

Power 2025



AWARE

Maggio 2026



Who We Are

We are a **Think Tank** founded on the initiative of a group of university students eager to challenge themselves and put their knowledge into practice.

Over the last decade, the need for **new paradigms of social and economic development** has emerged with increasing urgency, characterised by tools, models, and values rooted in the concept of "Sustainability." At the same time, we have witnessed and taken part in the **digital revolution** that began in the early 2000s, transforming every sector of our society and driving profound structural change.

At **AWARE**, our goal is to contribute to **shaping the future ahead**. To pursue this mission, we have identified two broad areas that best represent the key drivers of our planet's future: the evolution of **technology** and the **digital sector** in all its dimensions (the entire ICT ecosystem), and **sustainable development**, grounded in its three core pillars: social, economic, and environmental sustainability.

Index

About the authors — p. 6

Glossary — p. 9

Abstract — p. 16

1. Introduction — p. 17

Context and background: rising prices and structural stress — p. 18

Main challenges to be addressed by the EU — p. 19

Scope of analysis and key insights — p. 20

2. The evolution of the emission factor of the EU's energy grid — p. 22

Principal energy policies supporting the EU's green transition — p. 22

Modelling of the EU's emission factor from 2023 to 2030 — p. 25

Objectives of the model — p. 25

Model architecture and scenarios — p. 26

Emission factor evolution: theoretical simulation based on three different scenarios — p. 27

Quantitative simulation for 2030 — p. 38

Impact of key EU Policies on the simulation model — p. 38

Modelling outcomes — p. 44

Modelled scenarios and their effects on energy costs — p. 46

Interoperating grid — p. 47

Hypothetical system with French energy mix extended to the EU — p. 48

Hypothetical system with Italian energy mix extended to the EU — p. 49

Conclusions — p. 50

3. Green Policies & Technologies: Old and New Dependencies — p. 51

Old dependencies: moving away from fossil fuels — p. 51

The fossil fuels phase out process: from 2002 to today — p. 52

Transition dynamics — p. 53

The energy transition and its “messy middle” — p. 54

Socioeconomic and supply chain challenges — p. 54

Main EU green transition policies and enabling technologies — p. 55

Solar — p. 56

Wind — p. 58

Hydrogen — p. 60

Geothermal — p. 61

Carbon capture and storage — p. 62

Renewable energy sources: penetration level breakdown — p. 63

Wind energy: onshore and offshore — p. 63

Solar photovoltaics — p. 64

Hydropower plants — p. 64

Index

Bioenergy and geothermal plants – p. 65

Cross-sector integration and emerging technologies – p. 65

Weakness analysis of emerging dependencies – p. 66

The Green Transition and the uneven distribution of its benefits – p. 66

From the EU-China asymmetry to global critical mineral constraints – p. 69

SWOT analysis of EU green policies and technologies: dependencies and strategic vulnerabilities – p. 69

Critical raw materials and the reshaping of global strategic dependencies – p. 71

Current as-is state of the international supply of critical raw materials – p. 71

The Issue of recycling – p. 73

Critical raw materials: a global overview of extraction and refining capacity – p. 74

Recommended actions for dependency mitigation – p. 88

Digital infrastructure, resource security and geopolitical exposure – p. 92

Digitalisation: smart grids and higher cyberattack risk – p. 92

Other potential changes to the status quo – p. 94

4. The price of the energy transition: market analysis and social consequences – p. 96

Analysis of the current energy market structure & its resilience – p. 96

Case studies – p. 97

Market shocks, institutional resilience and social instability: the role of institutional response – p. 100

Social disorders and market fluctuations – p. 100

A comparative analysis of economic shocks and social instability – case studies – p. 104

Mitigation of the economic and social consequences of the transition – p. 106

Ongoing EU initiatives – p. 106

The structural reform of the electricity market – p. 106

Decarbonising the gas grid and the hydrogen backbone – p. 107

Europe's building stock: renovation, solar integration and fossil heating phase-out – p. 107

Strategic autonomy and the role of the "Clean Industrial Deal" – p. 108

The 2040 horizon and infrastructure resilience – p. 108

Policy recommendations – p. 109

Decarbonisation and grid stability – p. 109

Mitigation of new dependencies – p. 113

Supply chain de-risking - p. 113

Circular economy and innovation - p. 115

Social equity and market resilience - p. 116

Circular economy and innovation - p. 116

Index

5. The role of Italy and the UK within the energy transition – p. 119

The role of the UK within Europe's energy transition – p. 119

The North Sea power hub – p. 119

The financial and technical recoupling – p. 120

The role of Italy within Europe's energy transition – p. 122

Italy as a Mediterranean gateway and transitional stabilisation mechanism – p. 123

Italy as a Euro-Mediterranean interface for low-carbon molecules – p. 123

Italy as an industrial and technological enabler of network expansion and system integration – p. 124

Declarations – p. 126

Bibliography – p. 128

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Le opinioni espresse nel presente contributo sono formulate a titolo personale e non sono riconducibili al Ministero degli Affari Esteri e della Cooperazione Internazionale.

Glossary

Acronym	Extended form	Short explanation
ACER	Agency for the Cooperation of Energy Regulators	EU agency that monitors and supports the functioning of the internal energy market.
ADEME	Agence de la transition écologique	French public agency working on ecological transition, energy and climate policy.
aFRR	automatic Frequency Restoration Reserve	Ancillary service used to automatically restore system frequency after imbalances.
BAU	Business As Usual	Baseline scenario assuming no major additional acceleration in EU decarbonisation policies.
bcm	billion cubic metres	Unit used to express gas volumes, including natural gas, biomethane and hydrogen-equivalent substitution.
BEIS	Department for Business, Energy and Industrial Strategy	Former UK government department often cited in energy and emissions analysis.
CBAM	Carbon Border Adjustment Mechanism	EU instrument applying a carbon-related adjustment to certain imported goods to reduce carbon leakage.
CCGT	Combined-Cycle Gas Turbine	High-efficiency gas-fired generation technology used in electricity production.
CCUS	Carbon Capture, Utilisation and Storage	Set of technologies used to capture CO ₂ from industrial or energy processes and then utilise or permanently store it.

CDP	Carbon Disclosure Project	Global disclosure system through which companies and institutions report environmental data.
CEPS	Centre for European Policy Studies	European think tank frequently cited in policy and regulatory analysis.
CRMA	Critical Raw Materials Act	EU regulation aimed at strengthening supply security, refining, recycling and strategic autonomy for critical raw materials.
CRM	Critical Raw Materials	Strategic minerals and metals needed for clean technologies, digital infrastructure and industrial transformation.
CSRD	Corporate Sustainability Reporting Directive	EU directive requiring more structured and standardised sustainability reporting by companies.
CSDDD	Corporate Sustainability Due Diligence Directive	EU directive on due diligence obligations regarding environmental and human-rights impacts across value chains.
DSR	Demand-Side Response	Mechanism through which consumers shift or reduce electricity demand to improve flexibility and system balance.
EEA	European Environment Agency	EU agency providing environmental data, indicators and assessments.
EF	Emission Factor	Indicator of carbon intensity, usually expressed as emissions per unit of electricity generated.
EF_m	marginal Emission Factor	Emission factor associated with the additional generation source dispatched during peak or residual demand hours.
EF_t	Total / structural Emission Factor	Average carbon intensity of the overall electricity mix considered in the model.

EFRAG	European Financial Reporting Advisory Group	European body supporting the development of sustainability reporting standards.
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development	Italian public research agency active in energy, efficiency and sustainability.
ENTSO-E	European Network of Transmission System Operators for Electricity	Association coordinating European transmission system operators and long-term grid planning.
EPBD	Energy Performance of Buildings Directive	EU legislative framework aimed at improving the energy efficiency of new and existing buildings.
EPA	Environmental Protection Agency	Here mainly referring to the US EPA, used as a source for emissions-related benchmarks.
ESRS	European Sustainability Reporting Standards	Reporting standards developed for the implementation of the CSRD framework.
ESG	Environmental, Social, and Governance	A set of operational standards for corporate behaviour used to evaluate the sustainability and ethical impact of investments
ETS	Emissions Trading System	EU carbon market that prices greenhouse-gas emissions from covered sectors.
ETS II	Emissions Trading System II	Extension of EU carbon pricing to additional sectors such as buildings and road transport.
EU	European Union	Main institutional and geographic reference framework of the paper.
EU27 / EU-27	European Union of 27 Member States	Aggregate used for energy, emissions and market analysis.

EV	Electric Vehicle	Electrified vehicle technology relevant to demand growth and flexibility dynamics.
FRR	Frequency Restoration Reserve	Balancing reserve used to restore equilibrium between supply and demand after system deviations.
GDP	Gross Domestic Product	Macroeconomic indicator used in the discussion of economic performance and systemic shocks.
GHG	Greenhouse Gas	Climate-altering gases such as CO ₂ , methane and nitrous oxide.
LPG	Liquefied Petroleum Gas	Fossil fuel category appearing in the generation mix tables.
GW	Gigawatt	Unit of installed power capacity equal to one billion watts.
GWh	Gigawatt-hour	Unit of electricity volume often used for storage and system balancing.
H ₂	Hydrogen	Energy carrier considered in the analysis of REPowerEU and sectoral substitution effects.
IEA	International Energy Agency	Major intergovernmental organisation providing energy data, scenarios and market analysis.
IMF	International Monetary Fund	International institution cited in relation to macroeconomic and social resilience.
IPCC	Intergovernmental Panel on Climate Change	International scientific body providing authoritative climate and emissions references.
IRA	Inflation Reduction Act	Major US industrial-policy package supporting clean technologies through subsidies and tax credits.

LFP	Lithium Iron Phosphate	Battery chemistry used in storage systems and electric mobility.
LHV	Lower Heating Value	Measure of the usable energy content of a fuel, excluding latent heat from water vapour.
LNG	Liquefied Natural Gas	Natural gas transported in liquid form, central to Europe's recent diversification strategy.
LMO	Lithium Manganese Oxide	Battery chemistry used in some electrochemical storage applications.
Mt	million tonnes	Unit used for large-scale quantities, especially emissions and material flows.
MtCO ₂ eq	million tonnes of CO ₂ equivalent	Aggregate unit used to express greenhouse-gas emissions in CO ₂ -equivalent terms.
NECP / NECPs	National Energy and Climate Plan(s)	National plans through which EU Member States define and report their energy and climate strategies.
NIS2	Network and Information Security Directive 2	EU cybersecurity directive strengthening resilience obligations for critical sectors.
NZIA	Net-Zero Industry Act	EU act designed to strengthen domestic manufacturing capacity for strategic clean technologies.
PHS	Pumped Hydro Storage	Large-scale storage technology based on pumping water uphill and releasing it through turbines when needed.

PV	Photovoltaic	Solar electricity generation technology converting sunlight into electricity.
RED III	Renewable Energy Directive III	Updated EU directive increasing renewable-energy targets and accelerating deployment.
REPowerEU	REPowerEU Plan	EU plan launched to reduce dependence on Russian fossil fuels and accelerate clean-energy deployment.
RES	Renewable Energy Sources	Umbrella term for renewable technologies such as wind, solar, hydro, geothermal and bioenergy.
SCF	Social Climate Fund	EU fund designed to mitigate the social impacts of the green transition on vulnerable groups.
SCGT	Simple-Cycle Gas Turbine	A less efficient gas-fired generation technology often used for peak demand.
STEPS	Stated Policies Scenario	An exploratory IEA scenario that provides a sense of the prevailing direction of travel for the energy system, based on today's policy settings.
TWh	Terawatt-hour	Unit of electricity generation or consumption equal to one million megawatt-hours.
UK	United Kingdom	One of the key countries considered in the geopolitical and infrastructure analysis.
US	United States	External actor relevant to industrial policy, clean-tech competition and energy geopolitics.
V2G	Vehicle-to-Grid	System enabling electric vehicles to return electricity to the grid and provide flexibility services.

WGI	Worldwide Governance Indicators	World Bank indicators used to assess institutional quality and governance resilience.
€/MWh	euro per megawatt-hour	Unit used to express electricity market prices.
gCO ₂ eq/kWh	grams of CO ₂ equivalent per kilowatt-hour	Standard metric used to express the carbon intensity of electricity generation.
α (alpha)	flexibility efficiency coefficient	Parameter used in the model to estimate how effectively storage and DSR avoid marginal fossil generation.

Abstract

This report explores the structural transition of the European energy system as it moves from the emergency phase of 2022 towards long-term climate neutrality. Through a quantitative model of the EU-27's Emission Factor (EF), the study identifies that only scenarios prioritising significant investment in storage and Demand-Side Response (DSR) can successfully reduce grid intensity below 100 gCO₂eq/kWh by 2030.

The analysis further examines the geopolitical shift from "pipelines to metals", highlighting a burgeoning dual dependency, whereby the reduction of Russian gas reliance is offset by an asymmetric dependence on non-EEA countries, particularly China, for Critical Raw Materials (CRMs) and clean-tech manufacturing. Using global case studies, the report also establishes a correlation between energy price volatility and social stability, concluding that institutional response time, rather than price magnitude alone, is a crucial driver of civil unrest.

To ensure a resilient transition, the paper recommends the operationalisation of the Critical Raw Materials Act (CRMA) targets, the deployment of DSR potential for grid flexibility, and the strengthening of regional energy alliances, specifically through Italy's role as a Mediterranean hub and the UK's integration into the European North Sea energy architecture.

Keywords: *Energy Transition, Strategic Autonomy, Emission Factor Modelling, Critical Raw Materials, Social Stability, Energy Cooperation*

1. Introduction

A stable, affordable and secure energy supply constitutes a foundational pillar of modern societies, underpinning economic activity, social cohesion, domestic and external security, strategic autonomy and climate action. Energy systems are no longer neutral infrastructures: they increasingly operate at the intersection of geopolitics, industrial policy, environmental governance and social stability. Disruptions to energy supply chains reverberate across markets, institutions and households, amplifying vulnerabilities well beyond the energy sector itself.

The crises of the past decade, most notably the Covid-19 pandemic and the Russian invasion of

Ukraine, have exposed the structural fragility of the European energy system. Supply disruptions, price shocks and geopolitical coercion demonstrated how energy networks can be weaponised, blurring the boundaries between economic interdependence, political leverage and societal well-being. The sabotage of the Nord Stream pipelines in 2022 symbolised this shift, triggering unprecedented volatility in energy prices and placing severe pressure on households, firms and public finances across the European Union.

At the same time, persistent geopolitical instability in the Middle East and the growing unpredictability of US foreign policy further contribute to uncertainty in global energy markets. Against this backdrop, pan-European coordination is no longer a policy option but a structural necessity to ensure long-term resilience, strategic autonomy and economic competitiveness.

Context and background: rising prices and structural stress

Since the introduction of the Energy Union framework in 2015, the EU has progressively integrated energy policy with climate objectives, industrial strategy and internal market governance. This approach was further consolidated through the “Clean Energy for All Europeans” legislative package and the European Green Deal, which set the objective of climate neutrality by 2050 and established binding intermediate targets for 2030. These ambitions were reinforced following the 2022 energy crisis, which triggered an unprecedented acceleration of policy initiatives aimed at reducing dependency on imported fossil fuels, particularly from Russia, while scaling up renewable energy deployment and energy efficiency.

The crisis also revealed the limits of a fragmented energy system. Despite significant progress in electricity market integration, energy prices surged unevenly across Member States, reflecting differences in energy mixes, infrastructure availability, fiscal capacity and exposure to global fuel markets. Wholesale electricity prices more than doubled compared to pre-2022 levels and remained structurally higher through 2024, eroding industrial competitiveness, increasing production costs for energy-intensive sectors and amplifying social tensions. Households faced rising energy bills and generalised inflation, contributing to declining consumption and episodes of social unrest in several countries.

At the same time, the rapid expansion of renewable electricity generation has begun to reshape the European power system, reducing average emission intensity and fossil fuel use. However, this transition has introduced new forms of dependency linked to critical raw materials, clean-technology manufacturing and global supply chains, often concentrated outside the EU. As a result, the transition away from fossil fuels has not eliminated external vulnerabilities, but has reconfigured them along new technological and geopolitical dimensions.

Main challenges to be addressed by the EU

The current phase of the European energy transition confronts the EU with a set of interrelated challenges that extend beyond decarbonisation alone.

First, **energy system resilience** has become a central concern. The ability of the European power system to withstand price shocks, supply disruptions and extreme events depends on the integration of renewable generation with flexible assets such as storage, demand-side response and cross-border interconnections. Without sufficient system flexibility, rapid electrification risks increasing volatility rather than reducing it.

Second, **market fragmentation and price divergence** remain persistent issues. Differences in infrastructure development, regulatory implementation and national policy choices continue to generate asymmetric outcomes across Member States, undermining the effectiveness of the internal energy market and complicating collective responses to crises.

Third, the EU faces a growing **strategic dependency on external suppliers** for critical materials, clean-technology components and certain fuels, including natural gas and nuclear inputs. These dependencies pose risks to industrial competitiveness and long-term energy sovereignty, particularly in a context of intensifying global competition and geopolitical uncertainty.

Fourth, the **social dimension of the transition** represents a potential constraint on policy ambition. Energy price shocks act as stress tests for the social contract, and inadequate mitigation measures can erode trust in institutions, fuel political instability and weaken public support for climate policies.

Addressing these issues requires pan-European coordination across policy domains, combining climate ambition with market design, industrial strategy, infrastructure investment and social safeguards. The effectiveness of the transition will depend not only on technological progress but also on the EU's capacity to govern its economic and social consequences.

Scope of analysis and key insights

This paper examines the European energy transition as a systemic challenge that links decarbonisation, market resilience, strategic autonomy and social stability. It shows that the reduction of the EU electricity system's emission factor will depend not simply on expanding renewables, but on the combined effect of effective policy implementation, technological progress and, above all, the large-scale deployment of flexibility mechanisms such as storage and demand-side response. Through a semi-parametric deterministic model, the paper finds that only the more ambitious transition pathways can bring the emission factor close to or below 100 gCO₂eq/kWh by 2030, while also improving grid stability and reducing the structural role of fossil generation in peak hours.

At the same time, the analysis shows that decarbonisation does not automatically eliminate vulnerability: it transforms it. As Europe reduces its dependence on imported fossil fuels, new strategic exposures emerge around critical raw materials, clean-technology manufacturing, digital infrastructure and global supply chains. The paper therefore argues that the green transition must be assessed not only in environmental terms, but also through its implications for industrial competitiveness, geopolitical resilience and economic security.

A further central insight is that the quality of the future energy mix will directly affect price formation, volatility and market resilience. The paper shows that lower-carbon and more flexible systems tend to produce more stable and competitive outcomes, whereas systems that remain more exposed to gas and marginal fossil generation are more vulnerable to price shocks.

In this sense, the transition is not only a climate imperative, but also a market and governance challenge, because its economic effects can shape social acceptance, political stability and the overall credibility of the European project.

Finally, the paper highlights that Europe's transition will also depend on the strategic role played by key countries and regional alliances, particularly in strengthening interconnections, diversifying supply routes, supporting industrial capacity and reinforcing the geopolitical coherence of the wider European energy system. Overall, the paper's main insight is that a successful transition cannot be measured by decarbonisation alone: it must also deliver affordability, resilience, security of supply and the capacity to manage the new dependencies created by the green economy.

2. The evolution of the emission factor of the EU's energy grid

Principal energy policies supporting the EU's green transition

The European Union's energy policy is structured around the foundational framework of the Energy Union, introduced in 2015 to promote a secure, sustainable, and affordable energy system across Member States. This strategy is articulated through five interlinked dimensions: energy security, a fully integrated internal energy market, energy efficiency, decarbonisation through climate action, and innovation and competitiveness. Central to its governance structure is Regulation (EU) 2018/1999 on the Governance of the Energy Union, which mandates Member States to develop National Energy and Climate Plans (NECPs) in ten-year cycles. These plans are instrumental for the monitoring, reporting, and implementation of EU-wide binding targets, such as achieving at least a 55% reduction in greenhouse gas emissions by 2030 (compared to 1990 levels), attaining a minimum 42.5% share of renewable energy, and improving energy efficiency by 11.7%. The legislative package titled "Clean Energy for All Europeans", finalised in 2019, further consolidated this framework by revising key directives, including the Renewable Energy Directive (RED II and III), the Energy Efficiency Directive, and the Electricity Market Regulation [1] [2].

The European Green Deal, later introduced in 2019, builds upon this regulatory foundation by setting the trajectory toward achieving climate neutrality by 2050, integrating energy policy with broader environmental and socio-economic objectives. More than just a climate strategy, the Green Deal functions as a comprehensive socio-economic transformation agenda, integrating environmental, industrial, agricultural, financial, and social dimensions into a cohesive vision for sustainable development. Its overarching objective is to decouple economic growth from resource use, ensuring that the EU's financial prosperity is not achieved at the expense of ecological degradation or social inequity [2].

At the heart of the Green Deal is the commitment to achieve net-zero greenhouse gas emissions by mid-century, a goal that was later enshrined in the European Climate Law (Regulation (EU) 2021/1119). This legal instrument sets the binding 2050 climate neutrality target, while introducing an intermediate milestone: a reduction of net emissions by at least 55% by 2030 compared to 1990 levels. To meet these targets, the Green Deal includes a wide array of sectoral policies and legislative packages, such as the "Fit for 55" package, which comprises revisions to the EU Emissions Trading System (ETS), the Renewable Energy Directive (RED III), the Energy Efficiency Directive, and the introduction of the Carbon Border Adjustment Mechanism (CBAM)—an instrument designed to prevent carbon leakage by applying equivalent carbon pricing to imports [2].

The Green Deal recognises that the energy sector is central to the decarbonisation effort, given that energy production and consumption account for over 75% of the EU's greenhouse gas emissions. Consequently, the Green Deal prioritises a rapid transition to renewable energy, investments in smart and interconnected energy infrastructure, and support for energy system integration, including electrification and hydrogen development. Initiatives such as the EU Strategy for Energy System Integration and the Hydrogen Strategy for a Climate-Neutral Europe play critical roles in operationalising these goals. Moreover, the Green Deal is underpinned by financial mechanisms like the Sustainable Europe Investment Plan, which aims to mobilise at least €1trillion in sustainable investments over the next decade, and the Just Transition Mechanism, which supports the regions and sectors most affected by the transition [1] [2].

Under the renewed mandate of President Ursula von der Leyen, the European Commission has further refined its strategic energy agenda by adopting a more pragmatic, industry-oriented, policy trajectory. While reaffirming its commitment to the climate neutrality target by 2050 and to interim emission reductions of 55% by 2030, the Commission introduced several new instruments aimed at fostering industrial transformation alongside decarbonisation [2]. Among these are the Clean Industrial Deal and the Industrial Decarbonisation Accelerator Act, which are expected to mobilise substantial public and private investment—

anchored by the proposed creation of a €100 billion Industrial Decarbonisation Bank. Simultaneously, the Commission prioritised regulatory simplification to reduce administrative burdens, notably through revisions to the Corporate Sustainability Reporting Directive (CSRD) and the Corporate Sustainability Due Diligence Directive (CSDDD). These efforts reflect a strategic balancing act between maintaining high climate ambitions and fostering an enabling environment for economic and industrial actors. These initiatives suggest a more flexible and investment-driven approach to the energy transition, marking a shift in emphasis from rule-making to enabling mechanisms aimed at sustaining both ecological integrity and industrial competitiveness.

