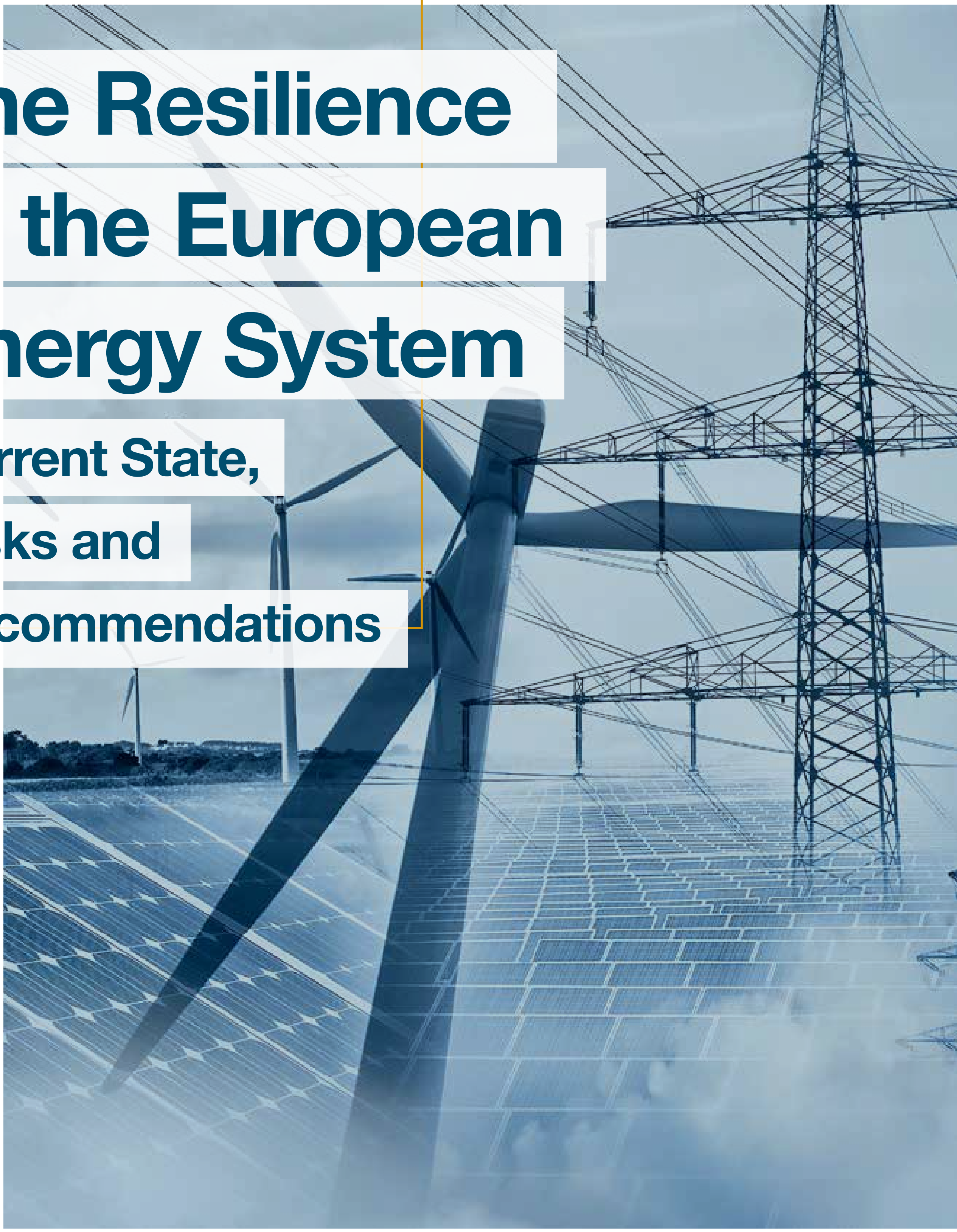
The Resilience of the European Energy System

Current State, Risks and Recommendations



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Content

Foreword

The resilience of the European energy system is a critical factor in ensuring the continent's socio-economic stability and achieving its climate ambitions. This document has been produced by EFCA's Future Trends Committee, in association with the University of Marburg. It provides a comprehensive analysis of the current state of the European energy sector, identifying key vulnerabilities, and proposing strategic solutions to enhance its resilience. It highlights the consulting engineering sector's vital role in addressing structural and operational challenges, mitigating geopolitical and climate-related risks, and ensuring a sustainable energy future for Europe.

With a number of recommendations regarding the structure of the energy market and its legal framework, we hope that this paper, part of our annual *Future Trends Report*, will stimulate further dialogue with EU and national policy makers and we look forward to sharing EFCA's expertise at this pivotal moment. The importance of shoring up our energy infrastructure and improving the overall supply system cannot be overstated.

I would like to extend my gratitude to all the contributors who have dedicated their time and expertise to this important work, which are listed below. Their invaluable insights and collaborative efforts have been instrumental in shaping this comprehensive study.

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Executive Summary

OVERVIEW OF THE SECTOR'S CURRENT STATE

The European energy system remains a cornerstone of the continent's socio-economic stability and climate ambitions. However, its current configuration reveals fundamental structural and operational challenges.

Key facts:

1. fossil fuels still represent approximately 70% of the EU's gross energy supply;
2. in 2022, the EU imported 63% of its energy, underscoring its ongoing dependency on external partners and exposure to global market volatility;
3. approximately 40% of the electricity distribution grid is over four decades old, and the current infrastructure is not equipped to accommodate the anticipated 60% increase in electricity demand by 2030;
4. while renewable energy generation has grown, end-use sectors – particularly transport and residential heating – remain dependent on fossil fuels.

In short, the system is not yet equipped for either the full energy transition or the resilience demands of a geopolitically unstable and climate-vulnerable world.

IDENTIFICATION OF KEY VULNERABILITIES

A number of internal weaknesses threaten the functionality and resilience of the European energy system, independent of external crises.

Major vulnerabilities include:

1. **fragmented energy market integration,** delaying cross-border electricity exchange and hampering the scalability of renewables;
2. **regulatory and legal bottlenecks**, such as the limited authority of the European Union Agency for the Cooperation of Energy Regulators (ACER) and excessively long permitting procedures for new infrastructure projects;
3. **ageing and underdeveloped grid infrastructure**, including outdated high-voltage lines and insufficient interconnectivity between Member States;
4. **insufficient and underutilised renewable capacity**, with frequent re-dispatching due to grid congestion and lack of storage;
5. **inefficient building stock**, with 75% of structures classified as energy inefficient, yet expected to remain in service well beyond 2050;
6. **lagging improvements in transport energy efficiency**, which remains the slowest-progressing sector in the EU's decarbonisation efforts.

These weaknesses not only reduce operational reliability but also amplify the impact of external shocks.

SUMMARY OF GEOPOLITICAL AND CLIMATE THREATS

Europe's energy security is increasingly exposed to a range of systemic threats originating from both geopolitical tensions and accelerating climate change.

Geopolitical challenges include:

1. **high dependency on a small number of suppliers,** increasing the vulnerability to diplomatic disputes, embargoes or supply disruptions;
2. **energy price volatility,** as seen during the 2021–2024 crisis, which exposed structural inflexibilities across the European market;
3. **cybersecurity threats**, with critical energy infrastructure facing growing risks of sabotage, ransomware, and targeted attacks.

Climate-related risks comprise:

1. **water scarcity**, affecting hydropower and cooling operations at nuclear and thermal plants;
2. **heatwaves**, which both increase electricity demand for cooling and reduce the efficiency of transmission lines;
3. **other extreme events**, such as floods and storms, damaging power plants and transmission infrastructure.

The cumulative effect of these risks is a heightened probability of cascading failures across sectors and borders.

PROPOSED SOLUTIONS AND RECOMMENDATIONS

To strengthen the resilience of Europe's energy system, a comprehensive, future-facing transformation is required - one that addresses both infrastructure and governance.

Recommended strategic actions:

1. **accelerate grid expansion and modernisation**, with required investments estimated at €500 billion, to prepare for better interconnection between countries, increased electrification, smart solutions and decentralised generation;
2. **expand and diversify renewable energy capacity**, including solar, wind, tidal, geothermal and waste-based bioenergy;
3. **develop flexible energy storage systems**, encompassing batteries, pumped hydro, hydrogen, and vehicle-to-grid solutions;
4. **reform the regulatory framework** by empowering ACER with enforcement capabilities and harmonising approval procedures across Member States;
5. **integrate geographic risk mapping into infrastructure planning** by involving climate scientists and geographers in all major energy projects;
6. **enhance cybersecurity standards and coordination**, treating energy infrastructure resilience as a matter of critical national and European security.

The path forward requires decisive political leadership, robust engineering expertise and a shift from reactive policy to anticipatory infrastructure strategy.

Introduction

In modern times, the energy sector is one most important parts of our critical infrastructure. In case the energy system fails, the resulting energy shortages would also cause the misfunctioning of other critical infrastructure like transportation, most communication services, health services and fresh water supplies due to cascade effects (Zivilschutz Österreich, n.d.). In some cases, this can not only lead to huge economic costs but also to the loss of human lives. The energy crises of 2022-2023 demonstrated that geopolitical dynamics are unpredictable, can shift rapidly and have significant impacts on energy supply and price stability (IEA, n.d.-b). Therefore, it is important to design and modernise the energy sector in a way to ensure its resilience.

This is why the first goal of this paper is to analyse the impact of internal vulnerabilities, climate related threats and geopolitical risks, and study the interconnections between them. Subsequently, this research aims to present an overview of technologies, methods, measures and general strategies to improve the resilience of the European energy sector. To do so, this study will rely on interviews of experts in this field and literature analysis.

However, this document merely aims to contribute to current research projects on the issue and does not claim to provide solutions for every specific problem. This is why additional research in the future will still be relevant and needed.

Current State of the Sector

OVERVIEW OF THE SECTOR

Energy Demand

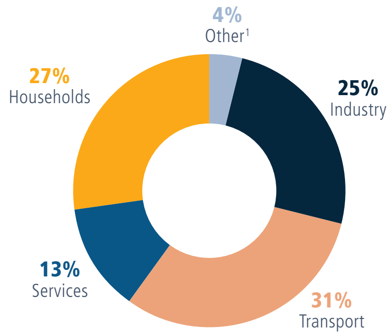
This section distinguishes between two key measures of energy demand. Gross available energy refers to the total amount of energy entering the system, including all primary energy input, and accounting for transformation processes, energy losses, and non-energy uses such as raw material input in industry (Eurostat, n.d.-b). In contrast, final energy consumption captures the energy actually used by end consumers - such as households, transport, services and industry - after the transformation and distribution losses have been deducted (Eurostat, n.d.-a). Understanding the distinction between these two indicators is essential for assessing both system-level energy flows and end-user demand.

Gross available energy in the EU peaked at around 70,000 Petajoules (PJ) in 2006 and declined to 58,461 PJ by 2022 - 4.5% lower than in 2021 and 6.3% below 1990 levels (Eurostat, 2024a). This decline reflects long-term trends and may be partly attributed to energy price shocks following the Russian invasion of Ukraine (Fulwood, 2023). In 2022, 23.8% of this energy was consumed in transformation processes and not available to end users (Eurostat, 2024a).

Final energy consumption followed a similar pattern, peaking at 41,447 PJ in 2006 and falling to 37,771 PJ in 2022 (Eurostat, 2024a). While

Figure 1. Final energy consumption by sector, EU, 2022 (Eurostat, 2024a)

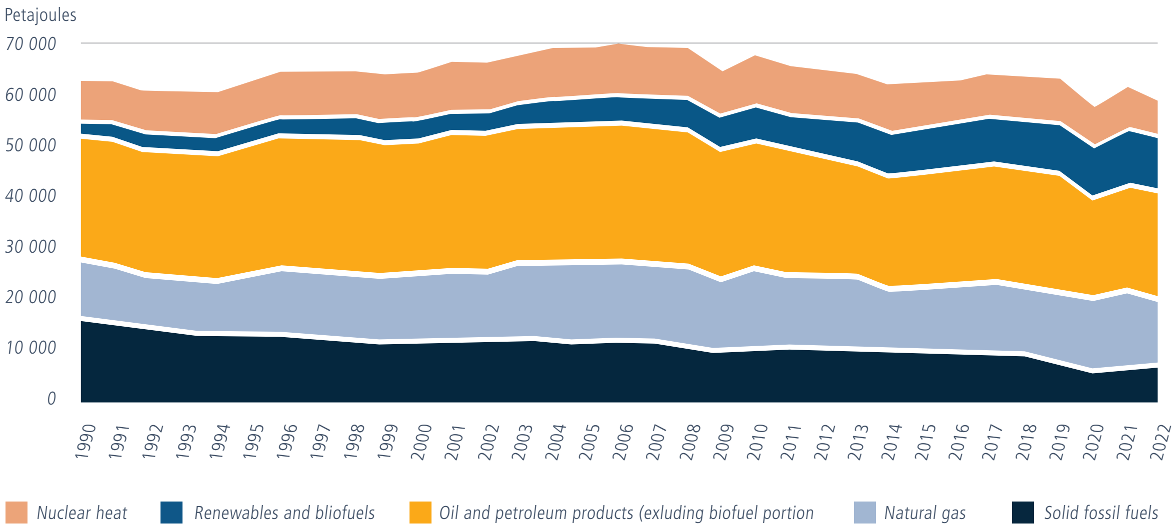
(% of total, based on terajoules)



1. *International aviation and maritime bunkers are excluded from catergory Final energy consumption for transport.*

Source: Eurosat (online data code: nrg_bal_s)

Figure 2. Gross available energy by fuel, EU, 1990-2022, (Eurostat, 2024a)



overall demand declined, the share of renewables and biofuels rose from 4.3% to 12.2% between 1990 and 2022, and the share of solid fuels dropped from 9.6% to 1.8% - a trend driven by national coal phase-outs (Schrems & Wieland, 2024).

