperlinks were working on 17 December 2025.)

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This commentary was written under auspices of EASAC's Energy Steering Panel whose members are as follows:

Michael Ornetzeder (Austria)
Derrick Gosselin (Belgium)
Neven Duic (Croatia)
Soteris Kalogirou (Cyprus)
Miroslav Chomat (Czech Republic)
Poul Erik Morthorst (Denmark)
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Richard van de Sanden (The Netherlands)
Asgeir Tomasgard (Norway)
Lidia Gawlik (Poland)
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Kateryna Kamyshnykova (Slovakia)
Fernando Briones (Spain)
Göran Andersson (Sweden)
Tünde Fülöp (Sweden)
Martin Patel (Switzerland)
Jenny Nelson (UK)
and William Gillett (UK), EASAC Energy Programme Director (until the end of 2025)

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EASAC contributes to the implementation of the

SUSTAINABLE DEVELOPMENT GOALS

EASAC Secretariat
Austrian Academy of Sciences
Dr. Ignaz Seipel-Platz 2
1010 Vienna Austria

tel: +43 1-515-811208
secretariat@easac.eu