Navigating the complex interplay between climate objectives, energy security, and economic performance remains a central challenge of the EU's energy transformation. The Green Deal Industrial Plan, which includes the Net-Zero Industry Act and the Critical Raw Materials Act, seeks to scale up domestic production capacity in sectors critical to the clean energy transition—such as solar panels, wind turbines, electrolyzers, and heat pumps—while reducing strategic dependencies on third countries, particularly China.

However, these supply-side strategies coexist with significant asymmetries across Member States in terms of energy mix, fiscal capacity, and industrial readiness. The EU also faces increasing competitive pressure from external actors, notably the United States through its Inflation Reduction Act (IRA), which offers substantial subsidies for clean energy technologies [2]. In light of these dynamics, recent regulatory adjustments—including the relaxation of gas storage requirements for winter 2025—signal a move toward greater policy flexibility. Nonetheless, intra-EU disagreements persist, especially concerning transparency in phasing out Russian gas imports, revealing limitations in the bloc's solidarity under crisis conditions [4] [5].

Modelling of the EU's emission factor from 2023 to 2030

Objectives of the model

In the context of the European energy transition and the commitments undertaken through the Green Deal and the Fit for 55 package, this analysis aims to provide a robust and transparent projection of the evolution of the Emission Factor (EF) of the European Union's electricity system for the period 2024–2030.

The EF, expressed in grams of CO₂ equivalent per kilowatt-hour produced (gCO₂eq/kWh), serves as a synthetic indicator of the emission intensity of the European electricity mix. It is a key tool for assessing the effectiveness of decarbonisation policies, the impact of remaining fossil fuel sources, and the benefits derived from the deployment of renewables, storage systems, and emerging technologies.

This analysis stands out for its approach, which goes beyond a linear projection of the energy mix. It explicitly incorporates the role of public policies—such as ETS II, RED III, REPowerEU, the fossil fuel phase-out, and CSRD/ESRS—by estimating their actual impact on emission reductions in the power sector. It also includes strategic variables that are often overlooked, such as the marginal Emission Factor (EF_m), the effectiveness of flexibility systems (electrochemical storage and pumped hydro), and the potential of demand-side response mechanisms.

The model therefore pursues a dual objective: on the one hand, to provide a numerical trajectory aligned with EU reference scenarios; on the other, to identify the most impactful and realistic levers to accelerate the decarbonisation of the electricity system—particularly during critical hours (peak load, low renewable generation)—offering a solid technical basis for dialogue among policymakers, industry players, and institutional stakeholders.

Model architecture and scenarios

The model is based on a semi-parametric deterministic structure, developed to integrate historical data, trend-based projections, and simulations related to the implementation of public policies. Its architecture allows for the annual modulation of inputs, progressively adapting to the evolution of the European regulatory framework, technological innovation, and market dynamics.

The analysis considers three distinct forecast scenarios, designed to reflect varying levels of ambition and implementation of decarbonisation strategies:

- **Business As Usual (BAU)**: an inertial scenario in which no new EU policies are introduced. The reduction in the Emission Factor relies solely on the modernisation of the thermal power fleet and the gradual optimisation of plant efficiency. The share of renewables remains limited, as does the contribution of flexibility mechanisms;
- **Fit for 55**: a scenario characterised by the full and timely implementation of the EU's Fit for 55 package, including RED III, ETS II, and REPowerEU. It assumes a strong level of penetration of renewable energy sources into the electricity mix and a modest rollout of storage systems.

Emissions decrease as a result of the combined effects of the coal phase-out, renewable energy production growth, and the initial impact of flexibility mechanisms;

Storage Diffusion: a highly technologically ambitious scenario, characterised by the widespread deployment of storage systems and demand-side response, alongside full implementation of planned EU policy measures. In addition to a rapid expansion of renewables, it highlights the role of flexible plants in reducing the marginal Emission Factor. The system becomes more resilient and stable during peak hours, contributing to a structural reduction in emissions.

For each year between 2024 and 2030, the model produces the following key outputs:

- Electricity generation by source (TWh);
- Emissions by generation technology;
- Average structural EF of the electricity mix;
- EF_m, related to peak demand hours;
- Policy-adjusted emissions based on the effectiveness of public measures;
- Total annual emissions of the EU electricity system (MtCO₂eq)

Emission factor evolution: theoretical simulation based on three different scenarios

Starting from a comparative analysis of historical trends and the projected trajectories under EU climate and energy policies, the model integrates a dynamic evolution of electricity demand by source ($E_{i,t}$), expressed in TWh/year (Figure 1) [6] [7]. Its estimated values account for both natural technological turnover and the cumulative effects of decarbonisation strategies, the electrification of final consumption, and the phase-out of the most emission-intensive fossil fuels [8] [9].

Figure 1

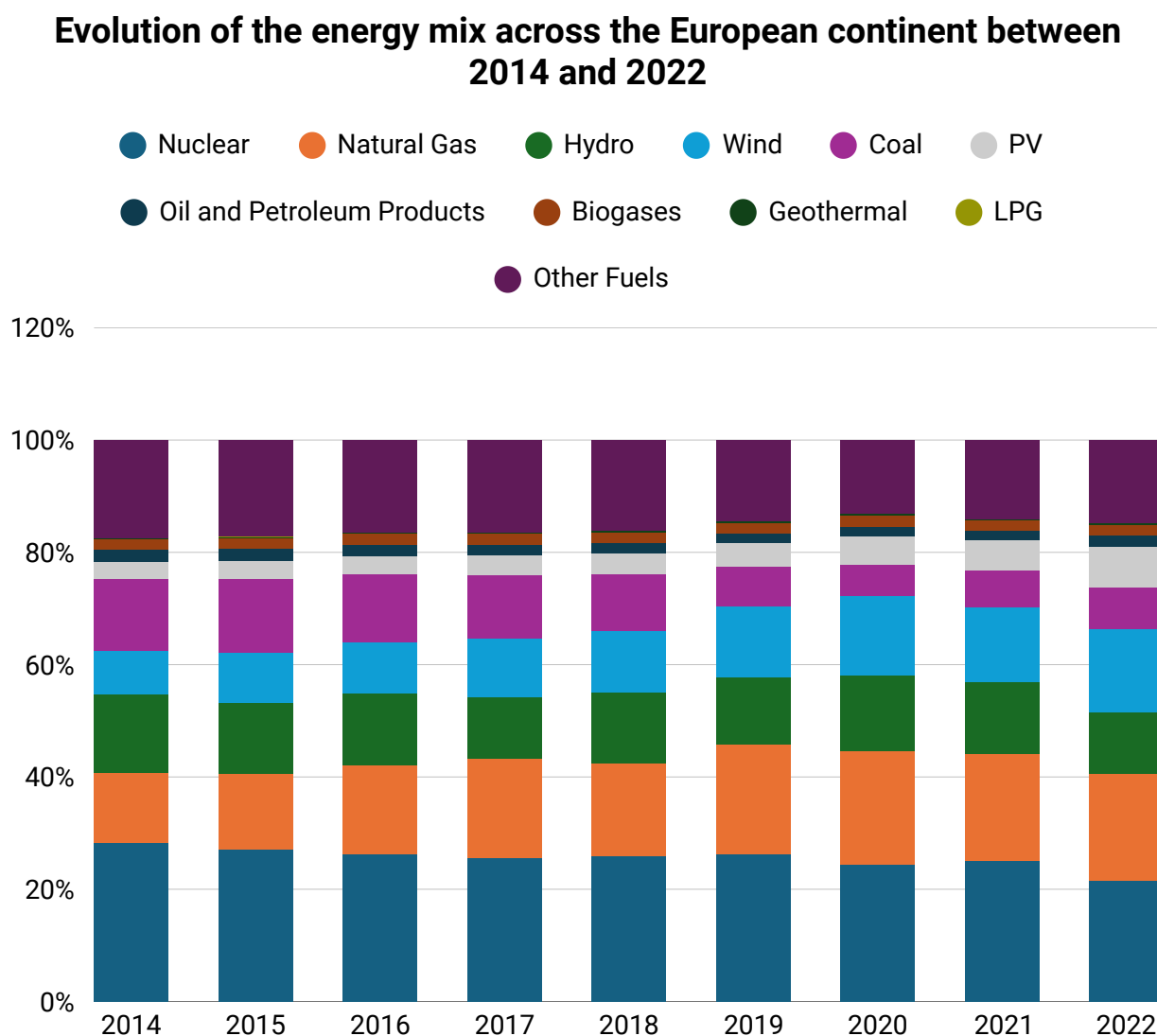
Gross Electricity Production per Source (TWh) in the EU27

Gross Electricity Production per Source (TWh)	2014	2015	2016	2017	2018	2019	2020	2021	2022
Nuclear	813	787	768	759	762	765	684	732	609
Natural Gas	357	396	466	525	491	569	561	554	538
Hydro	399	363	373	322	370	346	375	375	307
Wind	222	263	267	312	321	367	398	387	422
Coal	365	379	355	333	300	209	156	192	207
PV	89	95	95	102	108	118	140	159	206
Oil and Petroleum Products	61	63	62	59	55	52	48	47	56
Biogases	51	54	55	56	55	55	56	55	54
Geothermal	6	7	7	7	7	7	7	7	6
LPG	0,39	0,41	0,54	0,45	0,24	0,23	0,15	0,24	0,22
Other Fuels	499	499	480	485	475	419	365	409	417
EU27	2862,3	2906,4	2928,5	2960,4	2944,2	2907,2	2790,1	2917,24	2822,22

Note. Table created by the author. Data compiled from Eurostat, ENTSO-E, Ember [8] [9].

Figure 2 outlines the evolution of EU27's energy mix from 2014 to 2022 [10] [11] [12]:

Figure 2



Note. Graph created by the author. Data compiled from Eurostat, ENTSO-E, Ember [10] [11] [12].

These values serve as the basis for the annual estimates of electricity generation by technology for the 2023–2030 period, and represent the core of the structural EF model [6] [7].

Figure 3 shows the 2023–2030 energy mix projection for the Business As Usual (BAU) scenario [7] [6] [13].

Figure 3

Energy mix projection (2023–2030) for the Business As Usual (BAU) scenario

Gross Electricity Production per Source (TWh)	2023	2024	2025	2026	2027	2028	2029	2030	% change
Natural Gas	459	426	393	360	328	295	262	229	-50%
Oil and Petroleum Products	48	44	40	36	32	28	24	19	-60%
Hydro	361	361	361	361	361	361	361	361	0%
LNG	170	170	169	166	157	148	136	124	-27%
Geothermal	6	6	7	7	7	7	7	8	33%
Wind	478	519	560	601	642	683	724	765	60%
PV	247	275	303	332	360	388	416	445	80%
Biomethane	27	34	42	55	65	75	85	95	252%
Green Hydrogen	2	5	10	16	23	30	38	45	2150%
Nuclear	620	624	628	633	637	642	646	651	5%
Coal	140	126	112	98	84	70	56	42	-70%
Other fuels including LPG	337	322	308	294	279	265	250	236	-30%
EU27	2895	2912	2933	2959	2975	2992	3005	3020	4%

Note. Table created by the author. Data compiled from the European Commission, IEA, Ember [10] [11] [12].

This scenario unveils a clear trifold trend of declining fossil fuels reliance (i.e. coal, fuel, oil), consolidation of traditional renewable sources (i.e. hydropower and biogas), and strong growth in wind and solar [12] [7].

However, these trends will need to become more pronounced, requiring a significant acceleration in renewables penetration, to align with the EU's 2030 targets [9] [14]. As previously stated, the three scenarios, each reflecting different renewables penetration trajectories within the European energy mix, will be analysed and discussed.

In parallel, for each energy source considered, the model assigns an average emission factor expressed in gCO₂eq/kWh, based on harmonised sources (Figure 4) [15] [16]:

Figure 4

Emission factors used in the model per source of energy considered

Source	Average Emission Factor (gCO ₂ eq/kWh)
Coal	820
Natural Gas (CCGT)	450
Oil	700
Nuclear	12
Solar PV	48
Wind	11
Hydro	24
Biomethane	45
Green Hydrogen	0

Note. Table created by the author. Data compiled from European Parliament, IPCC [15] [16].

The progressive decline in fossil fuels reliance (i.e. gas, coal, oil), combined with the accelerated growth of renewables and nuclear energy, drives the decarbonisation trajectory of the electricity mix [15]. This evolution, incorporated in each scenario model, forms the basis for calculating the annual dynamic structural Emission Factor (EF_t).

Additionally, to estimate source-specific emissions from fossil fuels, the model takes into account the average annual efficiency of the existing power generation fleet for each power plant which uses fossil fuels (e.g. coal, natural gas), leaving unaltered the efficiency for clean technologies (worst scenario). Increases in efficiency—for example through plant upgrades or the transition to combined-cycle systems—help reduce the specific EF [17] [18].

Based on the estimated average efficiency of currently operating generation technologies, the resulting ranges of energy conversion efficiency are shown in Figure 5 [17] [18].

Figure 5

Energy efficiency range for different power plants which exploit fossil fuels

Technology	Estimated Efficiency Range
Traditional Coal-Fired Plants	33–38%
Simple-Cycle Gas Turbines	35–40%
Combined-Cycle Gas Turbines (CCGT)	50–62%
Traditional Coal-Fired Plants	Up to 64%

Note. Table created by the author. Data compiled from European Commission, IEA [17] [18].

The model incorporates a dynamic simulation wherein fossil fuel power plants are progressively optimised for efficiency; this evolution in average efficiency is captured in the data below (Figure 6, Figure 7) [18]:

Figure 6

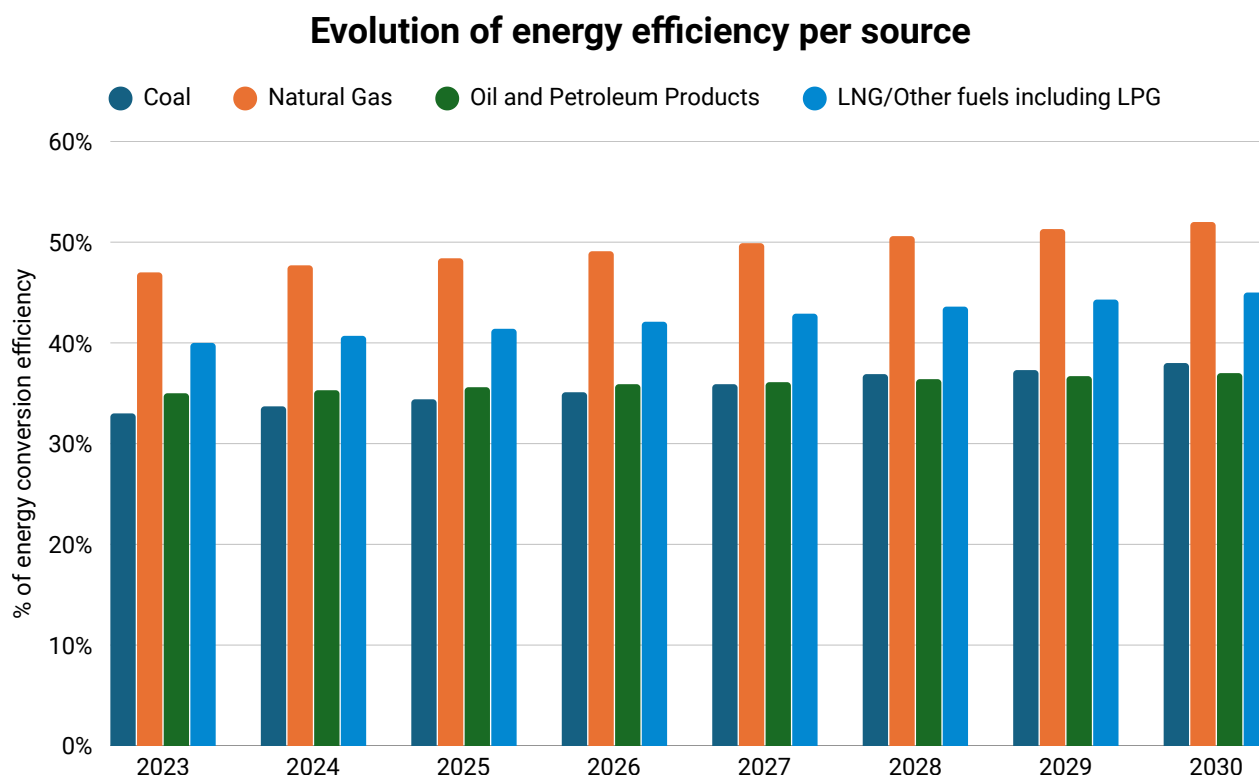
Evolution year on year of the energy efficiency for different power plants per source

Average Estimated Efficiency	2023	2024	2025	2026	2027	2028	2029	2030	Number of plants in 2023
Coal	33,00%	33,70%	34,40%	35,10%	35,9%	36,90%	37,30%	38,00%	150-200
Natural Gas	47,00%	47,7%	48,40%	49,10%	49,90%	50,60%	51,30%	52,00%	300-400
Oil	35,00%	35,30%	35,60%	35,90%	36,10%	36,40%	36,70%	37,0%	20-50
LNG/Other fuels including	40,00%	40,7%	41,40%	42,10%	42,90%	43,60%	44,30%	45,00%	10-30

Note. Table created by the author. Data compiled from European Commission, IEA [18].

Figure 7

Evolution year on year of the energy efficiency for different power plants per source



Note. Graph created by the author. Data compiled from IEA [18].

This enables the model to dynamically simulate fuel consumption, source-specific emissions per TWh, and the overall impact on the electricity system in terms of carbon intensity [19] [17].

Another key variable to consider is the role played by energy storage systems in the energy transition. Storage capacity and flexibility mechanisms are strategic components for the successful decarbonisation of the European power system, as they reduce the marginal reliance on fossil-fuel power plants during peak demand periods or when the output from non-dispatchable renewables is low [20] [3]. This enables a more efficient and stable management of the electricity mix, resulting in a lower marginal Emission Factor (EF_m); or the emissions generated per additional kWh produced to meet peak demand [7].

The principal flexibility technologies to be considered for a preliminary impact assessment are:

- **Electrochemical Storage Systems (Batteries):**
 - They provide fast response times (<1 second), making them ideal for secondary and tertiary balancing services (FRR, aFRR) [21] [22];
 - In Europe, installed capacity exceeded 15 GW in 2023, with RePowerEU targets aiming for over 50–60 GW by 2030 [3] [23].
- **Pumped Hydro Storage (PHS):**
 - More than 45 GW have already been installed in Europe (mainly in Austria, France, Spain, Italy, and Germany) [24];
 - It represents the most established form of large-scale energy storage (>1000 GWh available) [24];
 - Despite being the most mature storage technology, PHS is already widely used to manage current fluctuations in energy demand and supply. As no major investments are planned for further expansion at the time of writing, it is excluded from the forward-looking analysis [25].
- **Demand Side Response (DSR):**
 - It involves industries, buildings, and electric vehicles in consumption modulation [26];
 - Technical potential estimated at over 160 GW in Europe by 2030 (ENTSO-E) [27];
 - Essential to prevent inefficient and rapid ramp-ups of fossil power plants during peak hours [7] [26].

The final variable to be integrated in the model is the marginal emission factor by source. In fact, the power system frequently dispatches fossil-fuel plants in response to demand exceeding the total output from renewables and base-load sources (e.g. nuclear and continuous hydropower) [7] [28]. The **marginal Emission Factor (EF_m)** can vary significantly depending on the type of generation source activated (Figure 8) [15]:

Figure 8

Marginal emission factor per source integrated in the model

Marginal Source	Estimated EF _m (gCO ₂ eq/kWh)	Sources
Coal (lignite/bituminous)	850–950	IPCC, IEA, ENTSO-E
Simple-Cycle Gas Turbines	450–550	EPA, EEA
Diesel/oil Engines	750–900	UK BEIS, ADEME
CCGT	~400	IEA, ENEA

Note. Table created by the author. Data compiled from IPCC [15].

On average, these units operate 2,000–2,700 hours/year. Below are presented the activation rates for weighted EF_m (Figure 9) [15] [29]:

Figure 9

Activation rate per source for the hours of marginal activation [15] [29]

Source	% Peak Hours Active	Average EF (gCO ₂ /kWh)
Natural Gas (CCGT)	70–80%	450
LNG	30–40%	530
Coal	20–35%	820
Oil	2–5%	750

In this context, the link between the marginal emission factor and storage systems becomes evident, as these systems can prevent the dispatch of fossil-fuel power plants [20] [7].

To integrate this systemic dependency into the model, storage capacity and flexibility mechanisms are parameterised through a marginal fossil energy attenuation coefficient, defined as α (alpha).

This coefficient represents the efficiency with which flexible mechanisms prevent marginal fossil generation [30].

Simplified formula:

$$\Delta CO_2 = \alpha \times E_{flex} \times EF_m$$

Where:

- α is the efficiency coefficient of the flexibility mechanism;
- E_{flex} is the energy supplied by batteries or DSR;
- EF_m is the marginal emission factor of the non-dispatched fossil source.

Estimating the alpha coefficient for flexibility is complex, but three plausible scenarios can be identified (Figure 10) [30] [31]:

Figure 10

Different scenarios for a coefficient, author's assumptions

Scenario	Estimated α
Optimistic (high flexibility)	0.80–0.85
Realistic (2024–2030)	0.60–0.75
Conservative (limited dispatch)	0.50–0.60

Quantitative simulation for 2030

The model considers 60 GW of storage and 160 GW of activated DSR, for a total theoretical flexible capacity of 220 GW [3] [13]. Two scenarios were analysed by varying the alpha coefficient:

1. Fit for 55:

- Potentially avoidable hours: ~1080 h/year [29];
- Conservative alpha coefficient under limited dispatch: 0.5 [30]
- Avoidable marginal energy: ~120 TWh

2. Storage Diffusion:

- Potentially avoidable hours: ~1080 h/year [29]
- Conservative alpha coefficient under high flexibility: 0.8 [30]
- Avoidable marginal energy: ~190 TWh

The cumulative effect is a significant reduction in fossil-based energy produced during marginal hours, resulting in a structural decrease in EF_m and greater stabilisation of the overall structural Emission Factor (EF_t) of the system [20] [7] [31].

Impact of key EU Policies on the simulation model

This section outlines the rationale used to estimate the impact—in terms of $MtCO_2$ —of the principal EU policies affecting the **Emission Factor (EF)** of the European electricity sector. The estimates are based on official sources (European Commission, Ember, ENEA, IEA, CEPS) and on conversions derived from standard emission factors (Figure 11).