Three sectors accounted for 83% of the final energy consumption in 2022: transport (31%), households (27%), and industry (25%) (Eurostat, 2024a). Road transport dominates the transport category, accounting for 73.6% of its energy consumption in 2022, with gas/diesel oil (65.4%) and gasoline (25.2%) being the primary fuels. Electricity accounted for just 0.3%, underscoring the sector's heavy reliance on fossil fuels (Eurostat, 2024e).

Within households, space heating accounted for 63.5% of energy use. This need is primarily met through natural gas (36.3%), followed by renewables and biofuels (31.4%), oil (13.1%), and electricity (6.1%) (Eurostat, 2024d). Overall, household energy demand remains highly dependent on fossil fuels.

For industry, electricity (33%) and natural gas (32%) were the leading energy sources in 2022. Natural gas plays a dual role – providing heat and acting as a feedstock in chemical processes (Statistisches Bundesamt, 2022). While the total industrial energy use dropped by 27.1% from 1990 to 2022, the use of renewables and biofuels increased by 84.7% (Eurostat, 2024b).

Figure 3. Final energy consumption in the residential sector by use, EU, 2022, (Eurostat, 2024d)

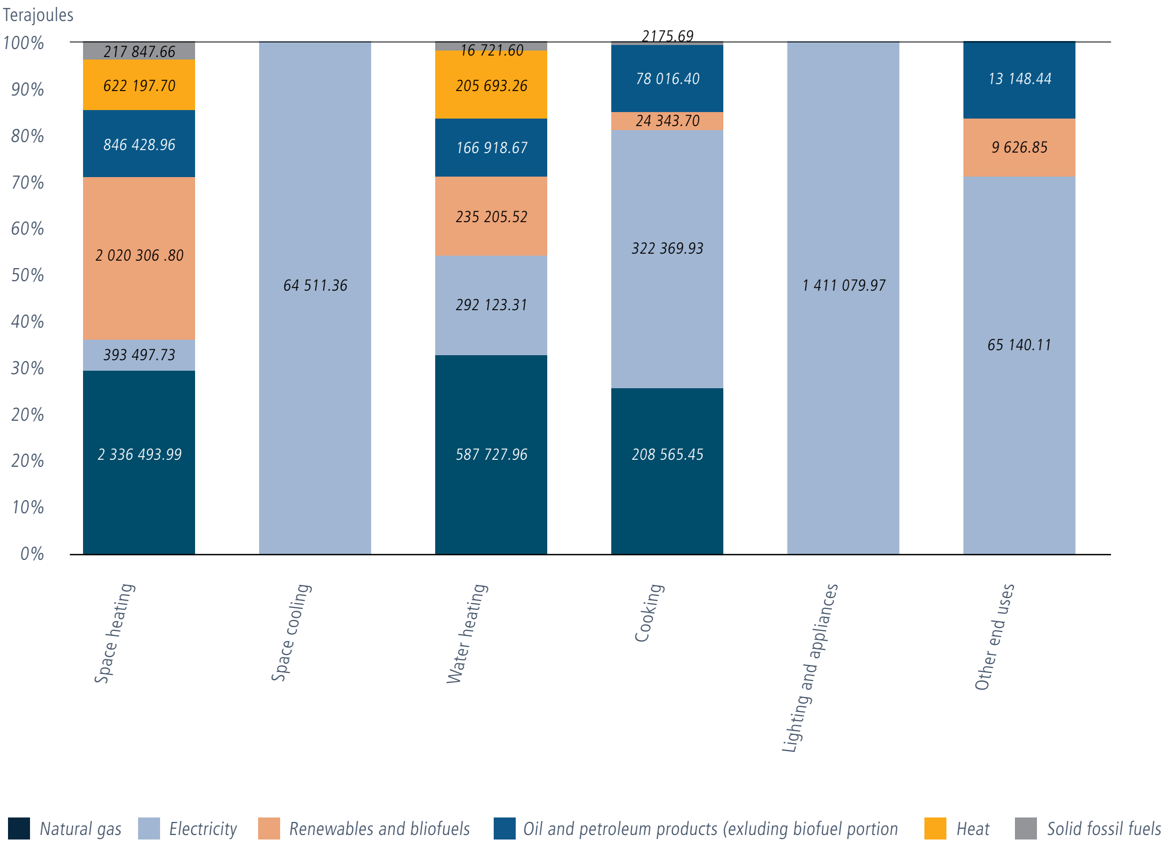
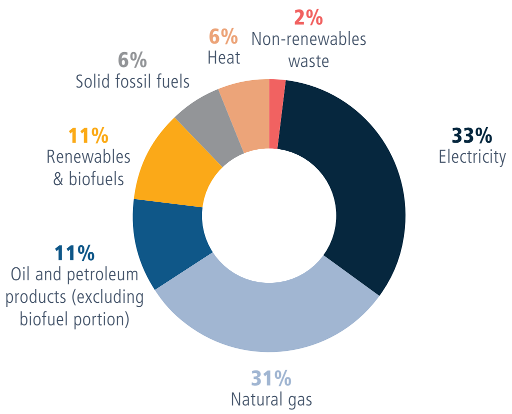


Figure 4. Final energy consumption in the industry sector by energy product, EU, 2022 (Eurostat, 2024b)



The most energy-intensive industries were the chemical and petrochemical (20%), non-metallic minerals (14.5%), and paper, pulp, and printing (13.5%). The chemical sector is especially gas-reliant due to its need for both energy and feedstocks (Eurostat, 2024b; Statistisches Bundesamt, 2022).

Energy Sources and Imports

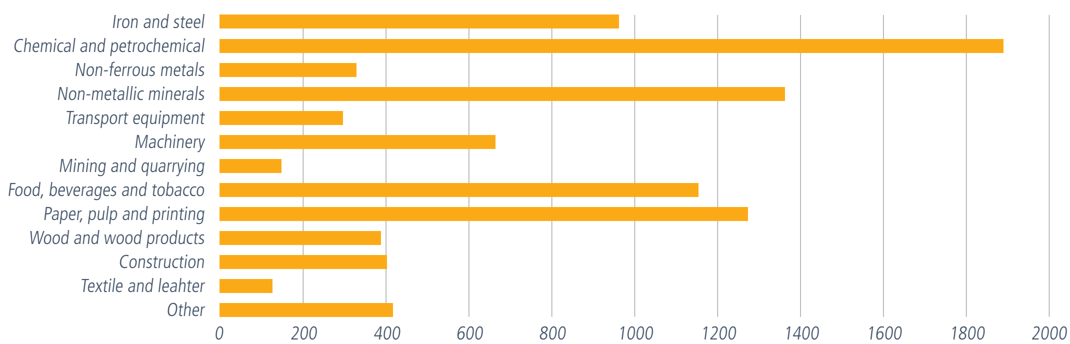
In 2022, the majority of the EU's gross available energy came from fossil fuels: oil and petroleum products (36.8%), natural gas (21.1%) and solid fossil fuels (11.6%), totalling 69.5% (Eurostat, 2024a). Renewables and biofuels contributed 17.9%, and nuclear heat 11.1%. While fossil fuels dominate overall energy supply, electricity generation tells a different story.

In the electricity sector, 39.4% of net power came from renewables, followed by nuclear heat (21.9%), gas (19.6%), coal (15.8%), and oil and others (3.3%) (European Council, 2024a). Though cleaner than the general energy mix, electricity generation still depends heavily on gas and coal.

Energy import dependency remains a key concern. In 2022, only 37% of the EU's energy was produced domestically, 63% being imported (European Commission, 2024c). Energy imports totalled €604 billion (3.8% of EU GDP) and made up 22.5% of the Union's total imports (European Commission, 2024b; Eurostat, 2024f).

Understanding this requires distinguishing between primary and secondary energy. Primary

Figure 5. Total final energy consumption by industrial sector, EU, 2022 (Eurostat, 2024b)



energy is sourced directly from nature – such as crude oil or hydro power – while secondary energy, like electricity from gas, results from transformation processes (Eurostat, n.d.-c; Øvergaard, 2008).

In 2022, the EU produced 23,566 PJ of primary energy - down 5.9% from 2021 (Eurostat, 2024a). Since 1990, fossil fuel production has fallen sharply. Coal dropped from over 12,500 PJ to below 4,000 PJ, and gas production fell by 64.9% from 2012 to 2022. Oil production also halved since its 2003 peak, while nuclear energy peaked in 2004 and declined thereafter (Eurostat, 2024a).

By contrast, renewables and biofuel production rose steadily and became the largest domestic energy source by 2016, surpassing 10,000 PJ in 2022 (Eurostat, 2024a). However, the recent decline in total primary energy output heightens the EU dependence on imports.

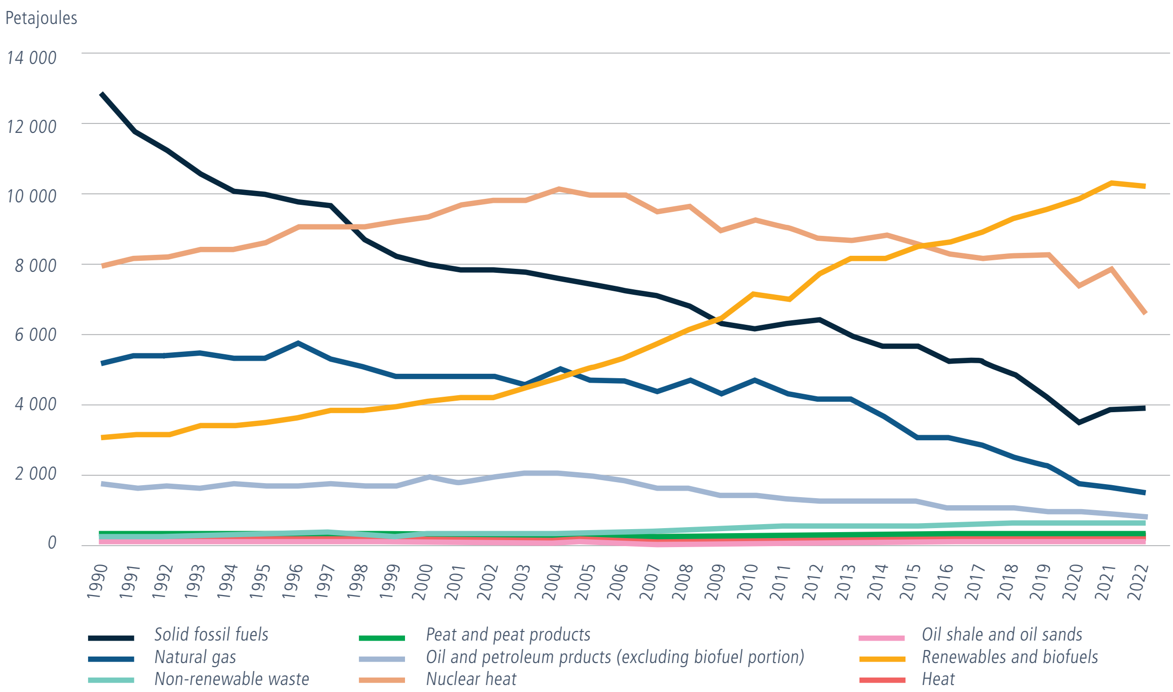
- Crude oil was the most imported energy product in 2022 (20,320 PJ), followed by natural gas (14,056 PJ) (Eurostat, 2024a). The main oil suppliers were the US (15.2%), Norway (13.9%), Kazakhstan (11.7%), and Libya (7.2%) (Eurostat, 2024f).