Figure 11

Breakdown of the contribution per single EU policy

Summary table of the effects of European policies on grid EF (MtCO ₂)		
Policy	Min	Max
ETS II	20	50
RED III	110	220
Phase out	130	280
REPowerEU	25	80
CSRD + ESRS	5	10
TOTAL	290	640

ETS II

In 2021, non-ETS sectors (transport and buildings) emitted approximately 1,000 MtCO₂eq across the EU [32]. The extension of the ETS to these sectors (ETS II) is expected to result in a 10–15% reduction by 2030, according to European Commission projections [33].

Applying a 10% reduction to 1,000 MtCO₂eq yields a theoretical mitigation potential of 100 MtCO₂eq. However, only a share of this reduction directly affects the electricity sector through fuel switching (e.g. heat pumps replacing gas boilers and electrification of light-duty transport). Based on the Commission's assumptions, it is estimated that between 20% and 50% of the total emissions reduction will be attributable to electrification [34].

This estimate is supported by technical studies on the inclusion of road transport in the EU ETS, which suggest that 25% to 60% of emission reductions in the road transport sector will depend on fleet electrification [35].

Furthermore, under the REPowerEU plan, which targets the installation of 60 million heat pumps by 2030, electric penetration in residential heating is projected to reach 20–50% depending on the scenario [36] [37].

Consequently, the estimated impact of ETS II on the electricity sector falls within the following range:

$$\Delta Emissions \{min: 0,2 * 1000 MtCO_2eq * 0,1 = 20 MtCO_2eq \text{ max: } 0,5 * 1000 MtCO_2eq * 0,1 = 50 MtCO_2eq$$

RED III (45% Renewables Target)

The increase in the share of renewable energy in the electricity mix from approximately 35% to 45% is projected to generate around 300 TWh of additional low-emission electricity by 2030 [38] [39].

Two boundary cases are considered to estimate prevented emissions:

- Best-case scenario: green hydrogen (EF = 0 gCO₂/kWh) replaces coal (EF = 820 gCO₂/kWh);
- Worst-case scenario: solar photovoltaic (EF = 48 gCO₂/kWh) replaces natural gas (EF = 450 gCO₂/kWh).

Based on this, the estimated prevented emissions range between 120 and 246 MtCO₂:

$$\Delta Emissions \{min: 400 \left(\frac{gCO_2}{kWh} \right) * \frac{300 TWh}{1000} = 120 MtCO_{2eq} \text{ max: } 820 \left(\frac{gCO_2}{kWh} \right) * \frac{300 TWh}{1000} = 246 MtCO_{2eq}$$

Rounding to account for uncertainties in actual substitution (e.g. part of the RES growth may serve new demand), and applying a conservative 10% impact reduction factor, we obtain a range of approximately 110 to 220 MtCO₂

Coal Phase-Out

In 2022, coal accounted for around 15% of the EU electricity mix, equivalent to approximately 400 TWh [40].

Two scenarios are considered:

- Worst-case scenario: coal is replaced by natural gas (EF = 450 gCO₂/kWh), resulting in an average reduction of 370 gCO₂/kWh
- Best-case scenario: coal is replaced by solar PV (EF = 48 gCO₂/kWh), resulting in an average reduction of 772 gCO₂/kWh

Estimated prevented emissions:

$$\Delta Emissions \{min: 370 \left(\frac{gCO_{2_{eq}}}{kWh} \right) * \frac{400 TWh}{1000} = 148 MtCO_{2_{eq}} \quad max: 772 \left(\frac{gCO_{2_{eq}}}{kWh} \right) * \frac{400 TWh}{1000} = 309 MtCO_{2_{eq}} \}$$

Applying a conservative 10% reduction factor, the estimated impact ranges from approximately **130 to 280 MtCO₂eq.**

REPowerEU (Storage, Hydrogen, Biomethane)

Biomethane production: The plan aims to reach 35 billion cubic meters per year (35 bcm) by 2030, as outlined in official statements from the European Commission (i.e. REPowerEU Impact Assessment) and related documents [41].

Renewable hydrogen production: The target is 20 million tonnes per year by 2030 (10 Mt domestic and 10 Mt imported), as clearly stated in the REPowerEU Impact Assessment [42].

Methodology and assumptions: Multiple scenarios can be envisaged. Considering that approximately 20% of the natural gas consumed in the EU is used for electricity generation, it's assumed that only 20% of the hydrogen and biomethane produced will replace natural gas for energy production.

While biomethane has a lower heating value (LHV) similar to natural gas, and can be directly substituted, hydrogen follows a different energy conversion logic:

- LHV of H₂: **33.33 kWh/kg**
- LHV of natural gas: **10 kWh/m³**

$$\text{Primary Energy Generated (1kgH}_2\text{)} = 1 * 33,33 = 33,33 \text{ kWh}$$

$$\text{Replaced Gas Quantity (m}^3\text{)} = \frac{33,33}{10} = 3,33 \text{ m}^3$$

Estimated emission reduction:

- **Biomethane:** $35 \text{ bcm} \times 20\% = 7 \text{ bcm}$ of biomethane used for electricity → estimated reduction: **~29 MtCO₂eq**
- **Renewable hydrogen:** 20 Mt H₂ could replace 66.66 bcm of natural gas if fully used in electricity generation. With the 20% assumption: $66.66 \times 0.2 = 13.33 \text{ bcm}$ replaced → estimated reduction: **~60 MtCO₂eq**

Two scenarios are considered:

- **Worst case:** only biomethane contributes → **29 MtCO₂eq** prevented
- **Best case:** both biomethane and hydrogen contribute → **89 MtCO₂eq** prevented

Applying a conservative 10% reduction factor:

- **Estimated impact:** between approximately **25 and 80 MtCO₂eq**

CSRD + ESRS (Scope 2 Emissions)

- Reputational and regulatory pressure is expected to drive large companies to purchase low-carbon electricity, thereby creating selective demand in the market.
- While quantitatively modelling the precise impact is challenging, it is estimated that this dynamic could lead to **5–10 MtCO₂eq/year** of prevented emissions in the power sector.

Assuming an annual reduction of 5–10 MtCO₂eq as a result of reputational and regulatory pressure related to Scope 2 reporting is consistent with previous analyses carried out by CDP, EFRAG, and the GHG Protocol [43] [44].

Modelling outcomes

The application of the semi-parametric deterministic model produced a detailed projection of the evolution of the Emission Factor (EF) of the European electricity system over the 2024–2030 period, differentiating between three scenarios characterised by distinct levels of political and technological ambition: Business as Usual, Fit for 55, and Storage Implementation.

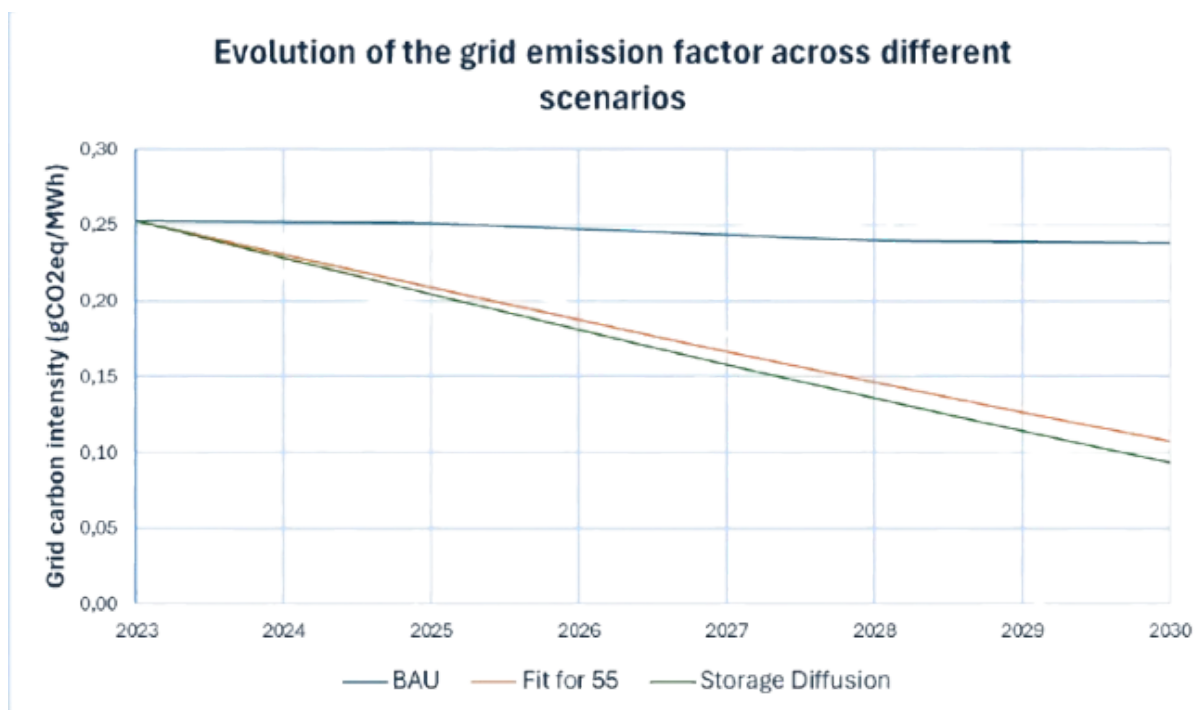
The results show that, assuming electricity demand remains constant, the system's emission trajectory depends heavily on the composition of the energy mix, technological progress (particularly in terms of thermal power fleet efficiency), the scale of renewables deployment, and the presence of flexibility mechanisms (Figure 12).

More specifically:

- **The Business as Usual (BAU)** scenario relies solely on incremental improvements in the efficiency of existing thermal power plants, with no significant investments in new technologies or EU policies. Under this model, the EF decreases moderately from 253 to 227 gCO₂eq/kWh by 2030, while the grid maintains a significant share of fossil fuels reliance and limited peak load response capacity;
- **The Fit for 55** scenario is marked by the full implementation of the EU environmental policy package (i.e. RED III, ETS II, REPowerEU), featuring strong renewables penetration , but still limited deployment of storage systems. The EF is substantially reduced to 108 gCO₂eq/kWh by 2030, supported by a cleaner energy mix and the progressive phase-out of coal;
- **The Storage Diffusion** scenario simulates an accelerated transition, where full EU policy implementation is accompanied by large-scale deployment of storage systems and demand-side response mechanisms. This allows for more efficient management of peak loads and a sharp decrease in marginal EF. The overall EF reaches 93 gCO₂eq/kWh, the lowest level across all scenarios.

Figure 12

Decreasing of the grid emission factor according to different analysed scenarios



Note. Graph created by the author.

In cumulative terms, over the entire 2024–2030 period, total emissions from the EU electricity system fall into three distinct levels:

- **7,200 MtCO₂eq** under the BAU scenario;
- **5,300 MtCO₂eq** under the Fit for 55 scenario;
- **4,300 MtCO₂eq** under the Storage Implementation scenario.

The model clearly shows that the full implementation of EU policies—when supported by targeted investments in storage, digitalisation, and flexible systems—can lead to emission reductions of up to 3,000 MtCO₂eq by 2030. Operational flexibility—on both the supply and demand side—thus emerges as a key element to amplify the systemic benefits of low-carbon technologies and to ensure a stable, sustainable decarbonisation trajectory.

Modelled scenarios and their effects on energy costs

The variations in the Emission Factor across the three modelled scenarios (BAU, Fit for 55, Storage Diffusion) directly impact the average cost of electricity, not only in environmental but also in economic terms [7] [6]. To realistically estimate these effects, a cross-model of hourly supply and demand was developed, separately taking into account cold and hot seasons, analysing:

- The average hourly electricity demand loads over 24 hours for each season (EU27 load curve) [45] [46];
- The electricity consumption seasonal profile, as it differs between the cold and hot seasons. In this paper, the cold season is defined as the period from October to March, whereas the hot season refers to the period from April to September. This distinction is relevant to the analysis because electricity demand generally rises during the hot season, driven by increased cooling loads associated with higher temperatures. Conversely, demand in the cold season is assumed to be relatively lower, as a significant share of heating demand is typically satisfied by non-electric energy sources.
- The hourly electricity generation profiles by source [45] [47];
- The theoretical marginal price of energy, based on the source required to meet residual hourly demand (according to a merit order logic) [48] [49].

For each scenario, the energy price (€/MWh) resulting from the interaction of these factors was estimated assuming that renewable sources (i.e. wind, solar, hydro) have zero marginal cost and that fossil sources (i.e. gas, coal, oil) define the price during peak hours and periods of renewables shortage [48] [49] [50].

Interoperating grid (highly integrated European network)

In a well-integrated and balanced grid, cross-border optimisation already allows for the moderation of average energy prices [45] [27]. However, only under the most ambitious scenarios is the price stabilised even during critical hours, thanks to the combined effect of renewables proliferation, storage diffusion and DSR mechanisms [50] [51]. It is worth noting that, even under optimistic circumstances, turning the European grid into a fully balanced and unified system presents major technical-engineering challenges (Figure 12) [13].

Figure 13

Energy cost variation for different scenarios analysed (interoperating grid)

Scenario	Cost (euro/MWh)		
	Cold	Hot	Average
BAU	22	14	18
FIT for 55	18	13	16
Storage Diffusion	18	13	16

Note. Table created by the author.

Hypothetical system with French energy mix extended to the EU

This scenario simulates a system dominated by nuclear power and a moderate level of renewables penetration. Costs decrease sharply under the Fit for 55 scenario, while, under the Storage Diffusion model, widespread storage deployment allows for further stabilisation of high-load prices (Figure 13)

Figure 14

Energy cost variation for different scenarios analysed (France energy mix)

Scenario	Cost (euro/MWh)		
	Cold	Hot	Average
BAU	52	87	69
FIT for 55	47	25	36
Storage Diffusion	40	25	33

Note. Table created by the author.

Hypothetical system with Italian energy mix extended to the EU

Assuming the EU adopted an energy mix structurally similar to Italy's (marked by high gas dependency), energy prices would be considerably higher. Nonetheless, the large-scale introduction of storage capacity modelled under the Storage Diffusion scenario, would still lead to a significant reduction in price spikes and to improved market stability (Figure 14).

Figure 15

Energy cost variation for different scenarios analysed (Italian energy mix)

Scenario	Cost (euro/MWh)		
	Cold	Hot	Average
BAU	143	81	112
FIT for 55	128	66	97
Storage Diffusion	122	31	76

Note. Table created by the author.

From an economic perspective, considering a realistic total annual electricity demand of approximately 2,800 TWh across the EU [6] [48], and excluding the hypothetical “fully interconnected grid” case (used only as a theoretical best-case), the cumulative policy impact could generate annual savings ranging between:

- **~€12 billion/year** in a scenario aligned with the Italian energy mix;
- **~€158 billion/year** in a scenario aligned with the French energy mix [52].

These are systemic economic benefits that complement environmental gains, highlighting how a decarbonised, digital and resilient energy mix is not only part of a forward-looking climate strategy, but also a key long-term competitive advantage for the European Union.

Conclusions

The evolution of the Emission Factor of the EU27 electricity system between 2024 and 2030 clearly demonstrates that the Union's emission trajectory will not depend solely on renewables growth, but rather on the synergy of ambitious policies, technological innovation, and the system's ability to respond flexibly to demand variability.

The modelling shows that improvements in plant efficiency alone (BAU scenario) are insufficient to achieve a significant emission reduction. Only through the full implementation of environmental policy packages—notably RED III, ETS II, and REPowerEU—can structural decarbonisation be achieved, bringing the average Emission Factor close to 100gCO₂eq/kWh. The widespread deployment of storage systems and demand-side response emerges as the key enabler to push the Emission Factor below 100gCO₂eq/kWh, making the grid more resilient, stable, and sustainable.

The model also highlights how the introduction of flexibility mechanisms can have a decisive impact on the marginal Emission Factor, mitigating the effects of peak loads and the variability of non-dispatchable sources, while contributing significantly to the overall emission reduction and to system stability.

Finally, the breakdown of the system-wide costs associated with the three scenarios shows a clear correlation between Emission Factor reduction and lower average electricity prices. The combination of a low-carbon mix and high operational flexibility allows, in the medium term, for greater price stability and a progressive decoupling of decarbonisation from system costs.

3. Green Policies & Technologies: Old and New Dependencies

Old dependencies: moving away from fossil fuels

For decades, the European Union (EU) and the United Kingdom (UK) have relied heavily on fossil fuels, coal, oil, and natural gas to drive industrial production, transport, and electricity generation. In 2000, fossil fuels accounted for nearly 80% of the EU's gross available energy and over 85% of the UK's total energy supply, underscoring the deep structural dependence on carbon-intensive sources. This dependence has proven economically and geopolitically costly, exposing both regions to price volatility, import insecurity, and rising emissions incompatible with their climate neutrality goals [53] [54].

The EU remains a net energy importer, with an import dependency ratio of 58.4% in 2023, meaning that more than half of its energy needs were covered by imports [53] [55]. Encouragingly, this dependency ratio dropped by nearly 15% in 2024, reflecting the impact of accelerated renewable energy deployment, improved energy efficiency, and reductions in fossil fuel imports driven by geopolitical pressures and policy shifts [54]. Within the 2023 energy supply mix, oil and petroleum products represented 37.6%, natural gas 20.4%, and solid fossil fuels 9.4%, cumulatively making up over two-thirds of the Union's energy supply.

The UK, despite its historic production in the North Sea, continues to experience declining domestic reserves and rising reliance on imported gas, especially following the closure of its last major coal mines in 2017.

This high dependence on fossil fuel imports has generated not only significant climate externalities but also pronounced strategic vulnerabilities. The 2022 energy crisis, triggered by Russia's invasion of Ukraine, starkly revealed how volatile and insecure these import patterns can be, motivating accelerated energy diversification efforts [55] [56].

The fossil fuels phase out process: from 2002 to today

The early 2000s marked the high point of Europe's fossil fuel dependency. In 2002, the EU derived roughly 79% of its gross available energy from fossil fuels, while renewables contributed less than 7% [53].

In the UK, fossil fuels represented approximately 85–90% of total primary energy supply, dominated by coal for power generation, oil for transport, and gas for residential heating [56]. These figures illustrate a system still defined by legacy assets, domestic extraction, and heavy carbon intensity.

Over the following two decades, the region entered a period of unprecedented energy restructuring. Between 2002 and 2023, the EU's fossil fuel share declined to about 66%, while the renewable energy share in gross consumption nearly quadrupled to 24.5%. In parallel, primary energy production from renewables increased by 30.7%, while natural gas production declined by 70.5%, and solid fossil fuel production fell by over 60% [53] [54]. These shifts confirm the deep structural transformation underway in Europe's energy system.

According to some studies, who analysed clustering patterns of European primary energy production from 1990 to 2022, the continental transition can be divided into three broad phases [57] :

1. **2000–2010: Stabilisation and early reform.** Moderate policy progress, with the 2001 Renewable Electricity Directive setting initial targets and early investments in wind and hydro;
2. **2010–2020: Acceleration and diversification.** Rapid decline of coal, scaling of solar and offshore wind, introduction of the EU ETS and UK carbon pricing mechanisms, and convergence of electricity markets;
3. **2020–2023: Consolidation and resilience.** Renewables overtaking fossil fuels as the dominant source of domestic energy production, reinforced by geopolitical and security shocks.

The impact of these stages is visible in the electricity sector, the clearest indicator of decarbonisation.

The EU's share of renewables in gross electricity generation rose from 15.8% in 2004 to 45.3% in 2023, while fossil fuel-based electricity fell from around two-thirds to 31.7% [53]. In the UK, renewables supplied less than 2% of power in 2002 but reached 47% by 2023, overtaking fossil fuels for the first time [58].

This transformation has also reshaped energy import patterns. EU import dependency on fossil fuels has remained high overall (58.4% in 2023), but the composition has changed dramatically: reduced coal and oil imports are partially offset by gas imports from diverse suppliers, while renewable electricity and green hydrogen projects begin to substitute external fossil sources [53].

As emphasised in different references, Europe's energy systems are clustering into transition groups. Northern and Western European states (such as Denmark, Sweden, Germany and UK) lead in renewable penetration, while Eastern and Southern states exhibit slower substitution but growing integration through cross-border interconnections and EU funds [57]. This heterogeneity implies that while the continental average shows significant progress, the pace remains regionally uneven.

From a market perspective, Europe's transition was also price-driven. Fossil fuels became less economically attractive as carbon pricing, ETS allowances, and renewable cost parity converged. Between 2010 and 2020, the levelised cost of energy (LCOE) for solar PV fell by 85%, and for onshore wind by 56%, making new renewables cheaper than any new fossil-based generation [58].

Transition dynamics

The transition away from fossil fuels has been shaped by a complex interplay of market signals, technological progress, and policy intervention.

As mentioned before, the declining cost of renewables and the rising volatility of fossil fuel markets have inverted the economics of energy supply. Solar and wind technologies now consistently undercut the marginal cost of new fossil-based capacity. In parallel, carbon pricing mechanisms have further eroded the competitiveness of coal and gas generation. In the UK, these instruments effectively rendered coal-fired generation uneconomic after 2016, leading to its near elimination from the power mix [58].

At the same time, EU-level frameworks have reinforced regulatory certainty for investors and set binding renewable targets by 2030, enhanced grid integration, and mobilised innovation funds. The outcome has been a steady decoupling of GDP growth from fossil fuel consumption, as evidenced by a 21% decline in fossil fuel use per unit of GDP across the EU between 2005 and 2022 [53].

The energy transition and its “messy middle”

As highlighted in several researches, fossil fuel phase-out strategies must navigate a “messy middle”, a transitional period when both old and new energy systems coexist. During this stage, gas often functions as a bridge fuel, supporting grid stability as variable renewables expand. Yet, the persistence of gas in electricity and heating sectors raises the risk of “carbon lock-in” if infrastructure lifetimes extend beyond 2040 [56] [57].

In the EU, several Member States (notably Germany, Italy, and Poland) continue to rely on natural gas for balancing supply, while others accelerate diversification through electrification, hydrogen, and heat pumps. The UK, too, still derives about one-third of its electricity from gas [54] [56].

Socioeconomic and supply chain challenges

Beyond carbon and import dependency, the transition also generates new forms of vulnerability. As fossil fuel extraction declines, energy systems become increasingly dependent on critical minerals (lithium, cobalt, nickel) and renewable technology supply chains, much of which are currently concentrated in Asia. This shift highlighted the need to develop domestic industrial capacity, circular material flows, and strategic reserves to mitigate these emerging dependencies [58] [57].

Socially, the fossil fuel phase-out entails significant labor market transitions. It requires coordinated efforts to support workers and communities dependent on carbon-intensive industries, ensuring that employment opportunities, skills development, and social protections evolve in step with the emerging low-carbon economy [58] [56].

Overall, the combined effect of these forces had created a new energy landscape: fossil fuels were no longer dominant in domestic energy production, and renewables had become the economic default for new capacity additions. Yet, the path forward remains complex. The rapid decline of coal and oil has been offset by persistent gas use and growing electricity demand. Both the EU and UK must therefore balance speed of decarbonisation with system resilience, ensuring that old dependencies are replaced by diverse, flexible, and regionally balanced energy systems [54] [55] [57].

Main EU green transition policies and enabling technologies

In recent years, and still today, the European Union has been actively promoting clean energy technologies by leveraging its most powerful policy instrument: public funding linked to measurable targets, binding KPIs and clear regulatory obligations [59] [60]. This approach allows the EU to steer both public and private investments along a defined trajectory aimed at strengthening energy independence while minimising the overall carbon footprint of the European energy system [61].

The legislative framework developed so far establishes a direct and intentional alignment between specific energy technologies and dedicated policy instruments, ensuring that incentives, funding mechanisms and permitting rules are tailored to the strategic role of each technology [62].

Below is an overview of how individual energy technologies are addressed, promoted and financially supported through EU legislation and strategies.

Solar

Solar energy is the fastest-growing renewable technology in the European Union and represents the backbone of the EU's renewable expansion strategy. Thanks to its scalability, declining costs and rapid deployment potential, solar photovoltaics are identified by EU legislation as the primary contributor to achieving the 2030 renewable energy targets and strengthening energy independence. The deployment of this technology is supported by the following EU policy instruments and funding mechanisms.

Renewable Energy Directive (RED)

The Renewable Energy Directive (RED) constitutes the main regulatory and financial backbone for the deployment of solar energy across the EU. Through its successive revisions—RED I (2009), RED II (2021) and RED III (2023)—the directive progressively strengthens binding renewable energy targets for Member States and defines the regulatory conditions under which renewable technologies can access public support [63] [64].

RED III sets a binding target of 42.5% renewable energy in gross final energy consumption by 2030, with an indicative ambition of 45%. Solar photovoltaics are explicitly identified as the primary technology expected to deliver this target, due to their scalability, cost-effectiveness and rapid deployment potential [60].

Member States are required to reflect these objectives in their National Energy and Climate Plans (NECPs), which serve as the key planning instruments for channelling EU and national funding toward solar deployment. RED III further facilitates access to incentives by simplifying permitting procedures, identifying go-to areas for solar installations, and easing grid connection rules, particularly for small-scale and rooftop PV systems [62].

REPowerEU – Solar Energy Strategy

In May 2022, in response to the Russian invasion of Ukraine, the European Commission adopted the REPowerEU Plan to rapidly reduce EU dependence on imported fossil fuels. Within this framework, the Solar Energy Strategy positions solar energy as a cornerstone of the EU energy system.

The strategy sets concrete deployment objectives: more than 320 GW of additional solar PV capacity by 2025 and approximately 600 GW by 2030. These targets are directly supported by EU funding instruments, including the Recovery and Resilience Facility (RRF), cohesion funds and the Innovation Fund.

A flagship initiative under this strategy is the European Solar Rooftops Initiative, which introduces a progressive obligation for installing solar systems on new buildings. Although initially non-binding, this initiative paved the way for subsequent legislative action [65].

Energy Performance of Buildings Directive (EPBD) – EU Solar Standard

The Energy Performance of Buildings Directive (EPBD), revised and adopted in 2023, transforms the political ambition of solar deployment into a legally binding obligation. Through the introduction of the EU Solar Standard, the directive requires the installation of solar systems—photovoltaic or solar thermal—on new buildings and on existing buildings undergoing major renovations, when technically and economically feasible.

The obligation is phased over time:

- from 2026 for new public and non-residential buildings;
- from 2027 for existing public buildings undergoing major renovations;
- from 2029 for all new residential buildings.

This framework creates a stable and predictable investment environment for solar technologies, directly linking regulatory obligations with access to public funding and incentives [65].

Green Deal Industrial Plan and Permitting Package

The deployment of solar energy is further supported through the Green Deal Industrial Plan and the EU Large-Scale Skills Partnership for Renewable Energy. These initiatives link deployment targets to labour market development, industrial capacity and skills funding [64] .

At the same time, the Permitting Package aims to accelerate authorisation procedures for renewable energy projects, reducing administrative barriers and improving the bankability of solar investments across Member States [59] [60].

Wind

Wind energy represents 39.1% of electricity generated from renewable sources in the EU in 2024. Wind energy represents a central pillar of the European energy system, accounting for a significant share of electricity generation from renewable sources in the EU. In particular, offshore wind is considered essential to achieving the EU's 2030 climate and energy targets, given its high capacity factors and system integration potential. The deployment of this technology is supported by the following EU policy instruments and funding mechanisms [59] [60] [61].

EU Strategy on Offshore Renewable Energy and TEN-E Regulation

The EU Strategy on Offshore Renewable Energy sets a target of at least 60 GW of offshore renewable capacity by 2030, primarily based on offshore wind. This strategy is closely linked to the revision of the Trans-European Networks for Energy (TEN-E) Regulation.

The revised TEN-E Regulation introduces offshore renewable energy projects as a new category of Projects of Common Interest (PCIs), enabling faster permitting and priority access to EU funding. It also mandates Transmission System Operators (TSOs), in cooperation with ENTSO-E and national regulators, to develop Offshore Network Development Plans, ensuring that grid investments are aligned with deployment targets [61] [62].

EU Wind Power Package

The EU Wind Power Package consists of two complementary initiatives. The first is the European Wind Power Action Plan, structured around six pillars: faster permitting, improved auction design, access to finance, fair international competition, resilient supply chains, and skills development. These pillars are operationalised through a set of immediate actions aimed at unlocking investment and stabilising the sector.

The second is the Commission Communication on achieving offshore wind ambitions, which identifies six priority areas for accelerating deployment, including grid reinforcement, maritime spatial planning, infrastructure resilience and supply-chain development [61].

Net-Zero Industry Act (NZIA)

Under the Net-Zero Industry Act, both onshore and offshore wind technologies are designated as strategic net-zero technologies. This designation enables accelerated permitting procedures, priority access to EU financing instruments such as the Innovation Fund, and targeted regulatory support for projects classified as net-zero strategic projects [66] [67].



Hydrogen

Hydrogen plays a central role in the EU's decarbonisation strategy for hard-to-abate sectors such as heavy industry, long-distance transport and chemicals. Under REPowerEU, the EU sets the objective of producing 10 million tonnes of renewable hydrogen domestically and importing an additional 10 million tonnes by 2030 [63]. The deployment of this technology is supported by the following EU policy instruments and funding mechanisms.

REPowerEU

The plan supports hydrogen through funding for electrolyser deployment, cross-border infrastructure, hydrogen hubs and storage facilities. It also targets 120 GW of electrolyser capacity by 2030, supported by EU-level financial instruments and coordinated investment frameworks [63] [68] [69] [70].

Hydrogen and Decarbonised Gas Market Package

Adopted in 2024, the Hydrogen and Decarbonised Gas Market Package establishes a dedicated regulatory framework for hydrogen markets. It introduces rules for network unbundling, market transparency and consumer protection, while enabling large-scale infrastructure investments [71] [72] [73] [74].

A key institutional innovation is the creation of the European Network of Network Operators for Hydrogen (ENNOH), responsible for coordinating hydrogen infrastructure planning at EU level. By 2030, the EU foresees a hydrogen network of approximately 28,000 km, partly based on repurposed gas pipelines, supported by estimated investments of €43–81 billion [75] [69].

RFNBO Delegated Acts

The RFNBO Delegated Acts define the technical eligibility criteria for renewable hydrogen and its derivatives to access EU support. By enforcing principles of additionality, temporal and geographical correlation, these acts ensure that only genuinely renewable hydrogen qualifies for incentives.

By 2030, at least 42% of hydrogen used in industry and 1% of fuels used in transport must come from RFNBOs, directly linking regulatory targets with funding eligibility [76] [77].

Geothermal

Geothermal energy is recognised by the European Union as a stable, local and dispatchable renewable source, particularly suited for decarbonising heating and cooling systems and improving energy efficiency in buildings and district heating networks. Its contribution is strategically linked to energy security and the reduction of fossil fuel use in the building sector. The deployment of this technology is supported by the following EU policy instruments and funding mechanisms.

RED III

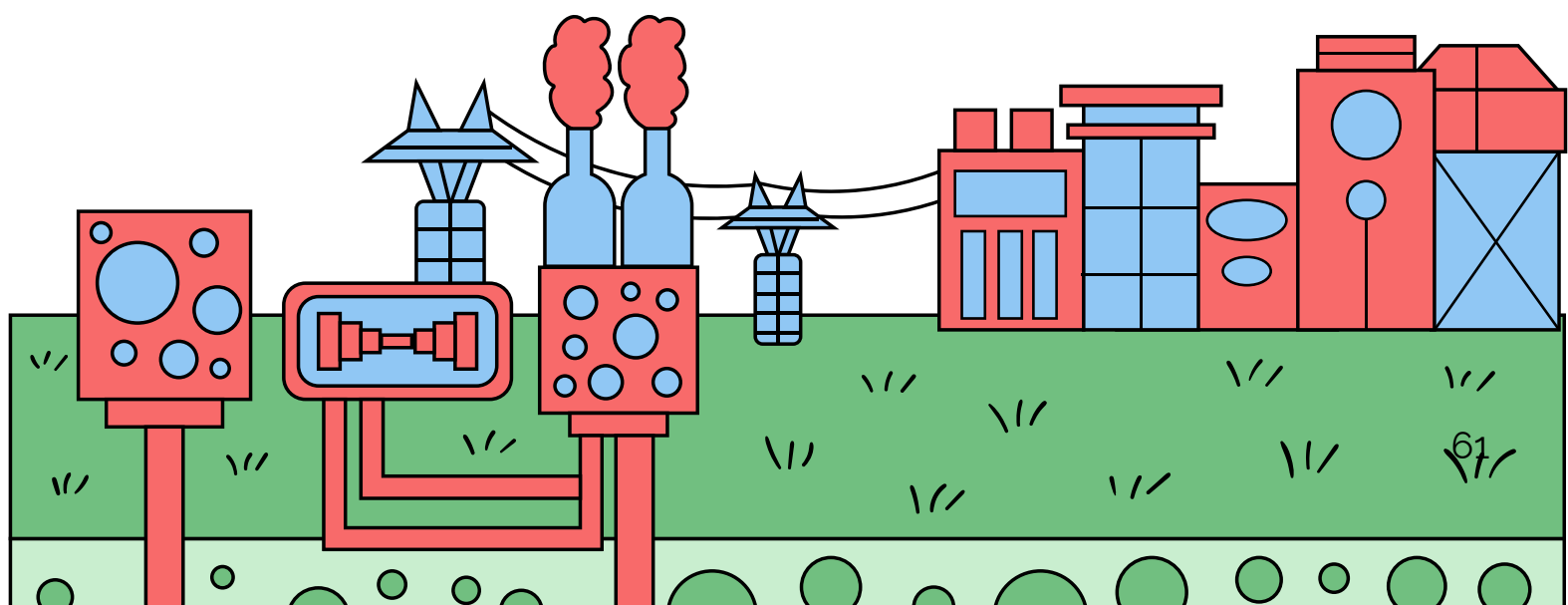
RED III explicitly recognises geothermal energy as a stable and dispatchable renewable source, essential for decarbonising heating and cooling. It supports geothermal deployment through binding renewable targets and dedicated support for innovative drilling and subsurface technologies [78].

EPBD

The revised EPBD promotes geothermal heat pumps and geothermal systems as key solutions for achieving zero-emission buildings. It mandates that all new public buildings from 2028 and all new buildings from 2030 must be zero-emission buildings, while setting ambitious renovation targets that directly support geothermal deployment [65].

Energy Efficiency Directive (EED)

The revised EED reinforces geothermal energy as a tool for achieving binding energy savings targets. It promotes the integration of geothermal energy into district heating and cooling systems and requires Member States to support geothermal infrastructure through national planning and funding mechanisms [79] [80] [81].



Carbon capture and storage

Carbon Capture, Utilisation and Storage (CCUS) is identified by the European Union as a key enabling technology for achieving climate neutrality in energy-intensive and hard-to-abate industrial sectors. EU policy frameworks position CCUS as a complementary solution to renewable energy deployment, supporting industrial decarbonisation while preserving competitiveness and security of supply. The deployment of this technology is supported by the following EU policy instruments and funding mechanisms.

Net-Zero Industry Act (NZIA)

The Net-Zero Industry Act assigns a strategic role to Carbon Capture, Utilisation and Storage (CCUS) technologies. It sets a target of 50 million tonnes of annual CO₂ injection capacity by 2030 and enables access to EU funding, accelerated permitting and cross-border infrastructure development.

Through the designation of CCUS as a strategic net-zero technology, the NZIA positions carbon capture as a critical component of the EU's industrial decarbonisation and competitiveness strategy [76] [77].

Renewable energy sources: penetration level breakdown

The penetration of renewable energy in the EU and UK has surged significantly, especially in power generation, transforming energy systems amid evolving policy frameworks such as the Renewable Energy Directive III (RED III), the REPowerEU Plan, and the Energy Performance of Buildings Directive (EPBD).

In 2023, renewables accounted for 24.5% of the EU's gross final energy consumption—an increase of about 1.5 percentage points from 2022—demonstrating accelerated deployment in response to ambitious EU climate targets [53]. This progress reflects the intensified efforts by Member States to meet the revised 2030 renewable energy target of 42.5%, driving substantial investment and structural shifts in the energy mix.

In the electricity sector, renewables reached 45.3% of gross electricity consumption in 2023, marking the largest single-year increase since data collection began in 2004. This growth is predominantly driven by wind and solar power expansions supported by regulatory reforms that smooth permitting processes, financial incentives, and grid integration enhancements. Fossil fuel-generated electricity declined correspondingly, reaching a share around 30%, reflecting the EU's ongoing phase-out of coal and gas under REPowerEU ambitions.

Wind energy: onshore and offshore

Wind power remains the dominant contributor to renewable electricity, accounting for 38.5% of renewables in 2023, bolstered by steady onshore and offshore capacity additions facilitated by legislation like the Net-Zero Industry Act (NZIA) and the revised TEN-E Regulation focused on offshore grid infrastructure.

The UK leads internationally in offshore wind, contributing approximately 30% of its electricity from wind sources, supported by over 14 GW of installed capacity against a target of 50 GW by 2030 [56]. The dramatic fall in the levelized cost of onshore wind, more than 56% since 2010, has cemented its role as a competitively priced renewable technology essential for decarbonisation.

Solar photovoltaics

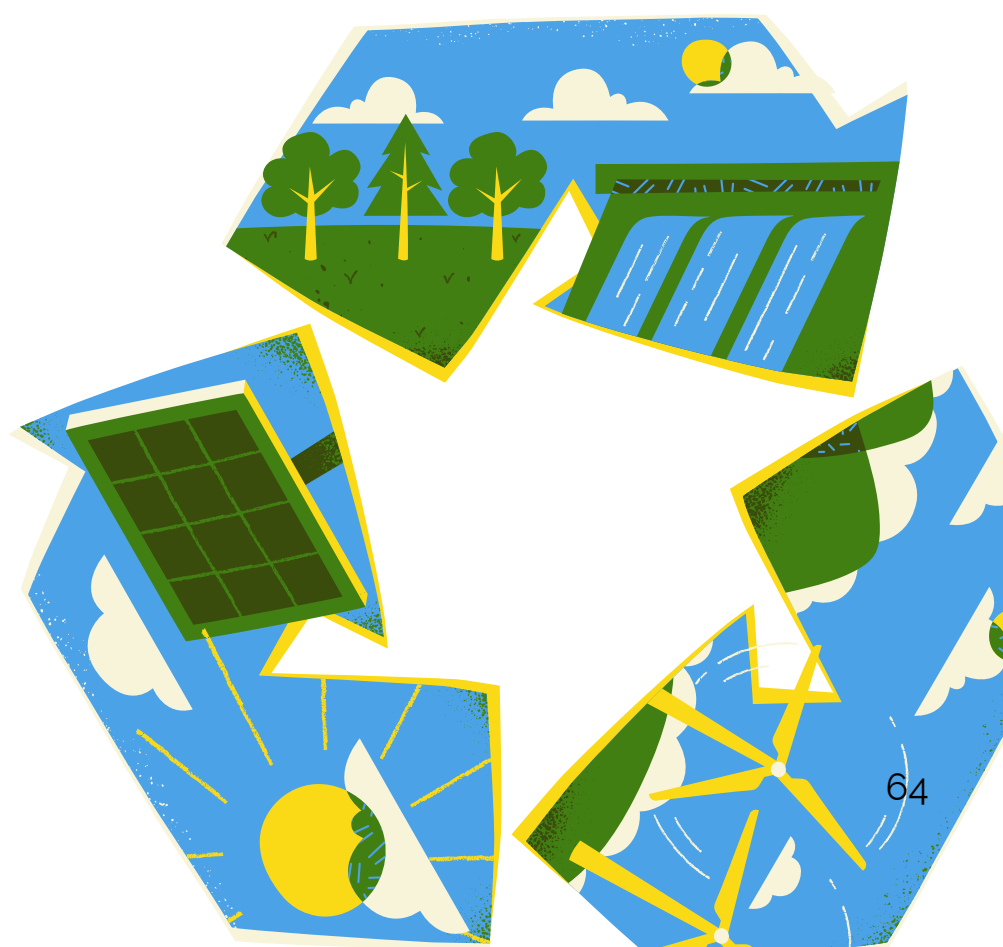
Solar PV has exhibited extraordinary growth, rising to 20.5% of renewable electricity in 2023 from less than 1% in 2005, reflecting sharp cost reductions, roughly 85% between 2010 and 2020, and targeted policies including the EU Solar Rooftops Initiative and EPBD solar installation mandates on new and renovated buildings [56] [54].

The UK's solar capacity surpassed 15 GW in 2023, supplying close to 5% of national electricity, with ambitious goals exceeding 70 GW by 2035, emphasising solar's integral role in the renewable mix.

Hydropower plants

Hydropower continues to provide a significant, stable share of EU renewable electricity, 28.2% in 2023, especially in Nordic, Alpine, and Iberian regions where it ensures grid flexibility and storage capabilities [54].

The UK's contribution remains modest (~1.8%) due to geographic constraints but benefits from pumped storage hydropower for balancing intermittent renewables.



Bioenergy and geothermal plants

Bioenergy accounts for approximately half of total renewable energy consumption across sectors, playing a major role in heating, industry, and transport areas less amenable to direct electrification [54].

RED III's stricter sustainability standards and RFNBO Delegated Acts support a shift towards advanced biofuels and sustainable biomass sourcing, mitigating environmental concerns. Geothermal energy, expanding through widespread heat pump deployment supported by RED III and EPBD, is increasingly recognised for its programmability and contributions to decarbonising building heating systems [57].

Cross-sector integration and emerging technologies

The next frontier in renewable deployment involves seamless sector integration, spanning electricity, heat, transport, and industry, driven by innovations in flexible storage, smart grids, and green hydrogen.

REPowerEU's hydrogen targets, reinforced by the Hydrogen and Decarbonised Gas Market Package, facilitate the scaling of renewable hydrogen production, which is crucial for decarbonising hard-to-electrify sectors. Concurrently, the NZIA accelerates deployment of core technologies including offshore wind, floating wind, and carbon capture, enhancing system resilience and industrial competitiveness [57] [54]. Emerging battery storage and grid-forming inverter technologies also significantly improve integration of variable renewables, ensuring reliable supply and fostering renewable penetration beyond power generation.

Overall, renewable energy adoption in the EU and UK reveals a dynamic transformation shaped by sustained policy support and disruptive technological advances.

Wind and solar have transitioned from niche options to central pillars of the energy system; bioenergy underpins heating and industry demand; and electrification paired with storage is increasingly addressing intermittency challenges.

However, as cited in different updated research, this growth introduces new dependencies on critical minerals, digital infrastructure, and supply chains that must be prudently managed to uphold Europe's energy sovereignty and environmental ambitions.

Weakness analysis of emerging dependencies

The Green Transition and the uneven distribution of its benefits

The global energy transition is profoundly reshaping industrial structures and geopolitical relations. The European Union, committed to climate neutrality by 2050 and to achieving at least a 42.5% share of renewable energy in its energy mix by 2030, has emerged as one of the main actors of global demand for green technologies [82]. This demand-led transition has accelerated the deployment of renewable energy across the Union, particularly in electricity generation.

However, the industrial and economic benefits associated with their production remain largely externalised, with China capturing a disproportionate share. China currently dominates the manufacturing of photovoltaic (PV) panels, batteries, and numerous critical raw materials essential for clean energy technologies [83] [84]. As a result, the European green transition has created a structural asymmetry between environmental gains within Europe and industrial gains abroad.

Europe's Demand for Green Technologies and the Limits to Domestic Industrial Capacity

In recent years, renewable energy has seen increasing relevance amongst electricity generation sources in the EU, accounting for 38.2% of total electricity production in 2022 [85], with a positive year-on-year expansion trend. This expansion was further accelerated by the war in Ukraine, which exposed Europe's vulnerability to Russian fossil fuel imports and reinforced the strategic importance of renewables as a prospective alternative to imported gas and oil [3].

It is important to note, however, that this progress primarily concerns electricity generation, while fossil fuels continue to dominate the EU's overall energy consumption, particularly in transport and heating. Renewables therefore strengthen electricity resilience but do not eliminate structural energy dependencies.

Solar photovoltaic energy plays a central role in this transformation due to its rapid deployment potential and sharply declining costs. Yet, growing European demand has not translated into a parallel strengthening of domestic manufacturing capacity. In 2023, the price of imported solar modules fell from 0.20 €/W to 0.12€/W, significantly undermining the competitiveness of European producers [86] [87]. The removal of EU anti-dumping tariffs on Chinese solar panels in 2018 further facilitated the influx of low-cost imports [88].

EU initiatives such as the European Solar PV Industry Alliance, which aims to establish 30 GW of manufacturing capacity along the solar value chain by 2030, reflect growing awareness of this imbalance [89]. Nevertheless, persistent cost differentials between European and Asian production, estimated at 70–105% for integrated PV manufacturing, have led multiple EU firms to scale down operations or relocate investment to more supportive policy environments, notably the United States following the Inflation Reduction Act (IRA) [90].

China's Structural Competitive Advantage

China emerged as the principal industrial beneficiary of Europe's green transition. In 2023, approximately 98% of photovoltaic panels imported into the EU originated from Chinese manufacturers [91]. This dominance is not limited to final products but extends across the upstream segments of green technology supply chains.

China supplies nearly all of the magnesium imported by the EU, dominates the refining of rare earth elements, and holds substantial shares in the processing of germanium, graphite, and battery-related materials [84] [92]. Beyond domestic production, China has strategically invested in mining and processing assets across Latin America, Africa, and Asia, reinforcing its position in lithium, cobalt, and nickel supply chains [83].