- For pipeline gas imports, Norway dominated with 42%, followed by Russia (17.6%), Algeria (16.0%) and the UK (14.3%) (Eurostat, 2024f).

- Liquefied natural gas (LNG) imports were firstly from the US (37.8%), with Russia (18.9%), Algeria (14.3%), and Qatar (10.3%) also being significant suppliers (Eurostat, 2024f).

- Coal imports were primarily sourced from Australia (36.6%) and the US (32.9%), with smaller contributions from Colombia (9.3%) and Kazakhstan (6.3%) (Eurostat, 2024f).

Figure 6. Primary energy production by fuel, EU, 1990-2022, (Eurostat, 2024a)



Taken together, Europe's energy security remains vulnerable due to its reliance on a few key suppliers. Norway and the US are particularly important – each supplying multiple fuel types – while Russia, Algeria, and Kazakhstan also play notable roles. Diversifying sources, reducing the dependency on fossil fuels and boosting domestic renewable energy sources (RES) production will be essential to improving resilience.

The Energy Grid

The European energy grid is technically complex and nationally diverse, but this section focuses on a high-level overview of the electricity and gas infrastructure.

The Electricity Grid

Electricity in Europe is typically generated by centralised plants and transmitted via high-voltage networks before being transformed via medium- and low-voltage systems for distribution (Kundur et al., 1994). Approximately 40% of EU distribution grids are over 40 years old, and electricity demand is projected to increase by 60% by 2030 (European Commission, 2023) due to rising renewables' production and electrification, adding more stress to the network or outright exceeding its capacity. Thus, the grid must both be modernised and expanded. Addressing this will require investments of up to €500 billion.

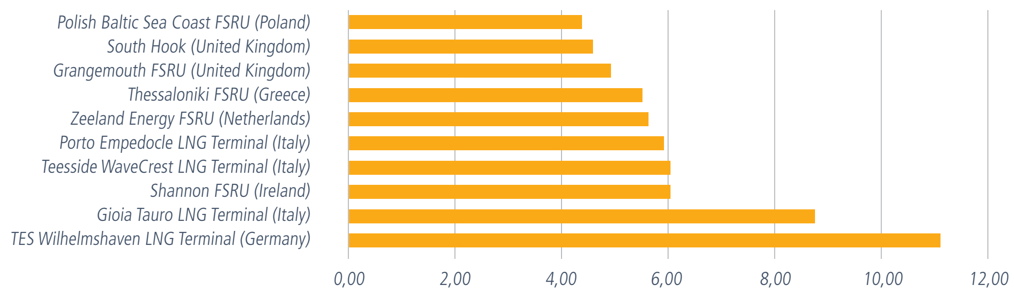
Although no single European power grid exists, most regional grids operate at 50 Hz, allowing cross-border flows and enhancing market flexibility. The EU has established interconnection goals - 10% by 2020 and 15% by 2030 - pursued through high-voltage direct current (HVDC) systems and coordinated by the European Network of Transmission System Operators for Electricity (ENTSO-E) (European Commission, 2015b).

The Gas Grid

Gas is distributed either via high-pressure pipelines or as liquefied natural gas (LNG) via ships and trucks. Compressor stations ensure pressure control and flow efficiency (Fügenschuh et al., 2015). The European Network of Transmission System Operators for Gas (ENTSO-G) manages the coordination and regulation of the EU gas grids under Regulation (EC) No 715/2009.

While regional differences remain, Europe's gas supply is significantly reliant on imports. Southern Europe sources gas from Algeria, Eastern Europe from Russia and the Caucasus, and Northern/Central Europe from Norway. To diversify, LNG imports have grown substantially – from 20% of total EU gas imports in 2021 to 42% in 2023 (European Commission, n.d.-b). However, LNG terminal infrastructure is uneven across member states.

Figure 7. Largest LNG import terminal projects proposed or under construction, by capacity, in the European Union as of 2025 (in billion cubic meters per year) (Statista, 2025a)



Despite structural fragmentation, both electricity and gas grids are increasingly interconnected, improving resilience and enabling competitive markets. Yet, modernisation is urgent to meet future energy and geopolitical challenges.

Energy Storage

Storage Facilities

Energy storage is a cornerstone of the energy system resilience. In the case of natural gas, large-scale underground facilities – such as depleted gas fields and saline caverns – are the preferred choice, offering secure, high-capacity storage. Germany's Rehden facility alone stores up to 4 billion cubic meters (bcm) (SEFE-Storage, n.d.), underscoring the critical role of subterranean infrastructure. Collectively, EU member states possess a technical storage capacity of roughly 120 bcm, rising to 154 bcm when including the UK, Ukraine and Serbia (GIE-AGSI, 2025). Yet, even when these are filled to the maximum, they covered only 32.5% of the EU's 2022 entire gas consumption, estimated at 353 billion cubic meters (Eurostat, 2024c).

Following the disruptions from the 2022 Russian invasion of Ukraine, the EU enacted a storage mandate requiring Member States that their storage facilities are filled to the 90% capacity level by October each year. By October 2024, EU storage exceeded 95%, providing a key buffer against future supply shocks (Regulation (EU) 2022/1032).

Unlike gas, other energy forms – electricity and heat – require a broader range of storage solutions. These include:

- mechanical (e.g., pumped hydro);
- thermal (heat tanks);
- electrical (e.g., superconducting magnetic energy storage (SMES));
- chemical (e.g., hydrogen);
- electrochemical (e.g., lithium-ion batteries) (European Commission, 2020).

Pumped hydro remains dominant, contributing with over 90% of the installed capacity due to its efficiency and scale as well as historic reasons. Spain's Cortes-La Muela plant exceeds 1,800 MW (Iberdrola, n.d.). However, deployment is now limited by geography, costs and environmental concerns.

Electrochemical storage is growing, particularly in the UK, Ireland, and Germany. As of 2020, the UK was the leader at the European level with 5,499 MW of operational and planned battery capacity (European Commission, 2020). These developments indicate a trend towards decentralised storage that supports renewable integration and grid flexibility, which must not only be maintained but also accelerated.

REGIONAL DIFFERENCES AND STRATEGIES ACROSS EUROPE

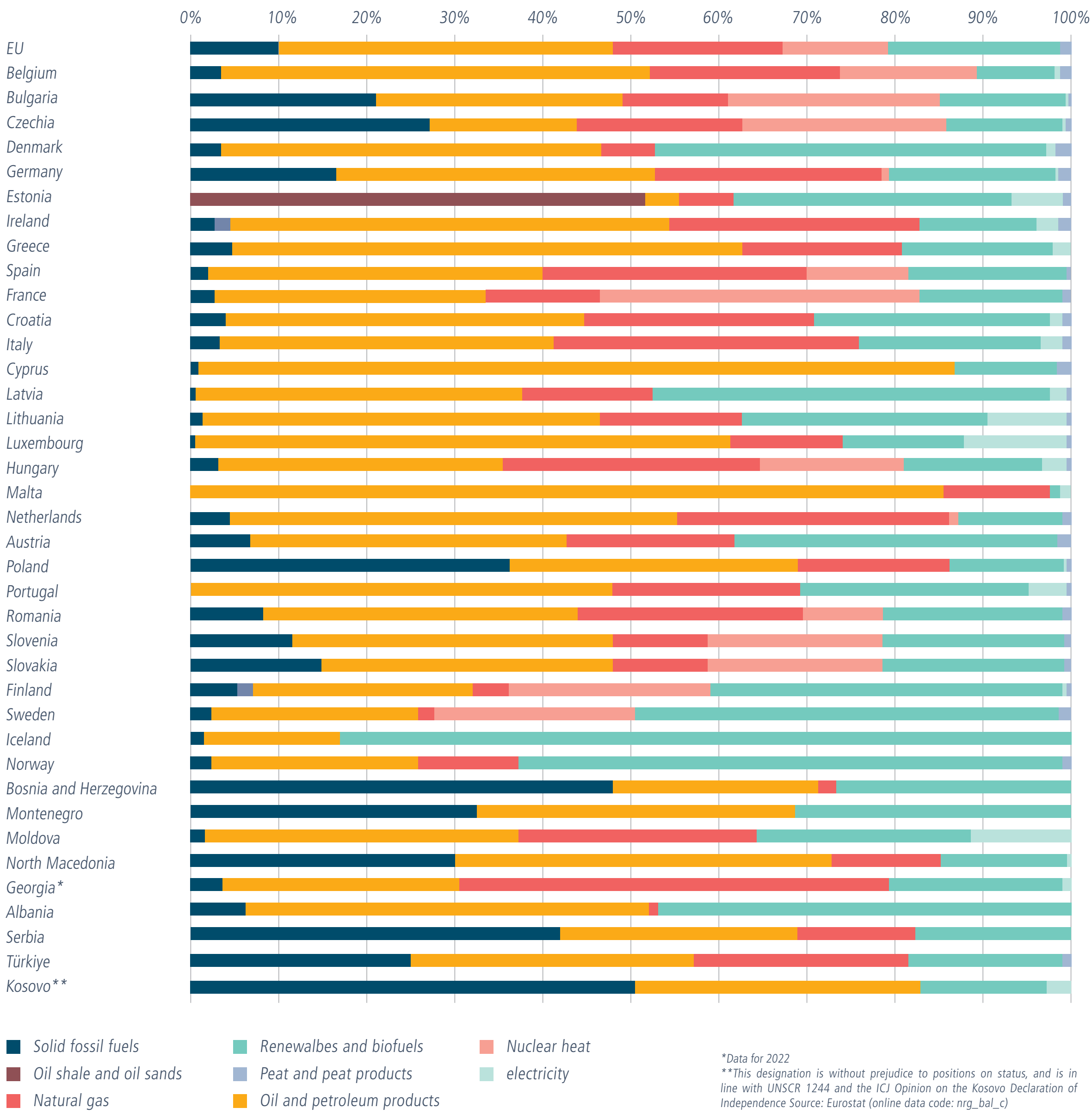
Europe's energy system is marked by stark regional differences in consumption patterns, energy sources and strategic approaches. Per capita energy use varies significantly – from over 200 Gigajoules (GJ) in Scandinavia to below 40 GJ in parts of South-Eastern Europe (Eurostat, 2024a). These disparities reflect broader variations in both energy mix and infrastructure maturity.

Northern countries such as Norway and Sweden rely heavily on renewable energy, while others – including Poland and Estonia – continue to largely depend on fossil fuels (Eurostat, 2024a). Nuclear energy further divides the continent. Thirteen EU countries operate nuclear facilities, with France and Sweden among the leading producers. Conversely, several Member States have fully opted out, underscoring the lack of a unified stance on nuclear power.

Energy dependency rates also differ substantially. In 2020, Malta relied on imports for more than 97% of its energy needs, whereas Estonia, benefiting from domestic oil shale, had a dependency rate of just 10.5% (European Council, 2024b). These structural contrasts influence national priorities and resilience strategies.

For consulting engineers, these regional distinctions present both challenges and opportunities. Tailored national strategies must account for local resources, consumption patterns and policy contexts while still contributing to EU-wide goals like carbon neutrality, energy security and grid resilience.

Figure 8. Gross available energy by fuel, 2023, (Eurostat, 2024a)



*Data for 2022
**This designation is without prejudice to positions on status, and is in line with UNSCR 1244 and the ICJ Opinion on the Kosovo Declaration of Independence Source: Eurostat (online data code: nrg_bal_c)

Internal Vulnerabilities Assessment

THIS SECTION WILL IDENTIFY SOME OF THE BIGGEST EXISTING AND POSSIBLE FUTURE INTERNAL VULNERABILITIES OF EUROPE'S ENERGY SECTOR. THESE WILL BE DISTINGUISHED INTO STRUCTURAL AND OPERATIONAL WEAKNESSES.

STRUCTURAL WEAKNESSES AND THREATS

Fragmented Energy Market Integration

The EU had set a target of 15% interconnectivity levels between national grids by 2030 to enhance integration, grid stability and renewables' uptake (European Commission, 2015b). Despite these goals, the implementation has lagged. A 2023 report by the European Court of Auditors noted that, seven years after the initial deadline, none of the planned integration guidelines had been fully implemented. Progress remains inconsistent across Member States (European Court of Auditors, 2023). This persistent fragmentation hinders renewables' integration, reduces efficiency, limits competition and contributes to higher consumer costs.