This vertical integration, spanning extraction, refining, manufacturing, and logistics, provides China with enduring industrial advantages. While this dominance does not imply unilateral power, given China's reliance on external markets such as the EU, it nonetheless creates asymmetric dependencies that translate into growing geopolitical leverage for the supplier.

The asymmetric benefits distribution

The benefits of the green transition are unevenly distributed across actors:

- China captures the bulk of industrial value added, leveraging its dominance in green technology manufacturing and critical raw materials processing;
- The EU benefits primarily in environmental terms (lower emissions and reduced fossil fuel exposure) but remains structurally positioned as a large consumer market dependent on external production;
- Other supplier countries, including the United States, Norway, Algeria, Kazakhstan, and Qatar, gain indirect advantages as exporters of fossil fuels, raw materials, and nuclear inputs during the transition phase;

Without more supportive industrial policies, targeted production incentives, strategic partnerships for raw materials, and sustained investment in advanced manufacturing and recycling, Europe risks further erosion of its competitive position in the global green economy.

The EU: Between Energy Diversification and Technological Dependence

The EU's dependency profile is increasingly dual in nature. In the traditional energy sector, Europe has significantly reduced its reliance on Russian gas, replacing it with imports from Norway, Algeria, and the United States [93]. This diversification enhanced short-term energy security in terms of fuel supply.

In contrast, the green transition introduced new forms of dependence, whereby external reliance is concentrated on fewer supplier countries, rendering diversification harder. In 2023, EU imports of rare earth elements originated mainly from China (39%), Malaysia (33%), and Russia (22%) [84]. Uranium supply remains almost entirely external, with Kazakhstan, Niger, and Canada as primary sources, while a significant share of enriched nuclear fuel continues to be provided by Russian companies [94].

From the EU–China asymmetry to global critical mineral constraints

Understanding who benefits from the green transition requires positioning the EU–China relationship within the broader global market for critical minerals. Demand for minerals linked to clean energy technologies is projected to grow rapidly across all scenarios outlined by the International Energy Agency (IEA) [83].

According to the IEA's Stated Policies Scenario (STEPS from the Global Critical Minerals Outlook 2025), lithium demand is expected to increase fivefold by 2040, while graphite and nickel are projected to double. Cobalt and rare earth elements are forecasted to grow by 50–60%, and copper demand by around 30% [83]. These trends are driven by the diffusion of electric vehicles, energy storage systems, grid expansion, and renewable technologies reliant on permanent magnets.

At the same time, recent downward revisions in electric vehicle deployment and the increasing adoption of Lithium-Iron-Phosphate (LFP) battery chemistries moderate demand expectations for some materials, particularly cobalt [95]. On the supply side, announced mining projects suggest significant future expansion, yet structural bottlenecks, such as long permitting times, capital intensity, and environmental constraints, mean that supply deficits for copper and lithium are likely to persist beyond 2035 even under optimistic scenarios [83].

SWOT analysis of EU green policies and technologies: dependencies and strategic vulnerabilities

Providing an overview of emerging dependencies is not sufficient to assess the overall impact of the green transition. For this reason, the table below identifies not only the main threats and weaknesses that Europe will have to address to ensure that the green transition does not generate new structural vulnerabilities, but also the areas where action is required to reduce existing fragilities. At the same time, the table highlights key strengths and opportunities that can be leveraged to reinforce and accelerate the green transition (Figure 15).

Figure 16

SWOT Analysis of EU Green Policies and Technologies

Strengths	Weaknesses
Strong and credible climate policy framework (climate neutrality by 2050; 42.5–45% renewables by 2030).	High production costs for green technologies (EU solar PV manufacturing 70–105% more expensive than Asia).
Rapid deployment of renewable electricity, with renewables accounting for 38.2% of electricity generation (2022).	Limited domestic manufacturing capacity for key green technologies (solar PV, batteries).
Improved short-term energy security through diversification away from Russian fossil fuels (towards Norway, US, Algeria).	Extreme dependence on Chinese imports for solar panels (98%) and upstream components.
Large and stable internal market generating sustained demand for green technologies.	High dependency on external suppliers for critical raw materials, especially China (REEs, magnesium, germanium, graphite).
Growing institutional coordination (ESIA, Net-Zero Industry Act) aimed at rebuilding industrial capacity.	Structural vulnerability in nuclear fuel cycle, with reliance on imported uranium and Russian enrichment services.
Opportunities	Threats
Reindustrialisation via targeted industrial policy, state aid, and strategic public investment (NZIA, CBAM).	Geopolitical risks from dependence on China (tech + critical materials) and Russia (nuclear fuel enrichment).
Diversification of raw material and energy suppliers through partnerships (LATAM, Africa, Australia, Canada).	Intense Chinese price competition risking EU solar manufacturer closures/offshoring.
Leadership potential in next-generation technologies (perovskite solar cells, hydrogen, advanced batteries, grid technologies).	Global competition for critical materials, especially US–China rivalry in LATAM and Africa.
Development of recycling and circular economy systems to reduce long-term import dependence.	Supply chain concentration risks: few-country suppliers for borates, graphite, uranium, etc., making disruptions highly impactful.
Market-driven demand growth for clean technologies ensures long-term relevance of EU green transition.	Delayed industrial response risks lock-in to external supply chains, making future autonomy more costly.

Critical raw materials and the reshaping of global strategic dependencies

Dependence on critical raw materials and related resources, shaped a novel balance in the global commodity market. Particularly noteworthy is the relevance these materials acquired following the launch of the twin transition (i.e. digital development and environmental sustainability) in Europe and most other advanced economies.

The race to develop effective and durable green technologies placed the world's two largest and most powerful economies—the United States and China—in a position of growing competition. While the United States has long been the metronome of innovation, over the past decade Asian countries have progressively transformed this technological dominance into a more dual system.

For this reason, understanding the origin of these highly critical materials can provide valuable insights into the international commercial landscape, along with the dependencies, risks, and opportunities that stem from it [96].

Current as-is state of the international supply of critical raw materials

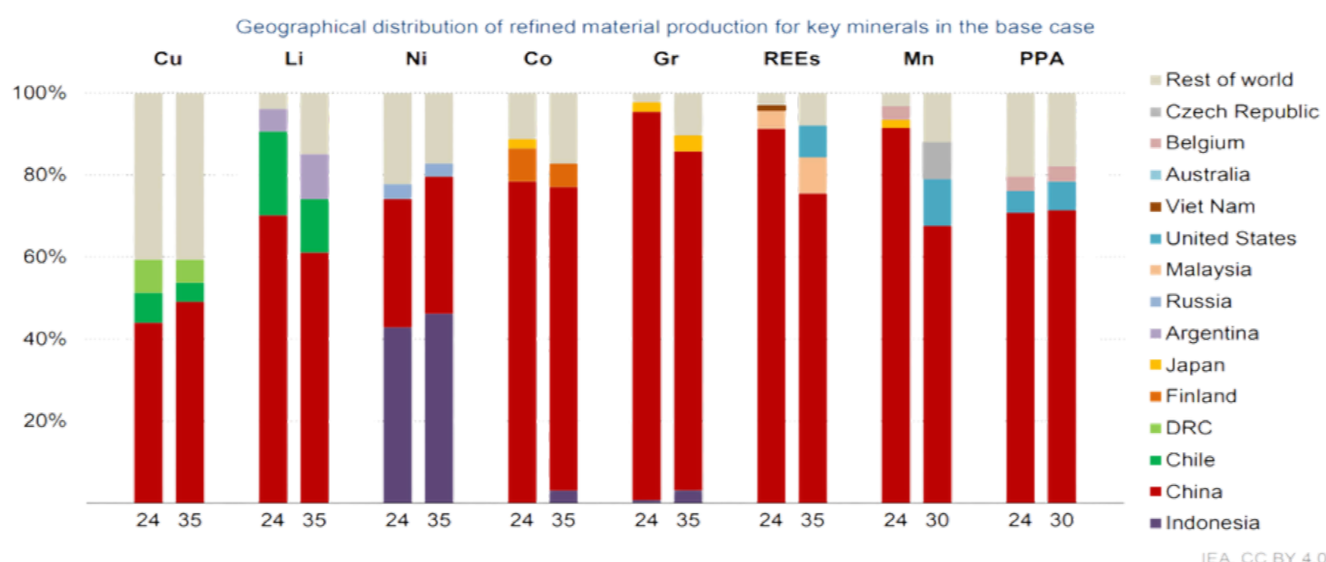
The following paragraphs present infographics and commentary on data published by the International Energy Agency in its annual Global Critical Minerals Outlook [97].

According to the IEA, demand for minerals linked to energy technologies is set to grow rapidly across all scenarios analysed by IEA's reports, driven primarily by the clean energy sector. In the STEPS scenario, demand for lithium is projected to increase fivefold by 2040, while it's expected to double for graphite and nickel. Cobalt and rare earth elements are also projected to rise by 50–60%, and copper—already widely used—is set to grow by 30%. This data refers to the total amount of minerals used across different sectors, such as clean technologies, electronics, aerospace and communications [97]. The spread of electric-vehicle batteries and energy-storage systems fuels demand for lithium, graphite, nickel and cobalt, while the expansion of electric grids and related infrastructure increases the need for copper. The growth of technologies requiring permanent magnets, such as electric vehicles and wind turbines, is driving up demand for magnetic rare earths. However, the projected increase in electric-vehicle sales has recently been revised downward, tempering demand expectations for certain metals—particularly cobalt, which is also affected by the wider adoption of LFP batteries.

With regard to supply projections, estimates are based on a review of announced mining projects, examined across two scenarios: a base case, which includes existing or highly advanced facilities, and a high-production case, which also incorporates earlier-stage but promising projects. Recent announcements indicate a significant expansion in future output, with the combined market value of lithium, copper, nickel, cobalt, graphite and REE expected to grow by 50% by 2040, largely driven by lithium. Latin America leads in mineral extraction thanks to copper, while China remains dominant in refining. Nonetheless, significant supply deficits are expected for copper and lithium by 2035, even under the high-production scenario, due to structural challenges in developing new projects. The outlook for nickel, cobalt and rare earths appears more balanced, though high geographical concentration persists. The identified shortfalls should be considered 'implicit' as higher prices could curb demand or incentivise new projects and recycling. The growing role of LFP batteries also highlights the importance of manganese sulfate and phosphoric acid, suggesting that expanded refining capacity will be necessary (Figure 16).

Figure 16

Geographical distribution of refined material production for key critical materials [97]



Notes: Cu = copper; Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; REEs = rare earth elements; Mn = battery-grade manganese sulphate; PPA = battery-grade purified phosphoric acid; DRC = Democratic Republic of the Congo. The figures for graphite are based on battery-grade including spherical graphite and synthetic graphite. The figures for rare earths are for magnet rare earth elements only. The figure depicts the value of the top three producing countries in a given year.

Note. From *Global Critical Minerals Outlook 2024*, by International Energy Agency, 2024 (<https://www.iea.org/reports/global-critical-minerals-outlook-2024>). CC BY 4.0.

The above chart illustrates near-monopolistic conditions for several critical raw materials. China dominates production with shares that other countries are unlikely to match in the short term.

The Issue of recycling

Considering the likely continuity of well-established, deeply structured, supply chains, it's necessary to take into account an additional variable: the role played by the recycling of materials which completed their initial life-cycle.

Recycling can, in fact, offer significant benefits in terms of security and sustainability of the critical mineral supply. While it cannot fully replace the need for new mining activities, it represents a reliable secondary source that reduces dependence on continued extraction, strengthens security for importing countries, and mitigates the risk of volatility-induced future disruptions. Expanding recycling infrastructure also helps to reduce the environmental and social impact of mining and refining activities, preventing unproductive waste.

By 2040, recycling could reduce the need for new mines by 5% to 30%, and, by 2050, this reduction could reach 35% for copper and cobalt, over 20% for lithium, and 15% for nickel. This would lower mining investments by 30% and reduce greenhouse gas emissions by 80% compared to primary materials [97]. Ensuring secure supply chains requires clear policies, defined targets, and support for national recycling infrastructure. It is also essential to develop industries that use recycled materials, strengthen recycling regulations, improve the collection of batteries, copper, and magnets, and invest in new technologies for recovering and processing mining waste.

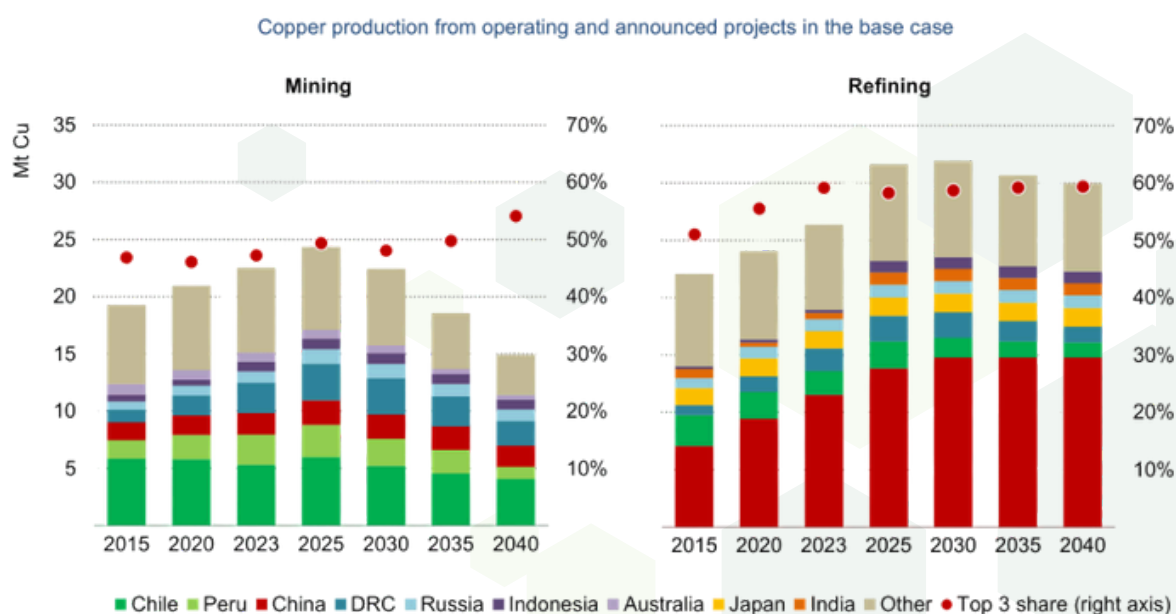
Critical raw materials: a global overview of extraction and refining capacity

Copper

As shown in Figure 17, copper supply remains only partially diversified and continues to display a significant degree of geographical concentration, particularly in refining. While mining output is distributed across several producing countries, a large share is still concentrated in a limited number of jurisdictions, including Chile, Peru, China, the DRC and Russia. Refining is even more concentrated, with China maintaining a dominant role throughout the period considered. Therefore, rather than indicating a balanced supply structure, the chart suggests a supply chain that remains materially exposed to geopolitical, strategic and country-specific risks. Overall, the level of exposure should be assessed as medium to medium-high, rather than medium-low, due not only to concentration itself but also to the political and strategic sensitivity of several key producing and refining countries (Figure 17).

Figure 17

Evolution of copper production (mining and refining)



Note: DRC = Democratic Republic of the Congo.

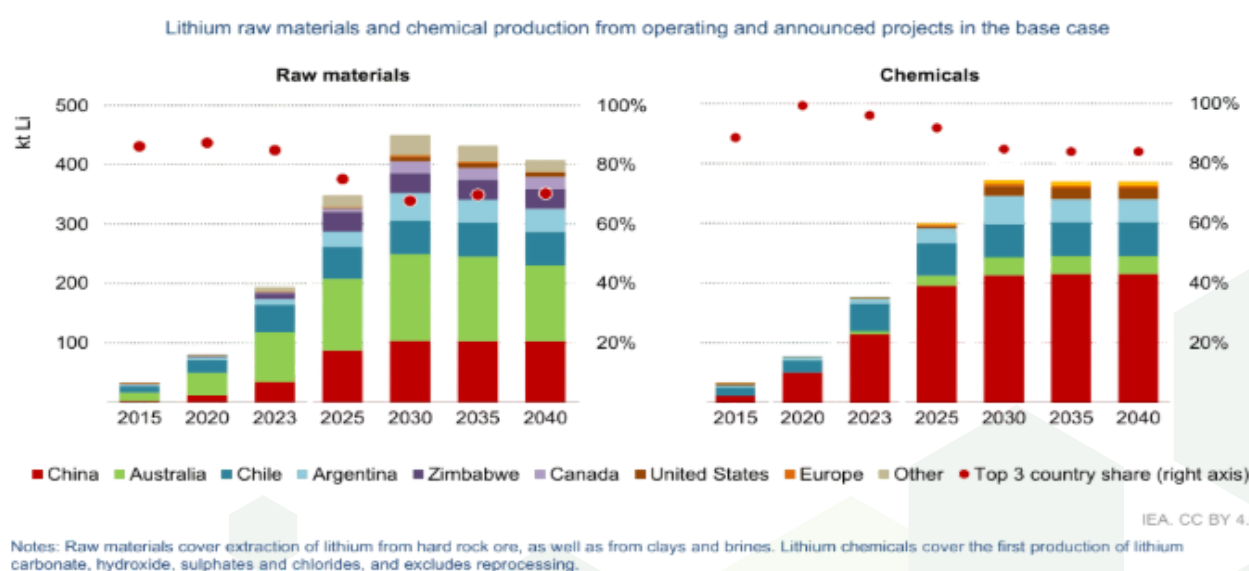
Note. From Global Critical Minerals Outlook 2024, by International Energy Agency, 2024 (<https://www.iea.org/reports/global-critical-minerals-outlook-2024>). CC BY 4.0.

Lithium

In the case of lithium, countries such as China, Australia, and Chile dominate extraction volumes, and, according to IEA projections, these figures are expected to remain largely unchanged over coming years. The overall exposure to geopolitical volatility for the lithium supply chain is medium–high, stemming from the limited diversification of supplier countries and the share distribution of their output (Figure 18).

Figure 18

Evolution of lithium production (from raw material to an added value chemical)



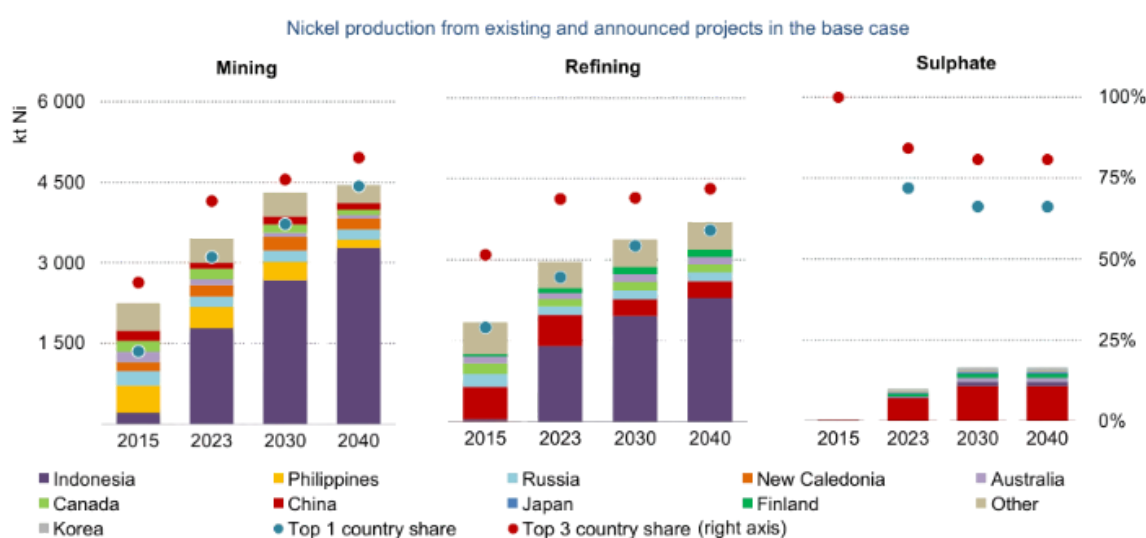
Note. From *Global Critical Minerals Outlook 2024*, by International Energy Agency, 2024 (<https://www.iea.org/reports/global-critical-minerals-outlook-2024>). CC BY 4.0.

Nickel

Indonesia dominates the global nickel supply, and future projections indicate that its share will continue to grow, both in terms of extraction and refining. Nickel is perhaps the only critical metal for which a single country holds such an overwhelming share across most of the value chain. As a result, Indonesia has never been incentivised to improve its extraction and refining technologies, leading to consistent reliance on outdated production processes that are extremely carbon-intensive and highly emissive in terms of CO₂ output. Given the predominance of a single supplier country across the value chain, the nickel supply chain faces a significantly higher susceptibility to volatility-induced disruptions (Figure 19).

Figure 19

Evolution of nickel production (mining and refining)



Note: Nickel refining includes nickel that is processed into either a metal, oxide, nickel pig iron (NPI), or ferronickel and excludes outputs from intermediate production steps. IEA. CC BY 4.0.

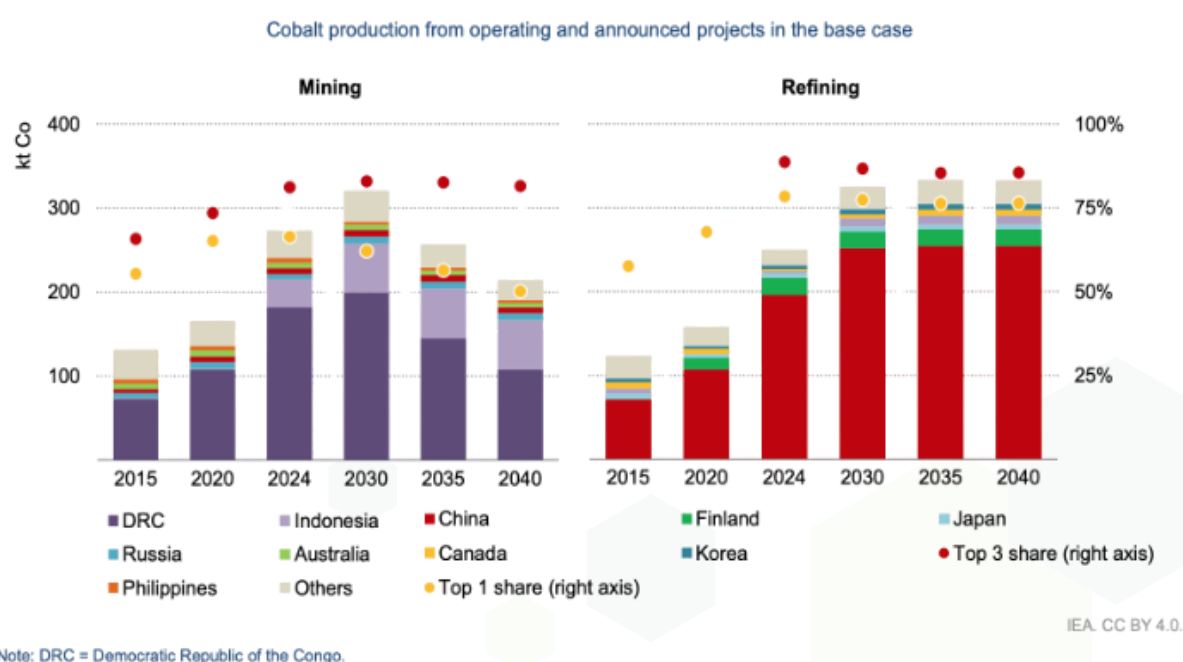
Note. From *Global Critical Minerals Outlook 2024*, by International Energy Agency, 2024 (<https://www.iea.org/reports/global-critical-minerals-outlook-2024>). CC BY 4.0.

Cobalt

As shown in the chart, the current cobalt supply landscape is dominated almost entirely by the Democratic Republic of the Congo (DRC). According to IEA projections, this high level of concentration is expected to diminish over the coming years, driven by growth in Indonesian cobalt mining and by a corresponding reduction in total supply from 2030 onwards. China, however, dominates cobalt refining, a trend that's likely to continue well into the 2040s. In light of a pronounced mining and refining concentration, cobalt is highly susceptible to disruptions, particularly due to supply chain reliance on a fragile state, the DRC, and on China (Figure 20).

Figure 20

Evolution of cobalt production (mining and refining)



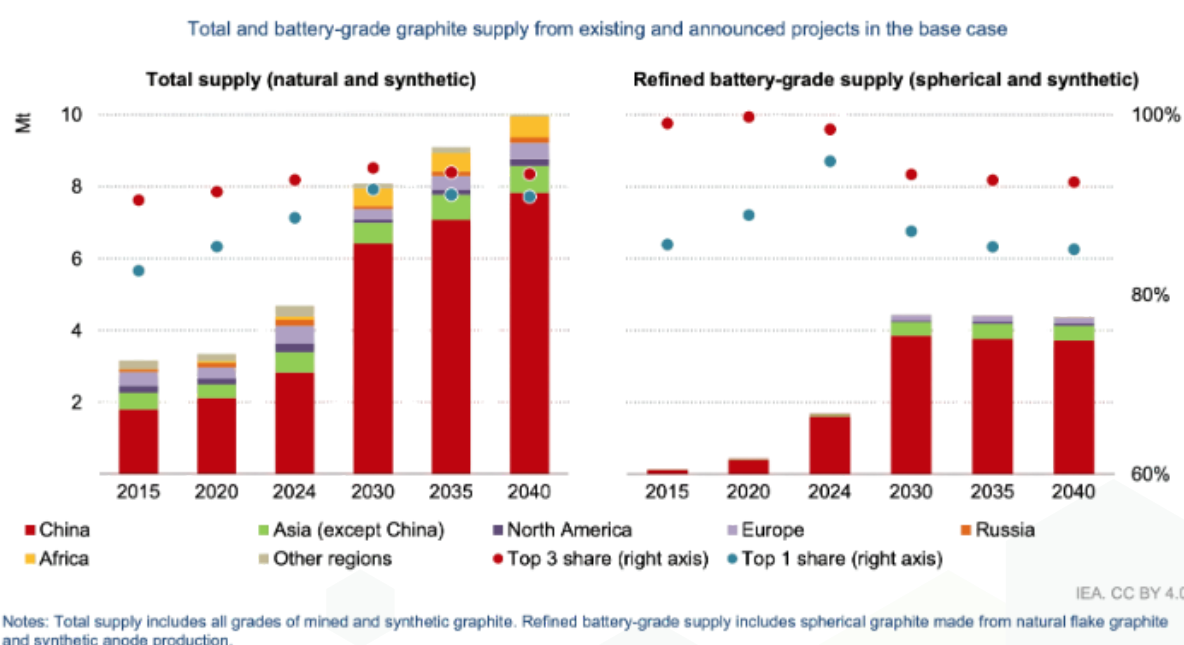
Note. From *Global Critical Minerals Outlook 2024*, by International Energy Agency, 2024 (<https://www.iea.org/reports/global-critical-minerals-outlook-2024>). CC BY 4.0.

Graphite

Figure 21 clearly illustrates China's dominance over the global graphite supply. What sparks concerns for countries across the international landscape is evident from the IEA's analysis: the Asian giant is the leading supplier not only of the raw mineral itself, but also the principal refiner of the components used in battery production. Thus, this elevated level of concentration within the graphite supply chain translates to a significant susceptibility to geopolitical volatility (Figure 21).

Figure 21

Evolution of graphite production (supply and refining)



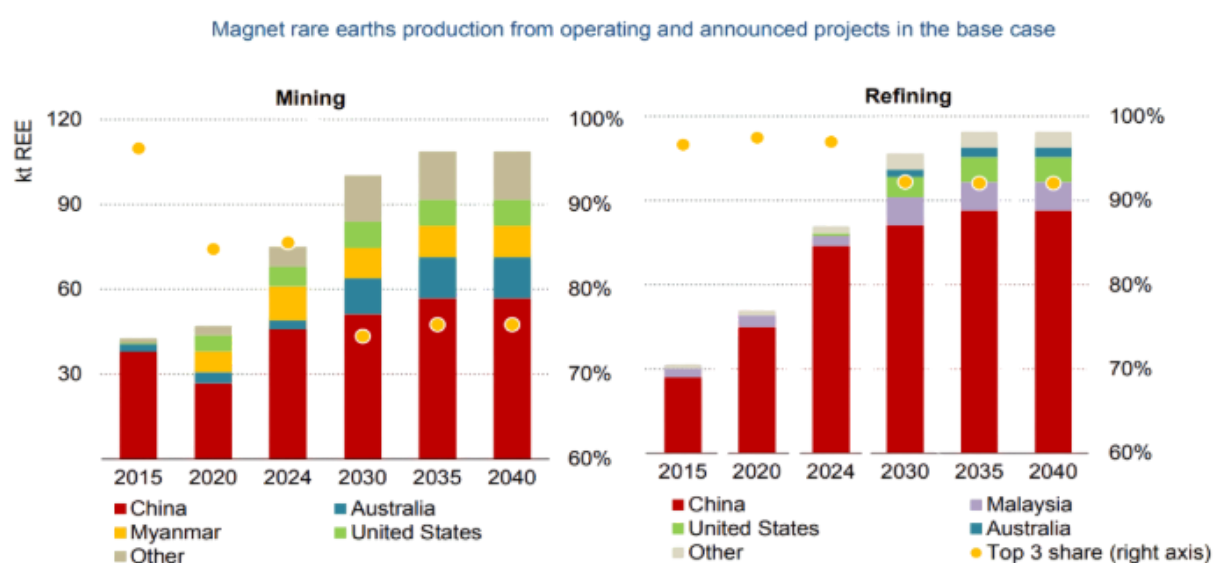
Note. From *Global Critical Minerals Outlook 2024*, by International Energy Agency, 2024 (<https://www.iea.org/reports/global-critical-minerals-outlook-2024>). CC BY 4.0.

Magnet rare earths

As shown in Figure 22, China holds a dominant position in terms of extraction and refining of magnet rare earths. These are especially relevant for the green transition, as they are upstream of multiple crucial technologies; in particular electric vehicles and wind turbines. However, the country's greatest advantage over its competitors lies – and will continue to lie – in its quasi-monopolistic control over the refining of rare earth elements. Although other actors, such as Malaysia, the United States, and Australia, are attempting to maintain moderate diversification of the supply chain, they do so with considerable difficulty. This exposes the magnet rare earths supply chain to a significantly higher risk of resource weaponisation from a single supplier, as well as to susceptibility to geopolitical volatility.

Figure 23

Evolution of magnet rare earths production (mining and refining)



IEA. CC BY 4.0.

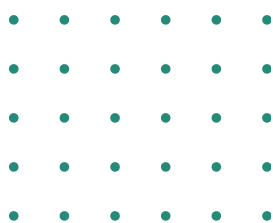
Notes: REE = rare earth elements. The figures are for magnet rare earths only.

Note. From *Global Critical Minerals Outlook 2024*, by International Energy Agency, 2024 (<https://www.iea.org/reports/global-critical-minerals-outlook-2024>). CC BY 4.0.

Critical raw materials: dependencies, vulnerabilities and supply risks

As countries around the world commit to net-zero carbon emission goals, the demand for critical materials such as lithium, cobalt, nickel, copper, and rare earth elements (REEs) has grown exponentially. These materials are essential for manufacturing renewable energy systems, electric vehicles and energy storage technologies. However, this transition comes with significant geopolitical and environmental challenges, as the supply of these resources is concentrated in a few regions of the world, many of which are more susceptible to political, economical and geopolitical disruptions. The economic stability, and potential for successful decarbonisation, of nations without domestic mineral resources is heavily dependent on continued and stable trade with resource-rich countries.

Due to the scale of its green transition, the EU is especially exposed to the risks derived from current supply chain structures. High concentration, particularly when a single country holds a significant share of production and refinement across multiple minerals, poses significant challenges for importers. Supplier nations may shift towards resource nationalism, restricting exports or increasing prices at will, resource weaponisation, leveraging their control over supplies to achieve strategic goals. Recent disruptions in mineral supplies, coupled with growing geo-economic fragmentation, have highlighted the EU's dependence on critical minerals sourced or processed abroad. This reliance poses significant vulnerabilities, including potential threats to economic competitiveness and delays in advancing its low-carbon transition. In March 2024, the European Union introduced the Critical Raw Materials Act (CRMA) to address future challenges related to the mineral supply. This regulation seeks to establish resilient and sustainable supply chains for critical minerals by strengthening domestic capabilities in extraction, processing, and recycling. However, achieving these objectives requires overcoming several obstacles, including the technical and economic feasibility of expanding domestic mining and ensuring public support for such initiatives[84].



The Energy Transition Commission (ETC), in its “Baseline Decarbonisation” scenario [98], highlights concerns regarding the future supply of copper and nickel, suggesting that these resources may not meet growing demand despite efforts to improve efficiency and increase recycling.

Although these challenges might be alleviated by the discovery of new mineral reserves, advancing technological innovation, and enhanced recycling and resource efficiency, they constitute an obstacle in the short-to-medium term. A critical aggravating factor are the lengthy lead times for mineral exploration and extraction, which average around 15.5 years but vary depending on the type of mineral [99]. For instance, while the development of lithium mines is typically faster, copper and nickel mines experience longer lead times due to technical, regulatory, and organisational constraints. Another factor influencing the average lead time for new extraction projects, especially within the EU, is the length of the exploration phase, often coupled with delays in securing financing and obtaining construction permits. Another critical issue is represented by the geographical burden, since many countries don't possess the geological factors required for critical material extraction. As illustrated before, only a few countries retain quasi-monopolistic control over CRMs extraction and refinement, granting them a competitive advantage over alternative suppliers and high leverage with regards to importing countries. More specifically:

- Australia, the DRC and China are key players in global critical material extraction, accounting respectively for approximately 14%, 10% and 25% of the global share [100];
- China is responsible for around 70% of REE and graphite mining;
- Australia contributes about 50% of global lithium extraction;
- The DRC dominates cobalt production, being responsible for over 60% of the global supply.

The concentration of mineral processing becomes even more pronounced at the refining stage. China refines over 40% of the critical materials needed for the low-carbon transition, including 60% of cobalt, manganese, lithium, and up to 95% of REEs. This dominance is attributed to its strategic focus on energy independence and the development of high-tech industries, such as renewable energy, as outlined in its 10-year “Made in China 2025” initiative [101].

Furthermore, China's competitive edge in refining stems from its historically low labour costs and relatively lenient labour and environmental regulations, which have attracted Western companies since the mid-1980s. Through this combined approach, China has successfully acquired foreign technologies, outpaced its competitors, and bolstered domestic production. However, this strategy has also placed a significant ecological burden on the country due to the environmental impact of mining operations.

Russia plays a pivotal role in the global supply of critical materials, particularly nickel, palladium, and aluminium. Nickel is vital to the production of high-performance lithium-ion batteries, which are commonly used in EVs. Russia accounts for approximately 20% of the world's production of Class 1 nickel, the high-purity variety used in batteries [102]. For instance, Russia is a major nickel supplier to Finland, the Netherlands, Ukraine, and China, respectively providing 84%, 34%, 23% and 13% of their total imports. Palladium, widely used in catalytic converters to reduce vehicle emissions, is another critical mineral over which Russia possesses significant control, supplying approximately 40% of the global market [103]. Many countries depend on Russia for a substantial share of their palladium imports, among them Japan (43%), the United States (37%), the United Kingdom (30.5%), China (28.5%), Italy (26%), Germany (21%), and South Korea (20%). Aluminium, a lightweight metal used extensively in the production of several EV components and renewable energy infrastructure, is also one of Russia's key mineral exports. In light of the ongoing Ukraine War, the imposition of sanctions from Western countries caused significant disruptions to Russia's exports, further exacerbating pre-existing supply chain challenges and sparking an increase in price volatility [104]. This forced major economies to search for alternative suppliers, highlighting the risks derived from the overreliance on individual suppliers and low supply diversification (Figure 24).

Figure 24

Different countries role in selected critical material supply chains and associated geopolitical exposure

Material	Russian control share	Main use	Main dependent/importing countries identified	Supplier country posture towards the EU
Nickel (Class 1)	~20% of global Class 1 nickel production/supply	High-performance lithium-ion batteries, especially for EVs	Finland (84%), Netherlands (34%), Ukraine (23%), China (13%)	Russia: adversarial / sanctioned / high geopolitical risk for the EU. EU sanctions against Russia remain in force and have been repeatedly expanded and extended in response to the war against Ukraine.
Palladium	~40% of global market/supply	Catalytic converters for vehicle emissions control	Japan (43%), United States (37%), United Kingdom (30.5%), China (28.5%), Italy (26%), Germany (21%), South Korea (20%)	
Aluminium	~5.3–5.4% of global primary aluminum output	EV components, lightweight structures, and renewable energy infrastructure		

Latin America, and specifically the “Lithium Triangle” (comprising Argentina, Bolivia, and Chile), has emerged as another focal point in the global race for green energy materials. Together, these three countries hold more than half of the world’s lithium reserves, making them indispensable to the production of lithium-ion batteries [105]. Lithium is central to the electrification of transportation and the storage of renewable energy, and its demand is projected to grow exponentially over coming decades. However, from the point of view of supply chain risk, this region presents its unique set of challenges. Governments in the Lithium Triangle are increasingly asserting control over their natural resources. Moreover, the environmental impact of lithium mining, particularly in arid regions, has sparked concerns about water depletion and ecosystem degradation. The environmental footprint of these operations has led to resistance from local communities, complicating efforts to scale up mining operations [106]. The region’s political and economic instability further adds to this uncertainty, as high geographical concentration renders the lithium supply chain more susceptible to sudden shifts in domestic policy.

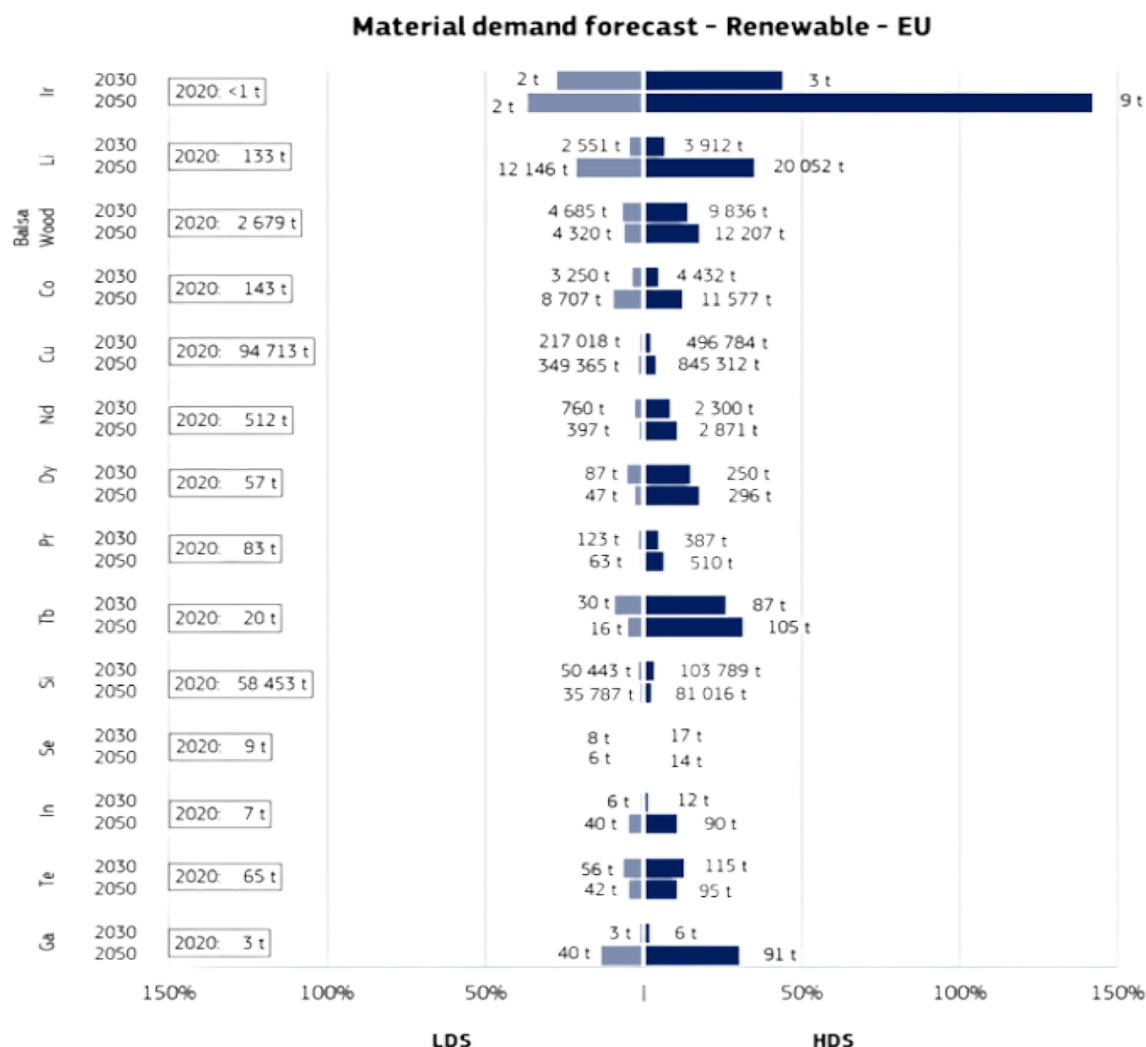
The United States and China are also engaging in an increasingly intense competition for technological dominance in the field of green technologies. China managed to establish itself as a global leader in solar panel manufacturing, battery production, and EV technology, largely through state subsidies and the strategic acquisition of critical materials. In response, the United States sought to counter China’s growing influence through policies such as the Inflation Reduction Act (IRA), which aims to bolster domestic manufacturing of green technologies via subsidies and tax credits [107]. This rivalry has potential broader implications for the global energy transition. As great power competition progressively encompasses the domain of green tech, countries around the world are likely to face pressure to align with either competitor, increasing the risk of global market fragmentation and potentially slowing progress on climate change mitigation worldwide.

In this landscape, the EU is lagging behind in terms of mining and processing capacity of critical materials, rendering the bloc susceptible to the considerable strategic leverage held by supplier countries. Nonetheless, mining activities in Spain, Greece, and Scandinavian nations cannot be discarded, as they collectively account for over 0.5% of the global share. By contrast, the European Union holds a stronger position in mineral refining compared to extraction. For instance, the EU contributes 17% of global cobalt refining, with Finland accounting for 11%, and Belgium and France providing the remainder. The EU also holds a significant position in nickel refining, with 4% of the global supply being processed in Finland, Greece, and France. Finland leads Europe's nickel supply with 38%, followed by Greece with 19% [97].

Despite these achievements, the EU remains highly reliant on imports of critical raw materials, particularly from China, which supplies around 90% of the EU's rare earth elements [100]. While Belgium and Finland together account for 91% of the EU's processed cobalt supply, emerging market economies dominate the mineral processing sector, leaving the EU vulnerable to supply chain disruptions. The EU's ability to secure sufficient critical material supply to meet projected demand is increasingly uncertain, particularly given the recent rise in geopolitical tensions.

Figure 25

Critical raw material demand forecast for clean technologies



Note. Ga = gallium; Te = tellurium; In = indium; Li = lithium; Tb = terbium; Pr = praseodymium; Nd = neodymium; Dy = dysprosium; Cu = copper; Co = cobalt; Se = selenium; Ir = iridium. From *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study* (p. 147), by European Commission, Joint Research Centre, 2023 (<https://publications.jrc.ec.europa.eu/repository/handle/JRC132889>). Copyright European Union.

The two scenarios projected represent varying levels of renewable energy deployment:

- **LDS** (low demand scenario) which assumes slower growth or greater material efficiency in renewables;
- **HDS** (high demand scenario) which assumes rapid deployment and higher material intensity.

In the low demand scenario, more than 100% of the current global supply is required by 2050, while in the high demand scenario this figure shoots up past 500%. Every mineral displayed shows a significant estimated increase in demand, with copper demand potentially rising up to 100.000 tonnes by 2050 (HDS), followed by cobalt, lithium, and neodymium, driven by their function in batteries and wind turbines. Iridium, although smaller absolute quantities are required for clean technologies, is forecasted to face the most dramatic increase, from 1 tonne to 9 tonnes by 2050 (HDS), and it's entirely processed in South Africa.

By 2030, cobalt demand for batteries alone will require almost 60% of the current world supply, while it's projected to decrease to 40% by 2050, partly due to the shift towards more nickel-rich batteries (Figure 24).

Recommended actions for dependency mitigation

The European Union's energy and industrial transition, accelerated by this decade's geopolitical crises and by ambitious 2030 climate objectives, is rapidly shifting the Union from dependence on fossil fuels to a new form of vulnerability; a multifaceted one that's linked to the access and control of critical raw materials and the technologies required for electrification, storage and digitalisation of energy systems. These dependencies risk undermining European energy sovereignty precisely as the Union seeks to strengthen it. The ongoing transformation does not eliminate external constraints but re-structures them on new material and geopolitical foundations, shifting the centre of vulnerability from pipelines to metals, and from gas fields to strategic nodes of global value chains [42] [84] [108].

As of 2024, the EU-27 imported 55% of its primary energy from third countries. Natural gas – although declining after the Ukraine war – remains the main fossil vector for electricity and heat generation, with 300–320 billion cubic metres consumed annually, 40% of which in the form of LNG supplied by the United States, Qatar and Nigeria [3] [12]. Oil, mainly used for transport and the chemical industry, is more than 95% import-dependent, while over 90% of the uranium for European reactors originates from Kazakhstan, Canada, Niger and Russia [109]. Only a marginal share of these supplies is currently covered by domestic production or strategic stockpiles, and the deployment of renewables, though accelerating, is not sufficient to guarantee structural autonomy in the short term [3] [53].