Legal Weaknesses

Complex and inconsistent legal frameworks across countries significantly delay energy infrastructure development. ACER plays a central role in advising on market design and cross-border transmission but has struggled with implementation and oversight due to limited enforcement power and regulatory complexity (European Court of Auditors, 2023).

Inadequate data aggregation further hampers ACER's ability to monitor the market and advise the European Commission effectively. This contributes to a cycle of weak oversight, unclear regulation and delayed policy implementation. ACER's limited mandate also prevents it from enforcing actions against market abuse, undermining its effectiveness in surveillance (European Court of Auditors, 2023).

Ageing or Missing Power Grid Infrastructure

Europe's grid infrastructure is ageing and underfunded. The EU currently operates 390,000 km of high-voltage transmission lines, averaging 30 years in age (European Round Table for Industry, 2024). Annual investment needs are estimated at €70–100 billion through 2050, with major funding gaps remaining (ACER, 2024).

Alongside modernisation, the grid must also expand to meet the projected demand increase of 60% by 2030 due to rising electrification (European Commission, 2023). However, international comparisons suggest that these forecasts may be conservative. For example, in the United States electricity demand is expected to double by 2035 in some parts of the grid, primarily driven by the rapid adoption of artificial intelligence (AI), data centres and electrification trends. These projections should prompt European planners to reconsider whether current assumptions sufficiently account for the disruptive technological demand drivers. Failing to make the necessary planning and investments to incorporate the real growth risks costly re-expansions and jeopardises stability both in the short- and long-term.

Legal and bureaucratic delays further impede grid expansion. In Germany, as of Q3 2024, over 50% of grid projects were still in the approval phase, while fewer than 40% were under construction or completed (Bundesnetzagentur, n.d.). Without streamlined permitting, expansions may lag behind technological needs, leaving (some) systems outdated even before they are operational.

In addition to infrastructure bottlenecks, recent incidents have revealed critical stability risks in grids with high shares of variable renewable energy. One such event occurred in 2025, when a large-scale blackout affected Spain and Portugal. According to recent analyses, the Spanish grid was at that moment 100% supplied by solar energy. This led to the shutdown of all conventional (rotational) power sources. Without the stabilising effect of rotating masses (inertial reserve) from conventional turbines, frequency stability in the grid could no longer be maintained. The resulting system instability triggered cascading consumer disconnections and ultimately caused a grid collapse.

This incident underscores a central technical challenge of renewable-dominant grids: the lack of physical inertia needed to stabilise frequency fluctuations. As the share of inverter-based renewables increases, grid operators must find technical alternatives, such as synchronous condensers, virtual inertia or grid-forming inverters, to preserve operational security.

Given the seriousness of the event, this blackout warrants close investigation. The lessons from Spain and Portugal should be used to inform grid design plans and policy decisions across Europe. Moreover, the ambition of achieving 100% renewable electricity supply should be critically evaluated – not to discourage decarbonisation, but to ensure that the system's resilience and security are not compromised in the process. A more balanced system combining renewables, dispatchable backup and storage, along with robust grid infrastructure and control technology, is essential to meet the dual goals of climate neutrality and reliability.

Risks Related to Nuclear Energy

Nuclear energy remains a pillar of the energy strategy for several EU countries, particularly France and Sweden. However, two critical vulnerabilities undermine its long-term viability: an ageing reactor fleet and the lack of permanent nuclear waste disposal facilities.

France, which derived 64% of its electricity from nuclear power in 2023 (IEA, n.d.-a), faces an impending decline in capacity. Many of its reactors are nearing the end of their technical lifespans, with significant shutdowns expected from 2028 onward (Zimmermann & Keles, 2023). More broadly, over 83% of EU nuclear reactors were already over 30 years old by 2019 (IEA, 2019), raising concerns over grid reliability and baseload security.

Nuclear waste presents a second major issue. While most of the EU's 2.3 million m³ of radioactive waste is low-level and suitable for near-surface storage, roughly 218,000 m³ is high-level waste requiring long-term geological disposal (European Commission, 2024a). Though transmutation and recycling technologies offer some mitigation, they cannot fully replace the need for final repositories (World Nuclear Association, 2024b).

No operational deep geological repository currently exists in the EU. Finland's Onkalo facility is pioneering this approach, but with a capacity of 6,500 tonnes, it falls far short of European needs. For comparison, Germany alone had over 15,000 tonnes of high-level waste as of 2016 (Bundesgesellschaft für Endlagerung, 2022; Tuohimaa, 2024). In the absence of a shared or regional solution, each Member State must plan its own disposal infrastructure – an expensive and politically sensitive process. Without clear solutions and technological progress, Europe's nuclear energy strategy remains vulnerable.

OPERATIONAL WEAKNESSES

Unused Energy Potential

One major operational inefficiency is the curtailment of renewable energy production. When grids become overloaded, surplus wind or solar generation is scaled back to maintain stability. In Germany alone, over 2,000 Gigawatts hour (GWh) of renewable electricity went unused in Q2 2024: 913 GWh from offshore wind, 603 GWh from solar and 570 GWh from onshore wind (Bundesnetzagentur, 2024). Though specific to Germany, similar inefficiencies likely exist across the EU. These losses reflect underutilised capacity and a mismatch between renewable production, storage availability and grid readiness. For instance, a better storage system might have spared Spain from experiencing at least part of the recent energy blackout.

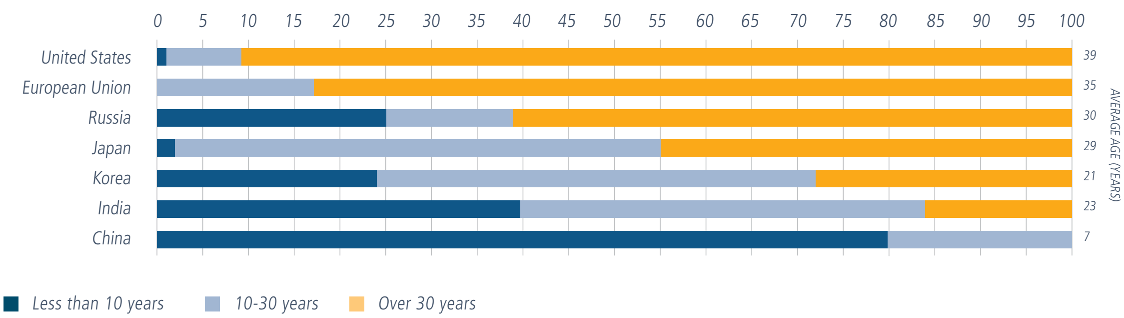
Energy Inefficiencies During Energy Use

Beyond production, end-use inefficiencies pose another challenge. Approximately 75% of EU buildings are deemed energy-inefficient by current standards, yet 85–95% of these buildings will still be in use by 2050 (Official Journal of the European Union, 2024). With the renovation rate at just over 1% per year, substantial upgrades are quickly needed to improve these buildings' energy performance.

The transport sector also lags in energy efficiency. While the residential and industrial sectors improved efficiency at 1.7% and 1.3% annually since 2000, transport has improved by only 0.7% per year (Lapillonne et al., 2024). This is concerning, given transport's 31% share in the EU's final energy consumption in 2022. Efficiency gains have stagnated due to increased SUV usage and reversing Diesel use trends, despite improvements in engine technology and electrification.

Together, these inefficiencies represent significant untapped potential. Improving energy use in the buildings and transport sectors is essential to closing the gap between energy supply and sustainable demand.

Figure 9. Age profile of nuclear power capacity in selected regions, (IEA. 2019)



Analysis of Climate Threats

IN ADDITION TO INTERNAL WEAKNESSES, EUROPE FACES GROWING EXTERNAL THREATS, MOST NOTABLY FROM CLIMATE CHANGE AND GEOPOLITICAL DISRUPTIONS. THE 2022–2023 ENERGY CRISIS DEMONSTRATED HOW INTERNAL VULNERABILITIES CAN INTENSIFY THE IMPACTS OF EXTERNAL SHOCKS. THIS CHAPTER OUTLINES KEY CLIMATE-RELATED RISKS FOR THE EUROPEAN ENERGY SYSTEM.

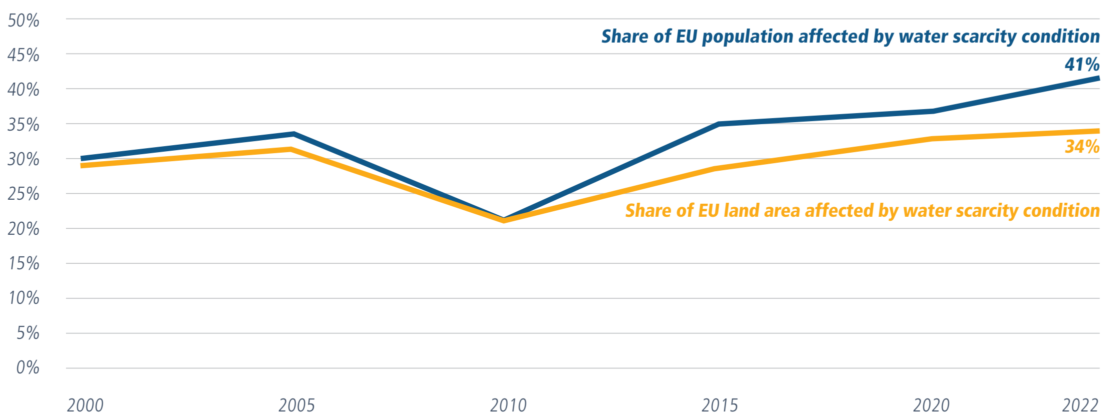
CLIMATE THREATS

Water scarcity is emerging as one of the most serious climate-induced risks. In 2022, 34% of EU territory and 41% of the population experienced seasonal water shortages (European Environment Agency, 2025).

These shortages directly impact thermal power plants – including gas, coal and nuclear – that rely heavily on water for cooling (European Environment Agency, 2019). A reduction in cooling water availability can force plants to reduce output or shut down, threatening grid stability and causing economic losses.

The risk is especially critical for nuclear facilities, which require continuous cooling – even when not generating power – to avoid core overheating (Suman et al., 2016). Competition for water among power stations and water-intensive industries can exacerbate the challenge

Figure 10. Area and population affected during at least one quarter of the year by water scarcity conditions in the EU, measured by the water exploitation index plus (European Environment Agency. (2025, January 17)



during droughts, creating supply bottlenecks, environmental damage and economic strain.

Hydropower is also very vulnerable. Southern Europe in particular, followed by regions in Eastern and Central Europe, faces reduced output due to changes in rainfall patterns, heatwaves and droughts (European Environment Agency, 2019). During prolonged dry spells, besides evaporation, stored water in pumped hydro reservoirs may be diverted for agricultural or domestic use, diminishing energy security.

Bioenergy is similarly affected. Bioenergy from agricultural crops may face declining potential in southern Europe and Eastern due to heat and drought, but alternatives such as waste-based bioenergy (e.g., manure or sewage) remain less vulnerable.

High temperatures also reduce transmission line capacity, by approximately 1.5% per degree of summer warming, while simultaneously increasing electricity demand for cooling (Sathaye et al., 2013; European Environment Agency, 2019). This compounds pressure on already strained grids, particularly in southern and eastern regions.

Additional extreme weather events further threaten energy infrastructure. Storms, floods, wildfires and blizzards can damage or destroy power plants, pipelines and transmission & distribution systems. Floods, for instance, can pose a critical threat to riverside power plants, including nuclear sites (European Environment Agency, 2019). The 2021 flood in Germany cut electricity for weeks in some areas (Seidel et al., n.d.), demonstrating how such events can paralyse critical infrastructure. Disruptions to power also affect essential services such as sanitation, communications and water supply (ASB, n.d.).

In sum, climate change is already straining Europe's energy infrastructure. Without adaptation measures such as decentralised grids, climate-resilient designs and diversified energy sources and storage, these risks can and will escalate, leading to severe societal and economic consequences.

5.2. REGIONAL DISPARITIES

Climate change will affect all of Europe, though the nature and severity of its impacts will vary regionally over the coming decades (European Environment Agency, 2019).

Northern Europe may see short-term benefits, including increased hydropower potential, enhanced offshore wind capacity and greater availability of biomass resources. There may also be some gains in oil and gas extraction. However, these advantages are offset by risks to offshore infrastructure, coastal energy facilities and grid networks vulnerable to extreme weather.

In contrast, Central Western and Eastern Europe, including the British Isles, will see fewer benefits. The main advantage is reduced heating demand due to milder winters. Nevertheless, these areas face growing vulnerabilities across coastal and offshore energy infrastructure, grid systems, substations and thermal power plants. Heatwaves will also become more common.

Southern Europe is projected to experience the most severe challenges. The region faces compounded disadvantages across all major energy sources – including hydropower, biomass and concentrated solar power – due to droughts, heatwaves and water scarcity. In addition, rising electricity demand for cooling and desalination will further strain energy systems (European Environment Agency, 2019).

Overall, regional disparities highlight the need for both European wider integration of grids and location-specific adaptation strategies. Engineering consultants must consider both risks and opportunities when supporting resilient infrastructure development across Europe.

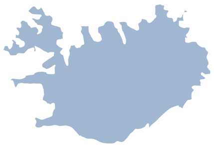
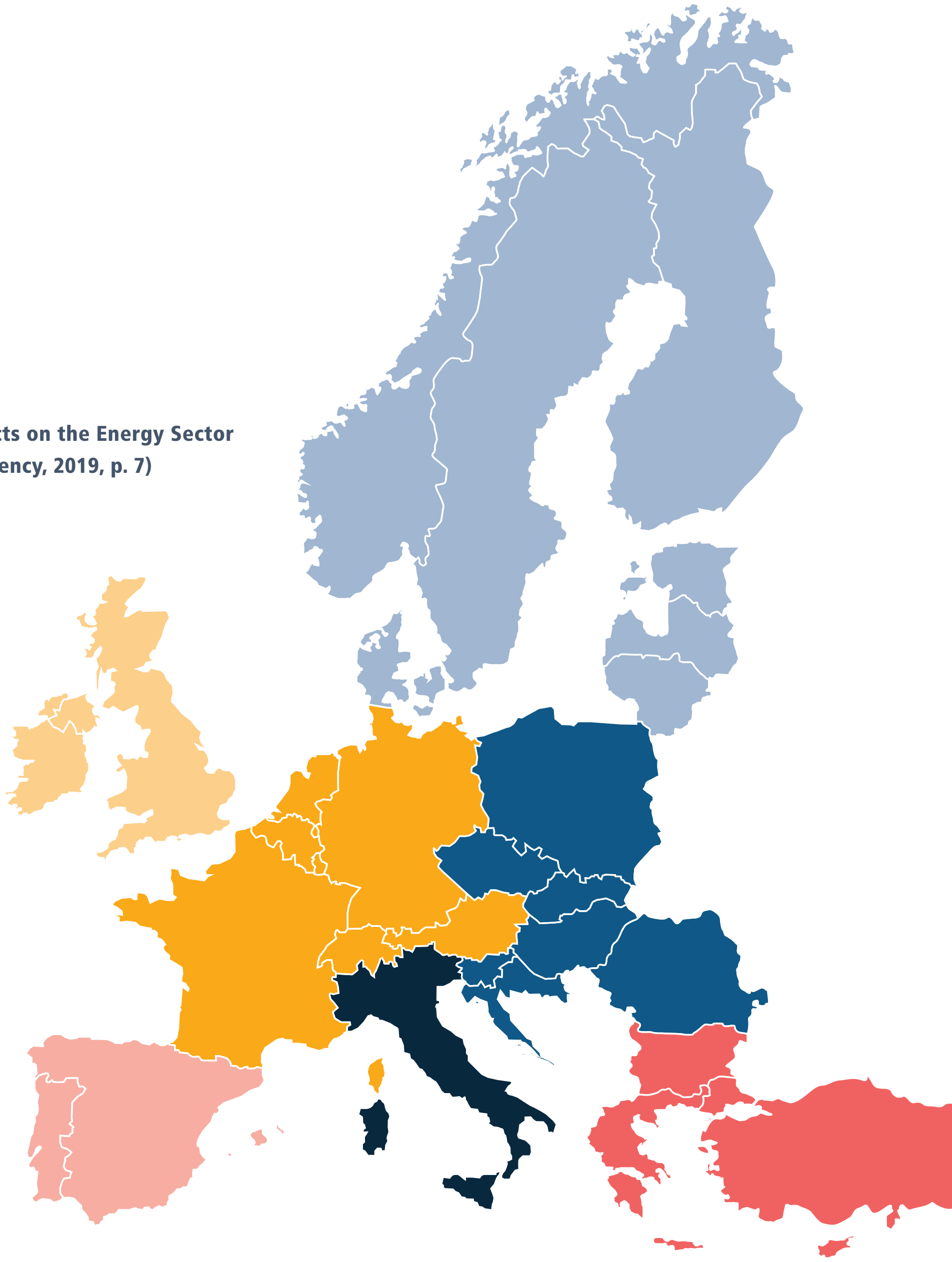


Figure 11. Selected Climate Change Impacts on the Energy Sector Across Europe (European Environment Agency, 2019, p. 7)



British Isles

- (−) Offshore energy production infrastructure (wind, oil, gas)
- (−) Coastal energy infrastructure (power plants and refineries)
- (−) Transmission and distribution grids
- (−) Electrical substations
- (+) Heating and cooling demand

Central-Western Europe

- (−) Offshore energy production infrastructure (wind, oil, gas)
- (−) Thermal power plants (fossil, nuclear and biomass)
- (−) Transmission and distribution grids
- (−) Electrical substations
- (+) Heating and cooling demand

Nothern Europe

- (+) Hydropower
- (+) Offshore wind power
- (+) Biomass energy
- (o) Oil and gas extraction
- (−) Offshore energy production infrastructure (wind, oil, gas)
- (−) Coastal energy infrastructure (power plants and refineries)
- (o)(−) Oil and gas transport
- (−) Transmission and distribution grids
- (+) Heating and cooling demand

Central-Eastern Europe

- (−) Thermal power plants (fossil, nuclear and biomass)
- (−) Transmission and distribution grids
- (−) Electrical substations
- (+) Heating and cooling demand

Iberian Peninsula, Apennine Peninsula and South-Eastern Europe

- (−) Hydropower
- (−) Concentrated solar power
- (−) Biomass energy
- (−) Therman power plants (fossil, nuclear and biomass)
- (−) Transmission and distribution grids
- (−) Pumped hydro storage
- (−) Peak electricity demand
- (−) Energy demand for desalination

(+) Predominantly beneficial impacts
(−) Predominantly adverse impoacts
(o) Impact not classifiable as beneficial or adverse due to colmplex economic and environmental effects
Renewable energy sources
Fossil energy sources
Other energy sources and carriers (nuclear, electricity, heating and cooling)

Analysis of Geopolitical Risks

EUROPE'S ENERGY SYSTEM FACES GROWING EXPOSURE TO GEOPOLITICAL RISKS. THESE THREATS VARY DEPENDING ON THE SEVERITY OF EXTERNAL CONFLICTS. THIS CHAPTER CONSIDERS TWO SCENARIOS: ONE WITHOUT DIRECT MILITARY CONFLICT INVOLVING THE EU OR EFTA COUNTRIES, AND A WORST-CASE SCENARIO INVOLVING OPEN WAR IN EUROPE.

FIRST SCENARIO WITH NO DIRECT CONFLICT/WAR

Energy Supply Shortages

Energy supply shortages represent a primary geopolitical risk. Disruptions can arise from trade wars, pipeline damage, embargoes or instability within supplier countries. Europe's vulnerability is heightened by its structural reliance on imports and limited diversification of trade partners.

Undiversified Trade Partners and Dependency on Energy Imports

In 2022, the EU imported 63% of its energy (European Commission, 2024c). While energy imports are not inherently problematic, the dependence on a few key partners – including Norway, the US, Russia and Algeria – amplifies supply risks. Should one of these suppliers reduce or halt exports, Europe would face immediate shortages (ref. Figures 11–13).

This dependency also exposes Europe to energy price shocks. The gas crisis triggered by Russia's war in Ukraine led to broad price surges and cascading effects across other sectors, contributing to inflation (Fulwood, 2023; Wehrhöfer, 2023). Market flexibility is key to mitigating such impacts, but Europe currently lacks agility and options in supplier choice. Much of its infrastructure – particularly for pipeline gas – is fixed, and LNG terminal capacity remains insufficient in some countries.

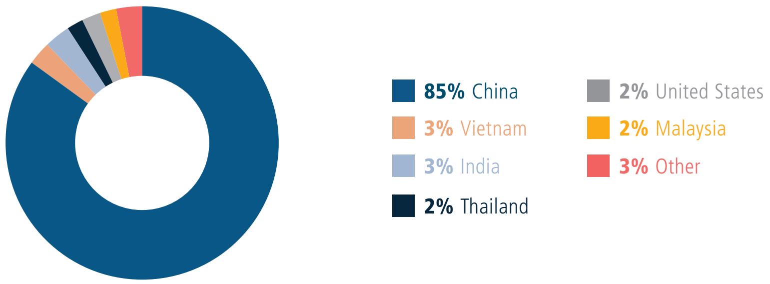
Shortages in Spare Parts and Rare Materials

Another risk involves supply chain vulnerabilities, including for energy infrastructure components. For example, China accounted for 86% of global photovoltaic production in 2023, while Europe held just 2% (Bett et al., 2024). Geopolitical tensions such as a trade conflict or a Taiwan crisis could severely disrupt access to solar technology and other critical (raw) materials. Although sector-specific effects vary, many parts of the energy system (e.g., grids, storage, power plants) could face similar disruptions.

Cyber-Security

Cyberattacks represent one of the most significant and evolving threats. Motivated by geopolitical tensions, terrorism or criminal activity, such attacks can target any part of the energy system, from power plants to transmission and distribution grids. Disruption to energy infrastructure can quickly cascade, affecting transport, communication and water services.

Figure 12. Distribution of solar photovoltaic module production worldwide in 2023, by country (Statista, 2025b)



Examples include the 2021 Colonial Pipeline breach in the US and multiple cyberattacks on Ukraine's power grid since the mid-2010s (Aljohani, 2022). These events illustrate that the same tactics could be applied to the energy systems in the EU. While infrastructure may differ across countries, the attack methodologies remain transferable. Therefore, proactive cybersecurity measures and continuous updates to security and defence capabilities are essential.

WORST-CASE SCENARIO

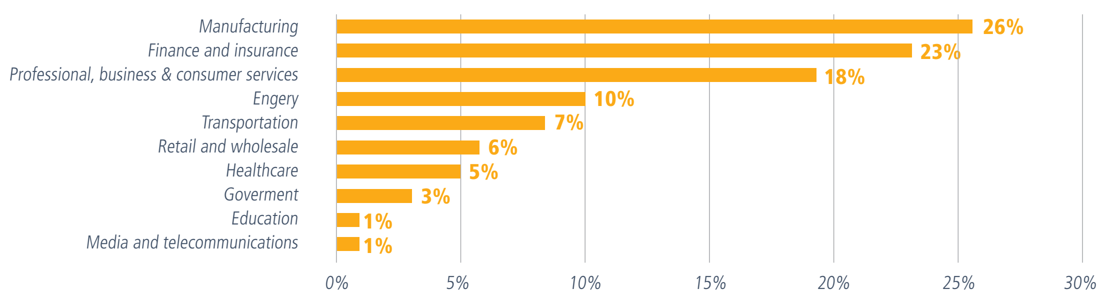
This section explores several additional threats in the event of full-scale military conflict within or against Europe. While the use of nuclear weapons is excluded given its catastrophic and unpredictable consequences (Bivens, 2022), conventional warfare still poses severe risks to the energy system.