In parallel, a new geography of dependencies is emerging along clean-technology supply chains. The Union imports more than 80% of global refining and processing capacity for critical materials (e.g. lithium, nickel, cobalt, graphite and REEs) from East Asia, particularly China, which accounts for over 80% of global refining activities and roughly 60% of global production of permanent magnets and battery cells. Chile and Australia extract most of the lithium currently available on the global market, while the Democratic Republic of Congo supplies 60% of primary cobalt. Indonesia and Russia dominate nickel supply, while Türkiye and Brazil are emerging as new hubs for boron and light rare earth elements [110]. The World Bank's Worldwide Governance Indicators show that more than 70% of these volumes originate from countries with medium-to-low governance performance and significant political instability, increasing systemic supply-risk exposure for European industry [111].

Projections to 2030, based on the three scenarios analysed — Business as Usual (BAU), Fit-for-55 and Storage Diffusion — outline diverging trajectories of dependence and autonomy. Under the BAU scenario, the reduction in fossil fuel consumption remains fragmented and uneven, while the demand for critical materials grows faster than the EU's capacity to diversify or recycle, due to the absence of foreseeable policies aimed at mitigating technological and mineral dependencies. Imports of lithium could triple compared to 2020 levels, and nickel and cobalt imports could double, with domestic production and refining left unable to compensate. Without new supply agreements and processing facilities located within the EU, dependence on a small number of global actors — particularly China — would deepen. As a consequence, decarbonisation would progress slowly, and the electricity system's Emission Factor would fall only marginally, reaching 270–290 gCO₂e/kWh by 2030, suggesting both persistent vulnerability and the inability to meet the Union's climate commitments [108] [47] [110] [3].

The Fit-for-55 scenario assumes the full implementation of the EU climate policy package adopted between 2021 and 2023, together with complementary frameworks such as the Critical Raw Materials Act (CRMA) and the Net-Zero Industry Act (NZIA). In this scenario, the EU accelerates the phase out of fossil fuels through an unprecedented expansion of wind and solar capacity, supported by streamlined permitting processes, binding targets, and significant public and private investment. The integrated implementation of RED III, CRMA and NZIA produces a moderating effect on demand growth for lithium, nickel, cobalt, graphite and rare earths [14] [84] [112].

Meeting the CRMA targets — at least 10% of extraction, 40% of refining and 15% of recycling to be carried out within the EU by 2030 — does not eliminate structurally higher mineral demand, especially for batteries, heat pumps and electricity networks, but significantly reduces the impact of external dependencies. Demand for lithium and nickel still increases, yet does not reach the tripling projected under BAU: growth stabilises around +150% for lithium and +70–90% for nickel and cobalt relative to 2020, driven by three key factors [84] [110]:

1. **Improved material efficiency** in next generation batteries;
2. **Deployment of alternative chemistries** such as LFP (lithium-iron-phosphate) and sodium-ion technologies, which require no nickel or cobalt;
3. **Commissioning of EU recycling facilities** capable of recovering meaningful volumes of critical metals from 2027–2028 onwards [84].

As a result, Europe's dependence on a restricted number of suppliers— particularly China for graphite and REEs, the Democratic Republic of Congo for cobalt, and Indonesia and Russia for nickel — exposes the continent to increased vulnerability relative to a BAU scenario. CRMA diversification thresholds and new strategic partnerships with Canada, Australia, Chile and Namibia, contribute to lowering the share of refined materials imported from low-governance countries, reinforcing the resilience of European clean-tech value chains [113].

The NZIA strengthens this trajectory by supporting the reshoring of clean-technology manufacturing and by setting the target that at least 40% of the EU's demand for key components — photovoltaic modules, wind turbines, batteries and electrolyzers — be met by production within the Union. Combined with REPowerEU investments, these measures enable substantial photovoltaic deployment, expanded battery manufacturing capacity and the overall growth of domestic renewable-energy technologies [3] [112].

On the electricity side, the combined effect of RED III, the strengthened EU ETS, REPowerEU and NZIA substantially reduces gas use in power generation. In the Fit-for-55 scenario, gas falls by more than 30% compared to pre-pandemic levels, while wind and solar become the dominant energy sources. Fossil-fuel plants are increasingly replaced by storage systems, demand-response solutions, digital flexibility tools and enhanced cross-border grid integration. The electricity system's Emission Factor falls to 150–170 gCO₂e/kWh by 2030 [47] [3] [114].

The Storage Diffusion scenario represents the most advanced pathway. The EU not only expands renewable generation but completes the shift to a flexible, interconnected energy system based on distributed storage, green hydrogen and smart grids. Fossil-fuel dependence declines by more than 40% compared to 2020. This scenario, however, entails a sharp rise in demand for critical materials — +300–400% by 2030 — driven by the increased demand for batteries, inverters and power-electronics components. The pressure on supply chains is partly mitigated by the deployment of LFP and sodium-ion technologies and by the expansion of EU recycling capacity, which begins supplying increasing volumes of domestically recovered lithium, graphite and rare earths [110].

The EU's 2030 strategy to reduce energy and mineral dependencies requires a coordinated set of interventions targeting international supply chains, domestic industrial capacity, and innovation aimed at reducing exposure to risks linked to the critical materials supply.

The first axis concerns geographic diversification of supply, supported by industrial and mining diplomacy with countries characterised by higher governance performance. Strategic partnerships with Canada, Australia, Chile and Namibia reinforce access to sustainable lithium, nickel, copper and REEs, integrating trade agreements, industrial cooperation, technology transfer and ESG obligations across entire value chains. The CRMA's requirement that no single third country may account for more than 65% of supply of any critical raw material establishes binding diversification thresholds and sets extraction, refining and recycling targets within the Union [84] [112].

The second axis concerns rebuilding European industrial capacity across clean-technology value chains. The NZIA target – 40% of demand for low-carbon technologies to be met by EU manufacturing by 2030 – is supported by initiatives such as the European Battery Alliance and the Solar PV Industry Alliance, which aim to strengthen European manufacturing, attract private investment, and expand value chains in power electronics, intermediate materials and magnetic components. The Commission also supports mining and refining projects in Member States such as Sweden, Finland, Portugal and Spain [112].

The third axis concerns innovation and circular-economy measures aimed at reducing material intensity. Advanced recycling of batteries, photovoltaic modules and electronic equipment is central: up to 15% of lithium and nickel demand may be met by recycled sources by 2030. The introduction of the digital product passport and new ecodesign requirements enhance traceability, reparability and reuse of strategic components. Complementary tools include sustainable-finance mechanisms, strategic stockpiles of materials and fuels, EU guarantee funds and blended-finance instruments – including those managed by the EIB – to support high-risk projects in third countries. Regulatory measures such as the Carbon Border Adjustment Mechanism and mandatory ESG clauses in public procurement help ensure that supply-chain expansion remains compliant with environmental and social standards. Incorporating WGI governance metrics into procurement decisions further aligns supplier-country governance quality with economic and security considerations [108].

Energy-system flexibility – via more than 200 GWh of storage capacity expected by 2030, demand-response markets, electrification of end-uses, deployment of advanced biofuels and heat pumps and gradual substitution of peaking gas plants – plays a complementary role. With regards to nuclear energy, supply-security measures for uranium include long-term agreements with Canada and Australia and the creation of EU-level fuel stockpiles to reduce reliance on post-Soviet supply routes [109].

Digital infrastructure, resource security and geopolitical exposure

Digitalisation: smart grids and higher cyberattack risk

The European energy grid is interconnected and inter-reliant. Nonetheless, joint crisis management among EU countries and efficient regional grid integration is lagging behind [119].

To make up for these pitfalls, the EU is pursuing the establishment of smart grids. Smart grids are modern systems with bidirectional electricity flows, which enable new functionalities and applications compared to the older one-way flows of energy [120]. Innovatively, smart grids can integrate intermittent electricity produced by wind and solar power plants, while linking decentralised smallholder energy producers, such as domestic photovoltaic rooftops and community-scale wind farms [121]. These shifts from the historical one-point-source energy production in centralised plants, unidirectionally flowing to domestic and business consumers, require a remarkable redesign and upgrade to transmission and storage technologies. Such infrastructural investments must proceed simultaneously with the transition from fossil-based to renewable energy production.

In this context, high-voltage and subsea power cables become a strategic enabling technology for both energy security and system reliability. Here, European private manufacturers occupy a leading position. In 2025, Prysmian reported €3.262 billion in Transmission revenues and a backlog exceeding €17 billion, with 88% of its Transmission sales concentrated in EMEA; Nexans recorded €1.657 billion in PWR-Transmission sales and a €7.7 billion adjusted backlog, largely driven by subsea interconnection and offshore wind projects; and NKT reported a €10.2 billion high-voltage order backlog, around 95% of which was linked to large European TSOs. Taken together, Prysmian, Nexans and NKT accounted for around 60% of global submarine power cable capacity in 2025, indicating that their leadership is primarily European in industrial base, but also highly significant worldwide in the strategic subsea and HV/HVDC cable segment. [120] [122] [123] [124].

Meanwhile, upscaling the EU's electricity storage facilities exposes the block to significant strategic risks related to the pronounced concentration of lithium-ion battery production. Namely, China manufactures over 70% of batteries sold worldwide, at prices that are 30% and 20% cheaper compared to those produced in Europe and North America respectively [125].

As a response, the EU is seeking to strengthen domestic battery manufacturing capacity through a combination of demand-side regulation, trade-defence measures, state aid approved under the EU framework, and public financing. Regulation (EU) 2019/631, which sets CO2 emission performance standards for new passenger cars and vans, supports the uptake of zero-emission vehicles and thereby indirectly increases demand for batteries. In parallel, the European Commission imposed definitive countervailing duties on imports of battery electric vehicles from China in October 2024, while battery production in the Union has also been supported through Member State aid schemes and EU-approved industrial initiatives such as the battery IPCEIs. According to the Commission, the two approved IPCEIs in the battery value chain involve 59 companies across 12 Member States, with up to €6.1 billion in State aid expected to mobilise more than €13.8 billion in private investment. In addition, the EIB Group increased its overall financing ceiling to €100 billion for 2025, and its 2025 activity included a record €11.6 billion in financing for European grids and storage. Foreign direct investment has also contributed to the expansion of battery manufacturing in Europe, notably from South Korean firms and, increasingly, Chinese market players.[126][127].

The fault lines of digitalised power grids stem not only from uneven development across Member States, but also from the way digitalisation itself expands the cyber risk surface. Smart grids rely on a much denser digital architecture than traditional power systems, including smart meters, sensors, automated substations, distributed energy resource management systems, remote-control platforms, and data exchanges between operational technology (OT) and information technology (IT) environments. While these features improve flexibility and allow the system to integrate intermittent renewables and decentralised producers, they also multiply potential entry points for malicious actors. In practice, cyberattacks may occur through compromised remote access tools, insecure software updates and third-party supply chains, vulnerabilities in connected devices, or the exploitation of legacy infrastructure that remains insufficiently protected but is now linked to more digitalised systems.

This is particularly problematic in an interconnected European grid, where disruptions can have cross-border consequences and where interoperability often depends on a patchwork of systems with uneven levels of cybersecurity maturity. In response, the EU has sought to harmonise minimum standards and crisis-management procedures. The Network Code on Cybersecurity for the electricity sector entered into force on 13 June 2024, establishing a common framework for cyber risk assessment, minimum requirements, monitoring, reporting, certification, and crisis management for cross-border electricity flows. However, implementation remains uneven, since the sector-specific framework relies in part on the broader institutional and supervisory architecture created by the NIS2 Directive, whose transposition was still incomplete in a significant number of Member States as of 2025. To strengthen coordination during large-scale incidents, the EU also relies on EU-CyCLONe, the European cyber crisis liaison organisation network, which was formalised under NIS2 and operates at the operational level between technical response and political coordination.[128][129][130]

Other potential changes to the status quo

The intensification of geopolitical competition over energy and strategic resources is increasingly evident as of early 2026, most notably due to the U.S.' military operations in Venezuela. Following a significant escalation in Washington's involvement in Venezuela's oil sector, U.S. policymakers signalled a general recalibration of national energy strategy towards reaffirming hydrocarbon resources as geopolitical leverage tools alongside ongoing national commitments to decarbonisation [145]. Such actions reflect broader great-power competition over access to energy and critical materials, where control over resource flows and supply chains is viewed as central to national security and power projection. This pivot amplifies the risk that energy policy will be subordinated to geopolitical competition, potentially encouraging analogous behaviour by other states seeking to secure a strategic advantage.

In East Asia, energy security intersects with military and cyber domains in the context of cross-Taiwan Strait tensions. Disruption risks to energy and infrastructure networks are underscored by a marked rise in cyber operations targeting critical systems in Taiwan [146], including its electrical grid; phenomena that illustrate the increasing vulnerability of digitised energy infrastructure to state-sponsored or proxy cyber threats.

The Arctic region exemplifies these intersecting pressures. Rapid warming in the Arctic - where temperatures are rising at multiples of the global average - has reduced sea-ice extent, thereby exposing substantial deposits of hydrocarbons, natural gas, and critical minerals such as rare earth elements outside of traditional supply chains. According to geological surveys, vast quantities of undiscovered conventional oil and gas lie beneath Arctic continental shelves, and Greenland—an autonomous territory of the Kingdom of Denmark - hosts some of the largest rare earth element deposits globally (e.g., Kvanefjeld, Tanbreez), alongside other strategic minerals vital for clean energy technologies and defence manufacturing. While extraction remains technically and environmentally challenging, melting ice and evolving market dynamics are increasing its economic plausibility [147].

Major powers' Arctic strategies diverge: the United States and Russia explicitly prioritise national strategic interests in resource access and military posture, whereas the European Union emphasises regulatory cooperation and conflict avoidance in regional governance [148]. China, even though not an Arctic coastal state, asserts itself as a “near-Arctic state” with interests in shipping, research, and resource participation - positions that are contested by Arctic littoral states [149] on legal and geopolitical grounds.

Greenland's growing strategic value stems from its resource potential and location astride emerging northern maritime corridors, making it a focal point of external interest. Its mineral wealth and geographic position offer both economic opportunity and leverage in broader Arctic geopolitics, but also raise complex questions about sovereignty, indigenous rights, and environmental governance [150].

To face possible threats to the status quo of Greenland, multiple presidents of NATO nations have released a joint communication (Joint Statement on Greenland), stating the capital importance of maintaining a conduct aligned with the UN Charter including sovereignty, territorial integrity and the inviolability of borders [151].

4. The price of the energy transition: market analysis and social consequences

Analysis of the current energy market structure & its resilience

The current structure of the European electricity market is the result of a long process of liberalisation, integration and regulatory harmonisation, centred on marginal pricing, cross-border coupling and competition among generators. This architecture has proven effective in normal conditions, enabling efficient dispatch, price convergence across interconnected markets and the rapid integration of renewable generation. However, recent shocks have exposed both its strengths and its structural fragilities. The energy crisis of 2021–2022 demonstrated that while market integration enhances resilience by allowing cross-border optimisation and mutual support among Member States, it also transmits price volatility rapidly across the system, amplifying the impact of supply disruptions and fuel price spikes. In this context, resilience is not defined solely by the ability to maintain physical supply, but by the capacity of the market to absorb shocks without generating destabilising price signals or undermining social and political acceptance.

From a structural perspective, the EU electricity market remains highly sensitive to marginal fossil fuel technologies, particularly natural gas, which continues to set prices during peak demand and periods of low renewable output. This exposure creates a disconnect between the falling average Emission Factor of the system and the persistence of high marginal prices, especially in scenarios characterised by limited flexibility. As a result, decarbonisation alone does not automatically translate into price stability. Market resilience increasingly depends on the deployment of flexibility mechanisms—such as energy storage, demand-side response and enhanced grid interconnections—that reduce reliance on fossil-based marginal generation and dampen price volatility. Where these mechanisms are insufficiently developed, the market structure remains vulnerable to external shocks, even in the presence of high renewable penetration.



Institutionally, the European market has shown adaptive capacity through temporary interventions, including emergency price caps, revenue clawbacks and coordinated gas storage obligations. While effective in stabilising short-term outcomes, these measures also highlight the limits of a purely market-based response in times of systemic stress. Long-term resilience therefore requires a structural evolution of the market design, aligning price formation more closely with the underlying decarbonised cost structure of the system. This implies a gradual shift from a market dominated by energy-only pricing and fossil marginality towards a hybrid framework that values flexibility, capacity adequacy and system services alongside energy production. In this sense, the resilience of the European electricity market is no longer a static attribute, but a dynamic property that depends on the coherence between market design, decarbonisation pathways and the governance of social and economic impacts.

Case studies

The European electricity market's marginal pricing structure, while effective for integrating renewables under normal conditions, reveals both vulnerabilities and adaptive potential amid high penetration of intermittent generation. Recent shocks, such as the 2021–2022 energy crisis, underscored how cross-border coupling transmits volatility yet enables mutual support, redefining resilience not merely as physical supply continuity but as the capacity to absorb shocks without destabilising prices or eroding social acceptance of the energy transition.

Best case

In this evolving context, best-case scenarios like Spain's Iberian market exemplify dynamic resilience, where accelerated renewable deployment—over 40 GW of solar and wind were deployed since 2019—generates frequent zero or negative wholesale prices without compromising system stability, thereby decoupling costs from fossil fuels and signalling the need for increased grid flexibility [152]. As mentioned above, Spain's electricity market has emerged as a notable best-case scenario for the energy transition, driven by the significant and rapid deployment of renewable energy, particularly solar photovoltaic (PV) and wind generation.

The Iberian market frequently experiences zero or negative wholesale prices in the day-ahead market, a phenomenon attributable to renewable output outpacing demand and to limited storage capacity [153].

In 2025, Spain recorded more than 500 hours with prices at or below zero, a historic level reflecting the extraordinary growth of intermittent generation alongside ongoing flexibility constraints. This pattern illustrates the low marginal cost of renewable generation within the Iberian footprint and the European marginal pricing mechanism, wherein the price is set by the most expensive resource needed to meet demand. When abundant solar or wind energy is available at low cost, the marginal price can dip into negative territory, effectively signalling to producers that supplying electricity can carry a payment to inject power into the grid. Negative prices thus function as market signals of oversupply and restricted flexibility, underscoring both the high penetration of renewables and the urgent need for enhanced demand response and storage solutions.

Contextualising these price dynamics, negative wholesale prices are not indicative of a market failure but rather reflect pronounced renewable generation capacity and the structural characteristics of the European electricity market. The low or negative day-ahead prices reduce exposure to fossil-fuel volatility and offer competitive advantages to energy-intensive sectors, contributing to Spain's positioning as a European leader in decarbonisation. However, it is important to acknowledge the policy and investment implications: persistently low or negative prices can pressurise producer profitability and invite calls for reform aimed at sustaining investment in further renewable capacity and in flexibility infrastructure, including energy storage and demand-side participation.

Retail and consumer implications add further nuance. Although wholesale price reductions may seem beneficial for households, the translation of wholesale dynamics to end-user bills is mitigated by regulated tariffs and grid charges, which can dampen the pass-through of lower wholesale costs to retail prices. This disconnect highlights the need for coherent retail market design and consumer-side signals that align incentives with system-wide flexibility needs. Nonetheless, Spain's experience provides a valuable empirical case of how a renewables-heavy electricity system can maintain supply security during periods of oversupply, while simultaneously revealing the market design and infrastructural adaptations required to sustain resilience and equity in the energy transition.

Worst case

By contrast, recent developments in other major European electricity markets illustrate worst-case dynamics, where structural dependencies and limited flexibility translate renewable variability or supply disruptions into sharp price spikes and heightened systemic stress. Germany provides a salient example. Despite its leading role in renewable deployment, the German power system remains highly exposed to periods of low wind generation (*Dunkelflaute*), during which gas- and coal-fired plants are required to set the marginal price. In several episodes between 2022 and 2024, prolonged low-wind conditions coinciding with high demand led to extreme wholesale price surges, with day-ahead prices reaching exceptionally high levels [154]. These events highlighted how insufficient short-term flexibility, combined with continued reliance on fossil marginal generation, can rapidly transform meteorological variability into market volatility, even in systems with substantial installed renewable capacity [155].

A different, but equally instructive, worst-case scenario emerged in France, where structural dependence on nuclear power—traditionally a source of low-cost and stable electricity—became a vulnerability during periods of widespread reactor outages. In 2022, extensive maintenance requirements and unexpected technical issues forced the temporary shutdown of a significant share of the French nuclear fleet, sharply reducing baseload availability. France consequently shifted from being a net exporter of electricity to a net importer, increasing pressure on interconnected markets and contributing to higher prices across neighbouring countries [156]. This episode underscored that low-carbon generation alone does not guarantee resilience if system reliability depends on a limited number of large, inflexible assets without sufficient redundancy or backup options.

Taken together, the German and French cases show how different structural weaknesses—intermittency without adequate flexibility in one case, and concentration risk in baseload capacity in the other—can produce similar outcomes in terms of price instability and systemic stress. Unlike the Spanish case, where oversupply manifests through negative prices, these worst-case scenarios demonstrate how supply constraints and inflexibility amplify marginal pricing effects, exposing consumers and industry to sudden and severe cost shocks. From a policy perspective, these experiences reinforce the conclusion that market resilience depends less on the generation mix itself than on the availability of flexibility mechanisms, diversification of supply, and the ability of market design to absorb shocks without transmitting extreme price signals to end users [157].

Market shocks, institutional resilience and social instability: the role of institutional response

Social disorders and market fluctuations

Over the past twenty years, in more than forty countries, sudden increases in energy prices, changes to subsidy schemes, tensions along food supply chains, or regulatory inefficiencies have triggered episodes of social instability which, despite differing in intensity and duration, share a common structural feature: when economic shocks are not effectively governed, they rapidly erode the relationship of trust between citizens and institutions and amplify pre-existing dynamics of contestation [158] [159]. The comparative analysis of the selected cases—from Mozambique to Chile, from Iran to France, and up to more recent episodes in Eastern Europe—shows that even relatively moderate changes in the prices of essential goods can act as catalysts for widespread mobilisations, particularly in contexts characterised by limited institutional capacity or already weakened public trust [160].

To assess these contexts, the analysis draws on internationally recognised indicators of institutional quality and political-administrative stability, in particular along the dimensions of *Government Effectiveness*, *Political Stability and Absence of Violence*, and *Rule of Law* of the World Bank's Worldwide Governance Indicators (WGI) [113]. The cases examined clearly indicate that market shocks generate markedly different social outcomes depending on pre-existing levels of institutional resilience, regardless of the democratic or authoritarian nature of the political system [161].