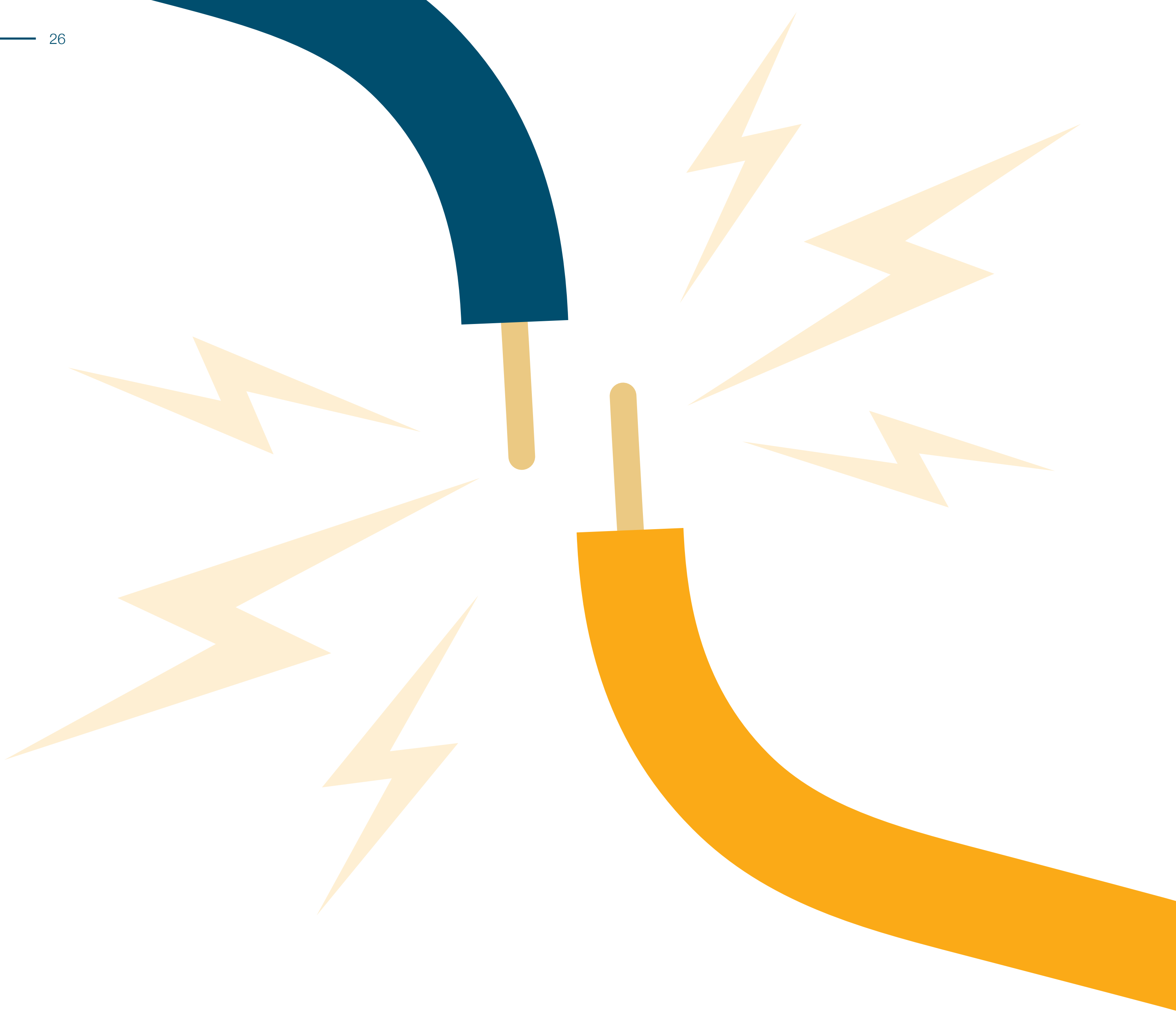
Nuclear Power Plants as Leverage

Nuclear power plants present a unique risk in armed conflict. Their potential for catastrophic radioactive release makes them a dangerous tool for leverage. A targeted attack or credible threat against active facilities could force political concessions or cause mass displacement, as illustrated by the 1986 Chernobyl disaster, which contaminated over 200,000 km² and spread radiation across Central and Northern Europe (Bundesamt für Strahlenschutz, 2025).

Despite being structurally robust – even against large aircraft crashes – modern weaponry such as precision-guided missiles or bunker-

Figure 13. Distribution of cyberattacks across worldwide industries in 2024 (Statista, 2024)





busting bombs could cause serious damage to nuclear power plants. Cyberattacks also pose a critical threat. The Stuxnet virus attack on an Iranian nuclear facility in 2010 manipulated physical operations and resulted in damaged uranium centrifuges (Baezner & Robin, 2017). Alarming reports suggest the malware remained undetected for nearly two years (Hansel, 2011), raising the possibility that European nuclear systems could already be compromised without detection.

Although attempts were made to assess the current cybersecurity status of European nuclear plants, interviews with staff were denied. Still, past precedents demonstrate that these facilities remain high-value targets, both physically and digitally, in future conflicts.

The Vulnerability of a Centralised System

Europe's energy infrastructure is heavily centralised, relying on large baseload plants. In wartime, the destruction of key plants or substations can trigger widespread blackouts. The ongoing war in Ukraine has already demonstrated how the targeting of energy systems can paralyse parts of the national infrastructure (Dugge, 2024).

Loss of power would have a domino effect, disabling sanitation, transport, communications and healthcare services. This highlights the need for enhanced physical and cyber protection as well as greater decentralisation to reduce systemic risk during armed conflict.

Recommendations and Possible Solutions

STRUCTURAL AND LEGAL RECOMMENDATIONS

As outlined in previous sections, the EU's fragmented energy market and complex legal framework have led to vulnerabilities such as supply insecurity and elevated prices. To improve integration, the EU must achieve the 15% interconnectivity target between national grids by 2030, which would enhance energy stability, competition and price efficiency (European Commission, 2015b).

Reforms at the institutional level are also essential. ACER must be empowered with effective regulatory and enforcement tools to advise the European Commission and ENTSO-E, monitor market developments and sanction misconduct independently (European Court of Auditors, 2023). Improved data collection and monitoring are critical for developing timely and effective policies.

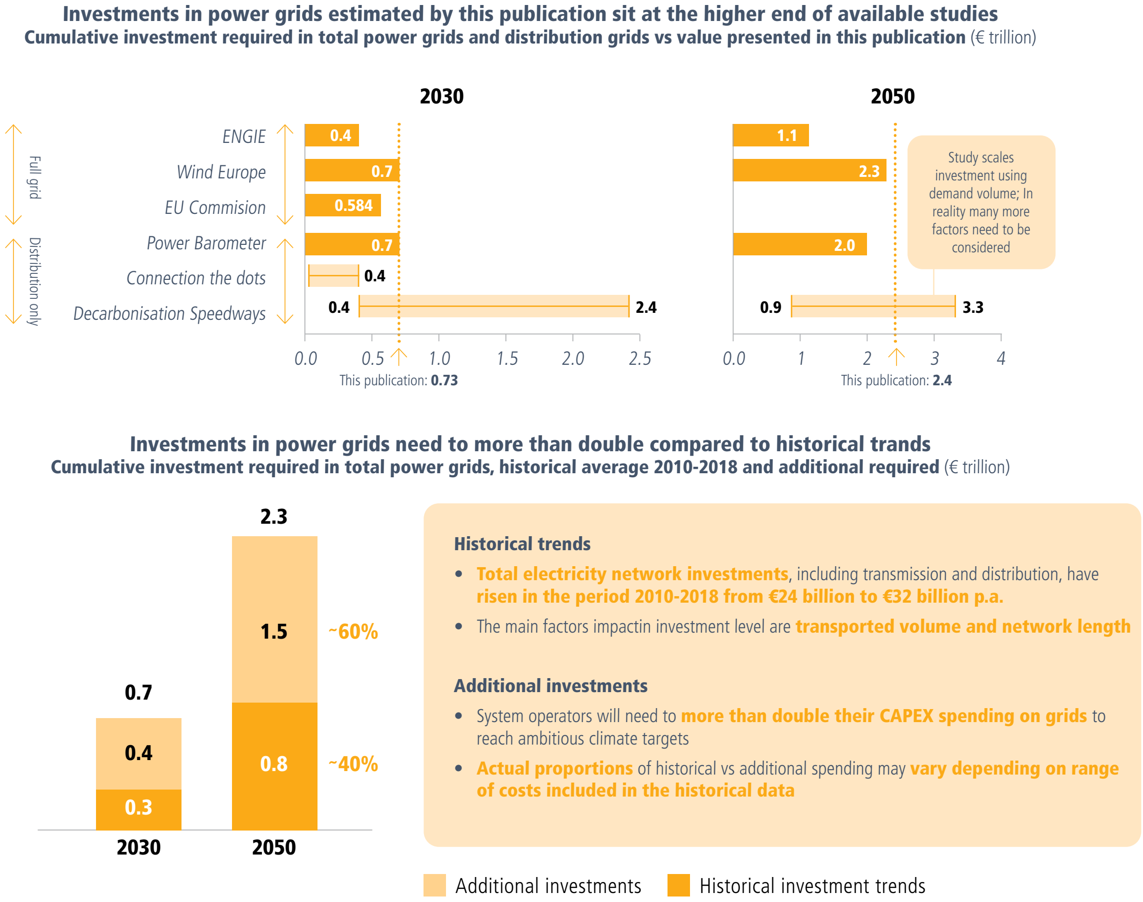
Beyond legal reform, streamlining approval processes for grid expansion is vital. Europe's grid infrastructure is ageing – e.g. the average transmission lines are 30 years old – and needs €70–100 billion in annual investment (European Round Table for Industry, 2024; ACER, 2024). Accelerating permitting and reducing bureaucracy across Member States will ensure infrastructure remains fit for future demand.

To achieve all this, an essential measure, and not just for energy infrastructure resilience but in general for the sector, is to increase the allocation of funding during the next Multi-Annual Financial Framework (MFF; 2023-2034), so that the TEN-E and other energy infrastructure projects eligible for EU funding can be built or modernised in a shorter timeframe. Such changes should also include dedicated EU funding for the maintenance of this infrastructure, or at least key elements of it, such as the border interconnections.

As a complementary measure, the current TEN-E legal framework should also be updated, where necessary, to ensure enhanced resilience of the EU energy infrastructure regarding both climate and man-made threats.

Given the current review of the EU public procurement legislative framework, the future rules should ensure, in general, that quality and resilience are properly included via the mandatory criteria in the tendering process. This should particularly be the case for tenders regarding critical infrastructure and the TEN-E network. Moreover, strategic purchases that are envisaged via the new public procurement legislation should consider the purchase of high-quality materials, equipment, etc. for the performance and resilience of key components of the energy infrastructure.

Figure 14. Investment in EU power grids (European Round Table for Industry, 2024; ACER, 2024)



Finally, while the trend now is to simplify the administrative and regulatory procedures related to permitting, this approach to 'cutting red tape' should not be done to the detriment of quality, environmental protection and resilience, in particular of the critical infrastructure and the TEN-E network.

EXPANSION OF RENEWABLE ENERGY

Expanding renewable energy – solar, wind, tidal, geothermal and bio-based – can address both supply resilience and emissions reduction. For instance, rooftop solar alone could achieve a result of 6 Global Warming Potential (GWp) annually from new EU buildings (Jäger-Waldau, 2020). The use of brownfield sites for solar energy and coastal zones for wave and tidal energy can increase RES output without consuming open land.

Renewables also mitigate the risks linked to water scarcity. Unlike thermal plants, solar and wind require little to no cooling water, preserving water for agricultural and industrial use (European Environment Agency, 2019). However, caution is needed with bioenergy: crops grown solely for energy use may exacerbate water shortages, whereas waste-based bioenergy presents a more sustainable alternative.

Greater RES capacity would also reduce dependence on imported fossil fuels, thereby enhancing Europe's energy autonomy and resilience to geopolitical shocks.

Finally, distributed renewable generation offers higher energy security, particularly in conflict scenarios. Unlike centralised plants, solar and wind installations are more decentralised, making them less vulnerable to targeted attacks, as illustrated by current energy disruptions in Ukraine (Dugge, 2024).

BUILDING SHORT- AND LONG-TERM ENERGY STORAGE

Energy storage is critical for stabilising renewable-based grids. Technologies such as sodium-ion batteries, which are cheaper and more abundant than lithium-based options, offer promising short-term solutions (Abraham, 2020). Subsidising local production can boost supply chain security.

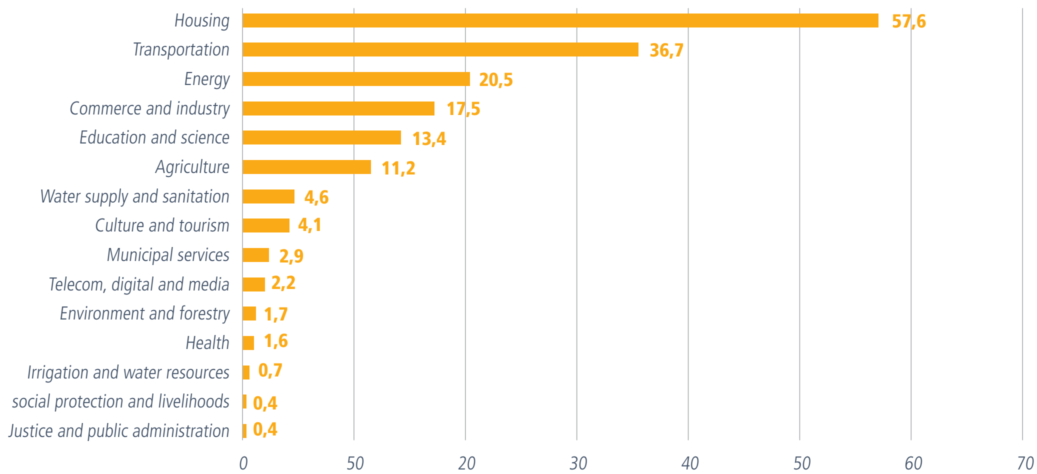
For long-term storage, iron-based chemical systems – where iron is oxidised and regenerated using electricity – can repurpose decommissioned coal plants and connect to existing grid infrastructure (Technische Universität Darmstadt, 2020; Kolorz, 2024). While still in development, this approach is seen as cost-effective and scalable.

Additionally, leveraging idle electric vehicles through bi-directional charging could turn millions of cars into grid-balancing assets, offering both financial and environmental benefits (Bundesministerium für Verkehr und digitale Infrastruktur, 2018; Vattenfall, 2024).

CLIMATE RESILIENCE

Given the rising climate threats, integrating geographic and engineering expertise is essential. Geographers can identify regional climate

Figure 15. Estimated total war damage value in Ukraine from February 24, 2022 to December 31, 2024, by sector (in billion U.S. dollars) (Statista, 2025c)



risks while engineers can adapt infrastructure accordingly. Tailored measures such as flood barriers, underground lines, and heat-resistant grid components must be prioritised (European Environment Agency, 2019).

Catastrophe insurance for municipalities can help mitigate economic damage, though prevention (e.g., wetland restoration, levees) remains critical where human life is at risk (Freie Universität Berlin, n.d.).

7.5 NEW NUCLEAR STRATEGIES

Europe's nuclear sector requires modernisation. The absence of final repositories for high-level radioactive waste remains a pressing concern (European Commission, 2024a). Additionally, many nuclear facilities are vulnerable to climate-related events like flooding and need to be retrofitted with barriers and emergency systems.

Cybersecurity is also paramount. As shown by the Stuxnet case, malware can remain undetected for years (Hansel, 2011). Nuclear plants must be audited and IT security systems stress-tested regularly. In conflict scenarios, governments must evaluate whether to protect nuclear facilities with reinforced air defence or phase them out to avoid security risks. This highlights the value of accelerating renewable deployment to reduce reliance on centralised, high-risk infrastructure.

7.6 RESILIENCE AGAINST ENERGY SHORTAGES AND PRICE SHOCKS

To mitigate risks from trade disputes, conflicts and supply chain disruptions, Europe must reduce import dependence. This includes scaling up domestic renewable fuel production – e.g., hydrogen, ammonia, and biogas – while diversifying sources to suit different end uses.

Investing in supply chains for abundant materials and organic-based technologies can further reduce strategic vulnerabilities. Meanwhile, LNG terminal expansion in underserved regions will boost import flexibility, ensuring better responsiveness to supply shocks and price volatility.

Finally, while the focus must indeed be on addressing resilience issues in the EU, both public and private stakeholders can also promote the use of the relevant technologies, methodologies, policies, etc. in countries outside the EU – e.g. via the Global Gateway initiative and its funded projects. This approach will help better address climate change, reduce the effects of conflicts on civilian infrastructure, ensure strong, long-lasting partnerships for energy supplies, and will better position European companies on the world markets.

Conclusion

Europe's energy sector currently faces significant resilience gaps due to internal structural and operational weaknesses, climate change impact and geopolitical threats. As outlined in the last chapter, addressing these vulnerabilities requires a multifaceted transformation of the energy system.

On the legal and regulatory side, overcoming bureaucratic inefficiencies and achieving greater interconnectivity between national grids is essential. Institutions like ACER must be equipped with enhanced monitoring tools and legal authority to enforce market regulations effectively (European Court of Auditors, 2023). Funding and resilience-oriented regulations are also necessary.

To tackle climate risks, infrastructure must be adapted using already available technologies. However, as regional climate impacts differ, tailored local strategies developed through collaboration between geographers and engineers are necessary.

Geopolitical instability, though unpredictable, demands preparedness. While peace remains the optimal condition for energy security, Europe must nevertheless strengthen its resilience to disruptions such as trade wars and supply embargos. This includes enhancing cybersecurity for energy infrastructure and developing more robust nuclear risk management strategies.

A critical long-term goal is increasing energy autonomy. This involves expanding domestic renewable energy and producing renewable fuels such as hydrogen and biogas. One expert emphasised the importance of "electrifying everything that is possible," while recognising that alternative fuels will still be required for industry and historic buildings that rely on high-temperature processes.

Despite these efforts, full energy autonomy is unlikely in the short term. Therefore, Europe must also improve flexibility and diversify its energy import portfolio to reduce vulnerability to geopolitical shocks.

In summary, enhancing Europe's energy resilience calls for comprehensive action across infrastructure, regulatory, climate and security dimensions. Continued research, especially on storage technologies and alternative fuels, will be crucial in shaping a secure, sustainable and adaptable energy future for Europe.

References

Abraham, K. M. (2020). *How Comparable Are Sodium-Ion Batteries to Lithium-Ion Counterparts? ACS Energy Letters, 5(11), 3544–3547.* **https://doi.org/10.1021/acsenergylett.0c02181**

ACER. (2024). *Electricity infrastructure development to support a competitive and sustainable energy system 2024 Monitoring Report.* **https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER_2024_Monitoring_Electricity_Infrastructure.pdf**

Aljohani, T. M. (2022). *Cyberattacks on Energy Infrastructures: Modern War Weapons (Version 1). arXiv.* **https://doi.org/10.48550/ARXIV.2208.14225**

ASB. (n.d.). *Krisenvorsorge bei Stromausfall: Was tun, wenn die Lichter ausgehen? Retrieved February 16, 2025, from* **https://www.asb.de/unsere-angebote/erste-hilfe/erste-hilfe-mit-selbstschutzinhalten/krisenvorsorge-bei-stromausfall#:~:text=Bei%20einem%20Stromausfall%20kann%20%C3%BCberlebenswichtige,den%20Zapfs%C3%A4ulen%20nicht%20mehr%20laufen.**

Baezner, M., & Robin, P. (2017). *Hotspot Analysis:S tuxnet.* **https://www.researchgate.net/publication/323199431_Stuxnet**

bdew. (2012, July 27). *50,2-Hertz-Problem: Allgemeine Informationen. h***ttps://www.bdew.de/energie/systemstabilitaetsverordnung/502-hertz-problem/**

Bett, A., Burger, B., Kost, C., Nold, S., Peper, D., Philipps, S., Preu, R., Reichel, C., Rentsch, J., Stryi-Hipp, G., Reuter, T., Wirth, H., & Warmuth, W. (2024). *©Fraunhofer ISE: Photovoltaics Report.* **https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf**

Bivens, M. (2022). *Nuclear Famine: Climate effects of regional nuclear war.* **https://www.ippnw.org/programs/nuclear-weapons-abolition/nuclear-famine-climate-effects-of-regional-nuclear-war**

Bundesamt für Strahlenschutz. (2025, January 15). *Der Unfall von Tschornobyl (russ.: Tschernobyl).* **https://www.bfs.de/DE/themen/ion/notfallschutz/notfall/tschornobyl/unfall.html#:~:text=Sie%20kontaminierten%20mehr%20als%20200.000,europ%C3%A4ischen%20Teil%20der%20ehemaligen%20Sowjetunion.**

Bundesgesellschaft für Entlagerung. (2022, December 31). *Aktueller Bestand.* **https://www.bge.de/de/abfaelle/aktueller-bestand/**

Bundesministerium für Verkehr und digitale Infrastruktur. (2018). *Mobilität in Deutschland – MiD.* **https://bmdv.bund.de/SharedDocs/DE/Anlage/G/mid-ergebnisbericht.pdf?__blob=publicationFile**

Bundesnetzagentur. (n.d.). *Monitoringbericht. Retrieved February 2, 2025, from* **https://www.netzausbau.de/Vorhaben/uebersicht/report/de.html**

Bundesnetzagentur. (2024, October 23). *Netzengpassmanagement im 2. Quartal 2024.* **https://www.smard.de/page/home/topic-article/444/215138#:~:text=Im%20zweiten%20Quartal%202024%20wurden,der%20Stromerzeugung%20aus%20Windenergieanlagen%20abgeregelt.**

Directorate-General For Energy. (2020). *Database of the European energy storage technologies and facilities [Dataset]. Publications Office.* **https://doi.org/10.2906/101110101114/1**

Dr. Wirth, H. (2024). *Recent Facts about Photovoltaic in Germany. Fraunhofer ISE.* **file:///C:/Users/janne/Downloads/recent-facts-about-photovoltaics-in-germany%20(6).pdf**

Dugge, M. (2024, May 17). *Angriffe auf ukrainische Kraftwerke.* **https://www.tagesschau.de/ausland/europa/ukraine-krieg-zerstoerung-infrastruktur-russland-100.html**

easac. (2007). *A study on the EU oil shale industry – viewed in the light of the Estonian experience.* **https://easac.eu/fileadmin/PDF_s/reports_statements/Study.pdf**

ENTSO-e. (n.d.). *ENTSO-E Mission Statement. Retrieved January 2, 2025, from* **https://www.entsoe.eu/about/inside-entsoe/objectives/**

ENTSO-g. (n.d.). *Mission. Retrieved January 3, 2025, from* **https://www.entsog.eu/mission#:~:text=ENTSOG%20continues%20its%20work%20as,security%20of%20supply%20and%20sustainability.**

EUR-Lex. (2022, October 31). *Natural gas transmission networks*. **https://eur-lex.europa.eu/EN/legal-content/summary/natural-gas-transmission-networks.html**

European Commission (n.d.-a). *Langfristige Strategie – Zeithorizont 2050. Retrieved January 19, 2025, from* **https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_de**

European Commission (n.d.-b). *Liquefied natural gas. Retrieved January 3, 2025, from* **https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/liquefied-natural-gas_en**

European Commission (2015a). *A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy.* **https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52015DC0080**

European Commission (2015b). *ENERGY UNION PACKAGE. European Commission. https://eur-lex.europa.eu/resource.* **html?uri=cellar:1bd46c90-bdd4-11e4-bbe1-01aa75ed71a1.0001.03/DOC_1&format=PDF**

European Commission (2023). *Grids, the missing link - An EU Action Plan for Grids.* **https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52023DC0757**

European Commission . (2024a). *REPORT FROM THE COMMISSION TO THE COUNCIL AND THE EUROPEAN PARLIAMENT on progress of implementation of Council Directive 2011/70/EURATOM and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects.* **https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52024DC0197**

European Commission. (2024b). *Report on energy prices and costs in Europe. European Commission. h***ttps://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52024DC0136**

European Commission (Ed.). (2024c). S*hedding light on energy in the EU: 2024 edition (2024 edition). Publications Office.* **https://doi.org/10.2785/88627**

European Commission. Directorate General for Energy., Artelys., Trinomics., & Enerdata. (2020). *Study on energy storage: Contribution to the security of the electricity supply in Europe. Publications Office.* **https://data.europa.eu/doi/10.2833/077257**

European Council. (2024a, April). *How is EU electricity produced and sold?* **https://www.consilium.europa.eu/en/infographics/how-is-eu-electricity-produced-and-sold/#0**

European Council. (2024b, April 9). *How dependent are EU member states on energy imports?* **https://www.consilium.europa.eu/en/infographics/how-dependent-are-eu-member-states-on-energy-imports/**

European Court of Auditors. (2023). *Internal electricity market integration: Complex legal architecture, delays, weaknesses in governance and incomplete market surveillance hamper full achievement of the ambitious objective. Special report 03, 2023. Publications Office.* **https://data.europa.eu/doi/10.2865/578602**

European Environment Agency (Ed.). (2019). *Adaptation challenges and opportunities for the European energy system: Building a climate-resilient low-carbon energy system. Publications Office of the European Union.* **https://doi.org/10.2800/227321**

European Environment Agency. (2025, January 17). *Water scarcity conditions in Europe.* **https://www.eea.europa.eu/en/analysis/indicators/use-of-freshwater-resources-in-europe-1?activeAccordion=**

European Round Table for Industry. (2024). S*trengthening Europe's Energy Infrastructure. ERT.* **https://ert.eu/wp-content/uploads/2024/04/ERT-Strengthening-Europes-energy-infrastructure_March-2024.pdf?utm_source=chatgpt.com**

Eurostat. (n.d.-a). *Glossary: Final energy consumption. Retrieved December 12, 2024, fro***m** ***https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Final_energy_consumption***

Eurostat. (n.d.-b). *Glossary: Gross available energy. Retrieved December 12, 2024, from* **https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Gross_available_energy**

Eurostat. (n.d.-c). *Glossary: Primary production of energy. Retrieved December 18, 2024, from* **https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Primary_production_of_energy**

Eurostat. (2024a, May). *Energy statistics - An overview.* **https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Gross_available_energy**

Eurostat. (2024b, May). *Final energy consumption in industry - Detailed statistics.* **https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics#:~:text=%2C%20renewables%2C%20etc.-,Energy%20products%20used%20in%20the%20industry%20sector,and%20biofuels%20(10.6%20%25).**

Eurostat. (2024c, May). *Natural gas supply statistics.* **https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_supply_statistics#:~:text=and%20euro%20area.-,Consumption%20trends,to%2012%20719%20409%20terajoules.**

Eurostat. (2024d, June). *Energy consumption in households.* **https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households**

Eurostat. (2024e, September). *Final energy consumption in transport - Detailed statistics.* **https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_transport_-_detailed_statistics**

Eurostat. (2024f, December). *EU imports of energy products - Latest developments.* **https://ec.europa.eu/eurostat/statistics-explained/index.php?title=EU_imports_of_energy_products_-_latest_developments**

Freie Universität Berlin. (n.d.). *Structural measures. Retrieved March 11, 2025, from* **https://www.geo.fu-berlin.de/en/v/iwrm/Implementation/technical_measures/Flood-protection-measures/structural_measures/index.html**

Fügenschuh, A., Geißler, B., Gollmer, R., Morsi, A., Pfetsch, M. E., Rövekamp, J., Schmidt, M., Spreckelsen, K., & Steinbach, M. C. (2015). *Physical and technical fundamentals of gas networks.* **https://www.ifam.uni-hannover.de/fileadmin/ifam/ordner/steinbach/publications/final/MO-21-Chapter-2.pdf**

Fulwood, M. (2023). *A new global gas order? Part 1. The Oxford Institute for Energy Studies.* **https://www.jstor.org/stable/resrep52177**

GIE-AGSI. (2025). *REMIT Storage Data [Tabel].* **https://agsi.gie.eu/#/**

Global Energy Monitor. (2024). *Europe Gas Tracker.* **https://globalenergymonitor.org/projects/europe-gas-tracker/tracker-map/**

Hansel, M. (2011). *Stuxnet und die Sabotage des iranischen Atomprogramms: Ein neuer Kriegsschauplatz im Cyberspace? In T. Jäger & R. Beckmann (Eds.), Handbuch Kriegstheorien (pp. 564–576). VS Verlag für Sozialwissenschaften.* **https://doi.org/10.1007/978-3-531-93299-6_47**

Iberdrola. (n.d.). *Cortes - La Muela, Europe's largest hydroelectric power complex in Spain. Retrieved January 16, 2025, from* **https://www.iberdrola.com/about-us/what-we-do/hydroelectric-power/hydro-plant-cortes-la-muela#:~:text=Cortes%20%2D%20La%20Muela%2C%20Europe's%20largest%20hydroelectric%20power%20complex%20in%20Spain&text=The%20Cortes%2DLa%20Muela%20hydroelectric,1%2C293%20MW%20of%20pumping%20capacity.**

IEA. (n.d.-a). *Where does France get its electricity? Retrieved February 3, 2025, from* **https://www.iea.org/countries/france/electricity**

IEA. (n.d.-b). *Wie die Krise begann, wie Energiemärkte unseren Alltag betreffen und wie Regierungen damit umgehen - Weltweite Energiekrise. Retrieved March 10, 2025, from* **https://www.iea.org/topics/global-energy-crisis?language=de**

IEA. (2019, May 28). *AGE PROFILE OF NUCLEAR POWER CAPACITY IN SELECTED REGIONS, 2019.* **https://www.iea.org/data-and-statistics/charts/age-profile-of-nuclear-power-capacity-in-selected-regions-2019**

Jäger-Waldau, A. (2020). *The Untapped Area Potential for Photovoltaic Power in the European Union. Clean Technologies, 2(4), 440–446.* ***h*ttps://doi.org/10.3390/cleantechnol2040027**

Jaller-Makarewicz, A. M., Russi, S., Scully, J., & Docherty, A. (2024, September 16). *LNG regasification terminals in Europe.* **https://ieefa.org/european-lng-tracker-september-2024-update**

Kolorz, N. (Director). (2024, March 31). *Energie-Speicher der Zukunft: Ist Eisen die neue Kohle? [Video recording].* **https://youtu.be/cqeIn0YPVyQ?si=h07ikr4nEdz3p8Ud**

Kumar, R., Lee, D., Ağbulut, Ü., Kumar, S., Thapa, S., Thakur, A., Jilte, R. D., Saleel, C. A., & Shaik, S. (2024). *Different energy storage techniques: Recent advancements, applications, limitations, and efficient utilization of sustainable energy. Journal of Thermal Analysis and Calorimetry, 149(5), 1895–1933.* **https://doi.org/10.1007/s10973-023-12831-9**

Kundur, P., Balu, N. J., & Lauby, M. G. (1994). *Power system stability and control. McGraw-Hill.* **https://dl.poweren.ir/downloads/PowerEn/Book/2019/Jun/Power%20System%20Stability%20and%20Control%20-%20Prabha%20Kundur%20%28PowerEn.ir%29.pdf**

Lapillonne, B., Payan, E., & Eichhammer, W. (2024, July). *Recent trends in energy efficiency in the EU.* **https://www.odyssee-mure.eu/publications/policy-brief/latest-energy-efficiency-trends.html**

Lungu, I., Dinu, F., Stoicescu, M., Suditu, S., & Mitrea (Rosu), I.-C. (2021). *Pro and con features regarding underground gas storage in depleted reservoirs versus saline deposits. MATEC Web of Conferences, 343, 09007.* **https://doi.org/10.1051/matecconf/202134309007**

NASA Science Editorial Team. (2024, October 23). *Extreme Makeover: Human Activities Are Making Some Extreme Events More Frequent or Intense.* **https://science.nasa.gov/earth/climate-change/extreme-makeover-human-activities-are-making-some-extreme-events-more-frequent-or-intense/**

Official Journal of the European Union. (2024). *DIRECTIVE (EU) 2024/1275 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 April 2024 on the energy performance of buildings.* **https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401275**

Øvergaard, S. (2008). *Issue paper: Definition of primary and secondary energy. Oslo Group on Energy Statistics.* **https://unstats.un.org/unsd/envaccounting/londongroup/meeting13/lg13_12a.pdf**

Pasi Tuohimaa. (2024, July 3). *Introducing ONKALO and its principle of operation.* **https://www.posiva.fi/en/index/news/pressreleasesstockexchangereleases/2024/thisisonkaloandthisishowitworks.html#:~:text=During%20the%20operational%20stage%20of,about%203%2C250%20final%20disposal%20canisters.**

Posiva. (n.d.). *Final disposal tests. Retrieved February 6, 2025, from* **https://www.posiva.fi/en/index/finaldisposal/finaldisposaltestsfisstytk.html**

Regulation (EU) 2022/1032. *Retrieved January 7, 2025, from* **https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32022R1032**

Royal Scociety of Chemistry. (n.d.). *Sodium. Retrieved March 5, 2025, from* **https://periodic-table.rsc.org/element/11/sodium#:~:text=Even%20so%20it%20is%20highly,charge%20balancing%20cation%20in%20zeolites.**

Sathaye, J. A., Dale, L. L., Larsen, P. H., Fitts, G. A., Koy, K., Lewis, S. M., & De Lucena, A. F. P. (2013). *Estimating impacts of warming temperatures on California's electricity system. Global Environmental Change, 23(2), 499–511.* **https://doi.org/10.1016/j.gloenvcha.2012.12.005**

Schrems, I., & Wieland, P. (2024). *Deutschland ist mit seinem langsamen Kohleausstieg Schlusslicht in Europa. Forum Ökologisch-Soziale Marktwirtschaft (FÖS).* **https://foes.de/publikationen/2021/2021-09_FOES_Factsheet_Deutschlands_langsamer_Kohleausstieg.pdf**

SEFE-Storage. (n.d.). *Rehden storage facility. Retrieved January 7, 2025, from* **https://www.sefe-storage.de/en/storage-locations/rehden-storage-facility**

Seidel, J., Lay, H., & Göddertz, M. (n.d.). *Ahrtal unter Wasser Chronik einer Katastrophe. Retrieved February 16, 2025, from* **https://reportage.wdr.de/chronik-ahrtal-hochwasser-katastrophe#chronik-hochwasser-im-ahrtal**

Statista. (2024). *Cyber Threat Intelligence.* **https://www.statista.com/study/117713/cyber-threat-intelligence/**

Statista. (2025a). *EU: Largest planned LNG import terminals 2025.* **https://www.statista.com/statistics/1251671/leading-lng-import-terminals-projects-in-the-eu-by-capacity/**

Statista. (2025b). *Regional distribution of solar module production.* **https://www.statista.com/statistics/668749/regional-distribution-of-solar-pv-module-manufacturing/**

Statista. (2025c). *Ukraine infrastructure damage by sector 2024. Statista.* **https://www.statista.com/statistics/1303344/ukraine-infrastructure-war-damage/**

Statistisches Bundesamt. (2022, July). *Fakten zur Gasversorgung: Erdgas wichtigster Energieträger für Industrie und private Haushalte.* **https://www.destatis.de/DE/Presse/Pressemitteilungen/2022/07/PD22_N044_43.html#:~:text=Den%20h%C3%B6chsten%20Anteil%20am%20gesamten,chemischen%20Produkten%20wie%20etwa%20D%C3%BCngemitteln.**

Stephan, A., Hettesheimer, T., Neef, C., Schmaltz, T., Stephan, M., Link, S., Heizmann, J. L., & Thielmann, A. (2023). *Alternative Battery Technologies Roadmap 2030+. Fraunhofer-Gesellschaft.* **https://doi.org/10.24406/PUBLICA-1342**

Suman, S., Khan, Mohd. K., Pathak, M., Singh, R. N., & Chakravartty, J. K. (2016). *Rupture behaviour of nuclear fuel cladding during loss-of-coolant accident. Nuclear Engineering and Design, 307, 319–327.* **https://doi.org/10.1016/j.nucengdes.2016.07.022**

Technische Universität Darmstadt. (n.d.). *About Clean Circles. Retrieved March 5, 2025, from* **https://www.tu-darmstadt.de/clean-circles/about_cc/research_summary_cc/index.en.jsp**

Technische Universität Darmstadt (Director). (2020, December 17). *Chemische Energiespeicher für die Energiewende [Video recording].* **https://www.youtube.com/watch?v=J8YI05Ssylg&t=179s**

Umbrex. (n.d.). *Round-Trip Efficiency A glossary of key terms relevant to the energy industry. Retrieved March 11, 2025, from* **https://umbrex.com/resources/energy-industry-glossary/energy-storage-glossary/round-trip-efficiency/**

Vattenfal. (2024, September 20). *Bidirektionales Laden: Das Elektroauto als Speicher.* **https://www.vattenfall.de/infowelt-energie/e-mobility/bidirektionales-laden#:~:text=So%20funktioniert%20bidirektionales%20Laden,-Ger%C3%A4te%20mit%20einem&text=Das%20geschieht%20mithilfe%20eines%20entweder,Gleich%2D%20wieder%20zu%20Wechselstrom%20werden.**

Wehrhöfer, N. (2023, November 28). *How do energy prices influence inflation expectations?* **https://www.bundesbank.de/en/publications/research/research-brief/2023-62-energy-prices-and-inflation-expectations-665786**

World Nuclear Association. (2024a, April 30). *Storage and Disposal of Radioactive Waste.* **https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/storage-and-disposal-of-radioactive-waste**

World Nuclear Association. (2024b, August 12). *Radioactive Waste – Myths and Realities.* **https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/radioactive-wastes-myths-and-realities**

World Nuclear Association. (2024c, August 23). *Lithium.* **https://world-nuclear.org/information-library/current-and-future-generation/lithium**

World Nuclear Association. (2025, February 4*). Nuclear Power in France.* **https://world-nuclear.org/information-library/country-profiles/countries-a-f/france**

Zimmermann, F., & Keles, D. (2023). *State or market: Investments in new nuclear power plants in France and their domestic and cross-border effects. Energy Policy, 173, 113403.* **https://doi.org/10.1016/j.enpol.2022.113403**

Zivilschutz Österreich. (n.d.). *Blackout Was tun, wenn der Strom ausgeht? Retrieved March 10, 2025, from* **https://zivilschutz.at/thema/blackout/#:~:text=Ein%20Blackout%20kann%20mehrere%20Tage,wenigen%20Stunden%20wieder%20vorbei%20sein.**

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