The statistical analysis confirms this pattern. It is not the economic magnitude of the shock that explains the emergence of social unrest, but rather the ability of the political system to respond in a timely and predictable manner. Among all the variables considered—shock intensity, duration of instability, and whether price increases are direct or indirect—the most relevant and statistically significant factor is the time required to plan policy countermeasures. Each additional day of decision-making uncertainty systematically increases the likelihood that latent social tension evolves into more structured and persistent forms of social conflict, understood here not as armed conflict, but as widespread protests, urban disorder, and crises of public legitimacy [162] [163].

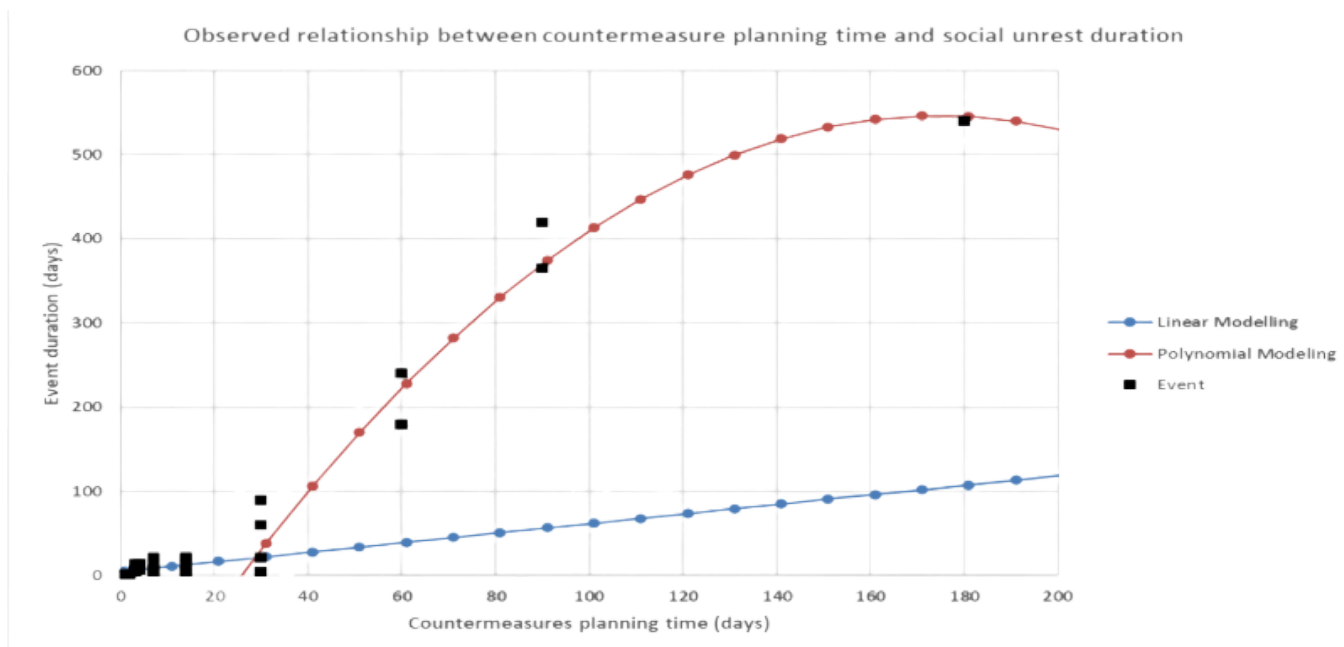
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Figure 26

Critical raw material demand forecast for clean technologies



Note. Graph created by the author. Data compiled from [199] to [238].

A closer inspection of the empirical relationship between response timing and unrest duration further refines this finding. When the time required to plan and deploy countermeasures remains below approximately thirty days, as in the cases of the 2016–2017 fuel crisis in South Sudan, the 2018 fuel price surge in India, and the 2019 gasoline price increase in Iran, where prices rose by up to threefold, the duration of social disorder follows an essentially linear pattern: delays are associated with proportional and relatively contained extensions of unrest. In this phase, mobilisation remains fluid and reversible, and institutional intervention—although not immediate—can still effectively prevent escalation. Beyond this threshold, however, the relationship changes qualitatively. Once the planning horizon exceeds roughly thirty days, unrest duration no longer increases linearly but follows a second-degree polynomial pattern, characterised by a rapid and non-proportional escalation. In this regime, even marginal additional delays are associated with sharp increases in the persistence of social disorder, suggesting that unrest has shifted from an episodic to a structurally entrenched condition (Figure 26).

This non-linear dynamic is clearly illustrated by the empirical distribution of cases, where observed episodes cluster along a linear trajectory only up to the initial response window, while diverging sharply thereafter. The existence of this tipping point highlights that delayed responses do not merely prolong unrest but fundamentally alter its nature, making it more resistant to corrective measures and significantly more costly—politically, socially, and economically—to resolve.

The model further reveals the absence of a significant correlation between the apparent severity of the economic shock—such as fuel price hikes or subsidy removal—and the scale of the social response. Shocks of comparable economic intensity have produced very different outcomes depending on the promptness, clarity, and credibility of the institutional response [164].

In this context, credibility should not be interpreted as an abstract or subjective perception, but rather as an observable combination of three elements: consistency of policy measures over time, predictability of public action, and the ability to clearly communicate the objectives, duration, and limits of the adopted interventions [165].

These findings point to a clear implication for government action: market shocks are not merely economic events, but politically sensitive moments in which the relationship between institutions and citizens is redefined [166]. There is no objective price threshold beyond which societies automatically react, but there is always a threshold of institutional trust below which even limited increases become socially unsustainable [159] [167]. The capacity of public authorities to respond—promptly, through pre-established instruments, and supported by coherent communication—represents today one of the main determinants of social stability in the face of energy and food price shocks [165] [162].

In a geopolitical context marked by market volatility, tensions along global value chains, and increasing exposure to climate-related shocks, strengthening mechanisms for prevention and rapid response is not merely a technical measure, but a strategic choice for institutional resilience [161] [168]. Empirical evidence shows that social stability does not depend on the size of the shock itself, but on the capacity of governments to govern its timing, expectations, and distributional impacts [162] [159].

A comparative analysis of economic shocks and social instability – case studies

To deepen the comparison, it is useful to look inside each case and trace how an economic shock does (or doesn't) translate into political instability through a recurring sequence: the policy decision itself, its social perception, the institutional response, and the subsequent trajectory of conflict. Comparative research shows that shocks to the prices of essential goods rarely operate in isolation; instead, they interact with pre-existing levels of political trust, state capacity, and social inequality, often acting as catalysts rather than root causes of mobilisation [169] [170].

In Mozambique, the increases in the prices of bread, fuel, and public transport between 2008 and 2010 (also known as “pão caro”) were not merely the result of market fluctuations. Rather, they stemmed from a combination of structural vulnerabilities: heavy dependence on food imports, currency depreciation, and external pressure to rationalise subsidy schemes [171] [172]. Government decisions were taken in a largely technocratic manner and presented as unavoidable, with little efforts to explain their underlying causes or to anticipate their distributive consequences. In urban areas, where incomes are fully monetised and spending on essential goods absorbs a substantial share of household budgets, price increases were experienced as an immediate threat to subsistence, not just an erosion of household spending [173]. The absence of effective institutional channels of mediation, given the country's weak trade unions, poorly representative political parties, and marginal local administrations, allowed discontent to escalate rapidly into widespread violence. The state's response, initially centred on repression and only later followed by the partial reinstatement of subsidies, reinforced a vicious circle: mistrust predated the shock but was ultimately crystallised by its mismanagement. Mozambique thus represents a “**worst-case**” scenario in which the shock not only triggers instability but also exposes and deepens a structural rupture between the state and society [174].

The Iranian case follows a different path but leads to a similarly corrosive outcome in terms of trust. In 2019, a sharp increase in fuel prices was introduced abruptly, without prior notice or public debate, despite the fact that cheap energy has long been a highly symbolic element of the redistributive bargain between the Iranian State and its citizens [175]. Against the backdrop of economic sanctions, high inflation, and growing inequality, the measure was widely interpreted as a signal that the State was no longer willing to shield households from declining purchasing power [176] [177].

Unlike Mozambique, Iran possesses strong coercive capacity, which allowed protests to be contained relatively quickly. Yet it was precisely this reliance on a purely securitised response that transformed an economic adjustment into a deeper crisis of legitimacy. The absence of credible compensatory mechanisms from the institutions and the closure of the information space (which included shutting down the internet), prevented any recomposition of the conflict, instead accumulating latent resentment. In this case, the shock did not result in prolonged visible instability but contributed to a quieter, more insidious erosion of trust, with potentially more destabilising effects over the long term [178].

The comparison is completed with France, which can be read as a “best-case” scenario despite the intensity and duration of social tensions. The increase in fuel taxes that sparked the Gilets Jaunes movement was part of a broader climate transition strategy, yet it was perceived as misaligned with the actual distribution of costs and benefits of environmental policy [179]. Rural and peri-urban areas, more dependent on private vehicles and less well served by public infrastructure, interpreted the measure as further evidence of a growing distance between decision-making elites and ordinary citizens [180]. What sets France apart is not the absence of protest, but the quality of the institutional response. The suspension of the measure, the introduction of compensatory policies, and the opening of deliberative spaces made it possible to partially rebuild trust and to channel conflict back into institutional arenas [181]. Protest did not disappear, but it was contained within a framework that prevented systemic crisis.

Taken together, these cases show that shocks to the prices of essential goods operate as stress tests of the social contract. Where the relationship between State and citizens is already fragile, shocks accelerate fragmentation; where it is contested but still negotiable, they may open space for reform; and where institutions are robust and responsive, they can even strengthen a system’s adaptive capacity [169] [182].

From this perspective, the distinction between best and worst case outcomes does not lie in the presence or absence of conflict, but in whether the shock is politically governed rather than merely endured or repressed.

Mitigation of the economic and social consequences of the transition

Ongoing EU initiatives

As of early 2026, the European Union has decisively moved beyond the reactive "emergency phase" triggered by the 2022-2023 energy crisis. The current regulatory landscape is characterised by a transition from crisis management to the structural implementation of the Green Deal. This consolidation focuses on three strategic pillars: ensuring long-term price stability for consumers, fostering a competitive "net-zero" industrial base, and accelerating the deep decarbonisation of the building and gas sectors. Listed below are the European initiatives in the energy field.

The structural reform of the electricity market

A cornerstone of this transition is the full-scale implementation of the Electricity Market Design (EMD) Reform in 2024. In 2026, Member States are focused on transposing these rules to decouple consumer prices from the short-term volatility of fossil fuel markets. By introducing a universal right to fixed-price contracts and establishing "supplier of last resort" schemes, the EU is institutionalising social protection against future energy shocks.

Furthermore, the concept of Energy Sharing is poised to become a reality starting from the July 17th 2026 deadline. This regulatory shift allows "active customers" to share renewable energy directly, bypassing the administrative complexities previously associated with energy communities. To support this decentralised production, the EU is simultaneously promoting Power Purchase Agreements (PPAs) and mandatory two-way Contracts for Difference (CfDs). These instruments are designed to provide renewable energy producers with revenue certainty while ensuring that industrial off-takers benefit from lower, predictable energy costs. [183] [184] [185]

Decarbonising the gas grid and the hydrogen backbone

In parallel with electrification efforts, the EU is aggressively pursuing the Hydrogen and Gas Decarbonisation Package. The primary objective in 2026 is to create a regulated market for hydrogen that mirrors the transparency and competition of the natural gas sector. Central to this effort is the establishment of the European Network of Network Operators for Hydrogen (ENNOH), which serves as the architect for a dedicated European hydrogen backbone.

To ensure market integrity, the EU has enforced strict unbundling rules, separating production and supply from network operation. Concurrently, the integration of biomethane is being fast-tracked. By reducing cross-border tariff barriers and subsidising connection costs—up to 70% in several Member States—the Union is leveraging existing infrastructure to meet the ambitious REPowerEU targets for renewable gas injection. [186] [187] [188]

Europe's building stock: renovation, solar integration and fossil heating phase-out

The residential and commercial sectors are undergoing a significant overhaul under the Energy Performance of Buildings Directive (EPBD IV). Following the submission of draft plans in late 2025, 2026 has become the "year of dialogue" between national governments and the European Commission to finalise National Building Renovation Plans (NBRP). These plans, due by year-end, will dictate the pace of renovation for the next decade. [189]

Key milestones in 2026 include the prohibition of subsidies for stand-alone fossil fuel boilers and the activation of the Solar Mandate. This mandate requires solar energy installations on all new public and large-scale non-residential buildings, signaling a shift towards a new role of buildings as active energy hubs. These measures are foundational for the long-term goal of a complete fossil fuels phase-out for heating by 2040. [190] [191]

Strategic autonomy and the role of the "Clean Industrial Deal"

The 2026 agenda is heavily influenced by the Clean Industrial Deal, an initiative designed to marry climate goals with industrial competitiveness. Through the Net-Zero Industry Act (NZIA), the EU is streamlining permitting processes for strategic technologies such as batteries, heat pumps, and next-generation nuclear power. The ambition is clear: to ensure that at least 40% of the Union's clean tech needs are met by domestic production.

This industrial push is supported by the newly established European Industrial Decarbonisation Bank, which provides the necessary capital for energy-intensive sectors (steel, chemicals, and cement) to transition to hydrogen or electrified processes. This is complemented by a temporary simplification of State Aid rules, allowing Member States to respond to global competition without fragmenting the Single Market. [192] [193] [194]

The 2040 horizon and infrastructure resilience

Extending the strategic horizon beyond the benchmarks established for 2030, the European Union delineated a preliminary institutional consensus regarding the achievement of a 90% net greenhouse gas (GHG) reduction by 2040. This target serves as a primary regulatory orientation for current legislative calibrations, including the preparatory stages for the introduction of the ETS 2 system. Scheduled for implementation in 2028, the expansion of the emissions trading scheme to the building and transport sectors is systematically integrated with the operationalisation of the Social Climate Fund—a pivotal instrument designed to mitigate the regressive socio-economic impacts of carbon pricing on the most vulnerable demographic segments. [195] [196]

Furthermore, it should be emphasised that security of supply remains a top priority. Following the 2026 "Fitness Check" on energy security, the Commission is proposing enhanced protections for the physical and cyber resilience of cross-border grids. Moreover, the emergency 90% gas storage obligation is being debated as a permanent fixture, ensuring that the Union remains resilient against hybrid threats and geopolitical shifts. [197] [198]

In conclusion, 2026 represents a pivotal year of convergence. While the EU continues to execute the REPowerEU plan to eliminate Russian gas dependency by 2027, it is simultaneously laying the groundwork for a post-2030 economy. The success of this transition relies on the seamless integration of market reforms, building renovations, and industrial strategy—all while maintaining the social cohesion necessary to sustain the green transition toward 2040.

Policy recommendations

The EU's energy transition objectives can be partially reconciled with the critical need for strategic autonomy. Over the past few years, the EU signalled the intent to carefully balance between the bloc's decarbonisation and its energy security, especially following the shifts prompted by Russia's invasion of Ukraine. While this paper does not represent a comprehensive overview of all the security risks associated with the energy transition, it provides a functional overview of three key risk areas:

1. **Decarbonisation and grid stability;**
2. **Supply chain de-risking;**
3. **Market resilience;**

We found these elements to be intertwined, whereby neglecting one could negatively impact the entire energy transition in terms of overall emission reductions, susceptibility to geopolitical volatility, and market stability.

Decarbonisation and grid stability

This paper analysed the European energy mix and its composition over the 2024-2030 period. Only under two out of the three analysed scenarios (Fit for 55 and Storage Diffusion) will the emission factor get close to or lower than 100gCO₂eq/kWh. This implies that, ceteris paribus, the following variables will significantly influence the trajectory of the EU's decarbonisation process:

- Effective and timely policy implementation;
- Diffusion of storage capacity and flexibility systems.

Thus, the EU needs to balance ambitious environmental objectives with the necessity for grid stability and resilience, as scaling up renewable energy production without consideration for the marginal emission factor will lead to continued dependence on fossil fuels, preventable emissions, and increased vulnerability to geopolitical tensions.

Optimisation of the 2030 emission factor

To bridge the gap between the Business As Usual (BAU) scenario and its ambitious Storage Diffusion counterpart, the EU should steer away from the uncoordinated addition of renewable capacity in favour of systemic optimisation. According to our models, the ambitious integration of storage systems and Demand Side Response (DSR) could slash the emission factor from 227 gCO₂eq/kWh to 93 gCO₂eq/kWh, preventing an additional 2,900 MtCO₂eq over the decade. Assuming no unforeseeable technological improvement, this paper presents the following recommendations to optimise the EU's emission factor:

1. **Integrated Flexibility Guidelines within REPowerEU.** A key recommendation is to enhance the strategic alignment of flexibility resources within the existing REPowerEU framework. This would involve developing harmonised guidelines for Member States to further integrate energy storage as a core infrastructure component within National Energy and Climate Plans (NECPs). Prioritising the expansion of energy storage capacity would allow the EU to improve efficiency of grid modulation during peak periods, optimising the displacement of higher-intensity marginal generation;
2. **A More Efficient Approach to the Coal Phase Out.** At the time of writing, the EU is traversing a transitional phase, wherein coal is being progressively swapped in favour of natural gas. While this will lead to an estimated reduction of 130 MtCO₂eq, replacing this capacity with renewable power sources could save up to 280 MtCO₂eq. As the marginal emission factor directly depends on the source dispatched to modulate demand, the EU should consider restricting the adoption and use of simple cycle gas turbines in favour of high efficiency CCGT;

3. **The Industrial Efficiency & Flexibility Framework.** To further optimise its emission factor, the EU should facilitate the expansion of industrial demand side response, treating it as a functional tool for load management. DSR is necessary to achieve an alpha coefficient (α) of at least 0.8, meaning that marginal fossil fuel usage attenuation is significant enough to achieve Storage Diffusion scenario outcomes. By incentivising the integration of flexibility within industrial processes, the EU could mitigate energy demand and price surges when the marginal emission factor is highest, while simultaneously maximising the utility of existing renewable capacity. Such an approach would position industrial facilities as decentralised flexibility resources, aligning consumption patterns with real time generation output. Implementation could focus on leveraging the Industrial Decarbonisation Bank (IDB) to support continued investments in smart energy management systems, while simultaneously exploring technical refinements within the Emissions Trading System (ETS II) and CBAM frameworks to reward the voluntary adoption of low-carbon consumption profiles, ensuring that the businesses partaking in grid balancing efforts receive appropriate recognition for contributing to the reduction of the systemic marginal emission factor;

Grid resilience and digitalisation

Optimising the emission factor requires us to consider how best to mitigate the economic shocks associated with decarbonisation, aiming to decouple climate action and systemic costs. The “Italian case” presents a cautionary tale of how the marginal emission factor not only contributes to increased environmental pollution, but also to higher average costs during peak demand hours (approximately €76/MWh). This is further reinforced by Italy’s grid continued dependence on natural gas, especially during the cold season, effectively off-loading the cost of systemic inefficiencies to end consumers.

Our models have shown that a highly integrated and interoperating system could theoretically achieve an estimated average electricity cost of €16/MWh, coupled with €158 billion in total systemic savings. However, this outcome is only achievable by sharing zero-marginal-cost renewable energy across borders and under the optimistic conditions modelled in the Storage Diffusion scenario.

At the time of writing, Member States’ national grids operate in relative isolation, meaning that cross-border energy exchanges are predominantly carried out by national grid operators between neighbouring countries. This is a critical inefficiency that could be addressed by progressively reinforcing grid planning to target specifically:

- **Interconnectors’ Capacity.** To meet the 2030 target of 15% electricity interconnection, the EU needs to address structural bottlenecks in major demand centres where interconnection is currently below the 2020 10% target [239]. Achieving optimistic decarbonisation scenarios requires a doubling of cross-border transmission capacity by 2040, jumping from today’s 116 GW to 318 GW [240]. In conjunction, the EU needs to accelerate the 55 GW missing projects in the current pipeline [240];
- **Cross-border Grid Integration.** Integration requires the enforcement of the 70% rule, ensuring that the majority of transmission capacity is available for cross-zonal trade [241]. Current utilisation of congested lines rests at roughly 54%, leading to over €580 million in annual lost economic welfare [241]. This should be coupled with efforts to digitalise the grid, allowing for the real-time coordination of the theoretical 160 GW potential for DSR that’s crucial to achieve the Storage Diffusion scenario.

Mitigation of new dependencies

The European energy transition is unprecedented in its scale and objectives. To achieve them, the EU is projected to require vast amounts of additional renewable and energy storage capacity, introducing the risk of dependency on a restricted group of non-EEA countries and of dangerous bottlenecks. When reconciling environmental objectives with strategic autonomy and energy security, the EU needs to implement comprehensive risk mitigation frameworks with regards to supply chain de-risking, coupled with an approach that favours re-use and domestic production.

Supply chain de-risking

The EU is transitioning from “pipelines to metals”, meaning that increases in energy production are growing reliant on the availability of critical raw materials and clean-tech components rather than fossil fuels import. This places the EU in a situation where the billions spent on environmental gains are partially decoupled from industrial and economic gains in favour of international competitors. This picture is further complicated by two distinct potential points of failure:

- **Sourcing.** Approximately 70% of global mineral volumes originate from few supplier countries characterised by medium-to-low governance performance [111]. Moreover, the average lead time for new mineral extraction projects stands at 15.5 years [99], rendering diversification less actionable over the short term;
- **Manufacturing.** China holds an extremely dominant position when it comes to exporting photovoltaic panels (98% of total EU imports) and magnesium, as well as a disproportionate share of the global refining capacity of REEs, that are essential for wind turbines, EVs and other clean-tech components.

This creates a significantly more complex risk environment for the EU, requiring a long-term and multi-faceted approach to mitigation. As these risks cannot be fully eliminated, due to geographic concentration of mining and refining operations, as well as long average lead times, the EU should instead aim to limit existing dependencies under the high-demand-growth scenario that forecasts indicate.

This could be partially achieved by:

- **Localising Manufacturing and Refining Capacity.** To enhance the EU's autonomy and industrial resilience, the Union should focus on localising the high-value manufacturing and refining capacity needed for critical technologies production. In order to do this, the EU should leverage the Innovation Fund and the Industrial Decarbonisation Bank to provide capital grants for projects that meet elevated resilience and sustainability benchmarks, such as advanced material recovery and low-carbon processing. Within the framework of NZIA Article 26 [242], Member States should utilise Non-Price Criteria (NPCs) in renewable energy auctions to reward supply chain diversification. This includes implementing Resilience Award Criteria that favour bidders with diversified supply chains, continuing to disincentivise the concentration of components from any single, high-risk non-EEA jurisdiction. To bridge the cost gap between standard and high-resilience products, a "Resilience and Sustainability Premium" could be introduced. This would provide bonus points to projects that demonstrate superior environmental performance, social responsibility, and cybersecurity standards, effectively incentivising the development of a secure and reliable domestic clean-tech ecosystem without violating international trade obligations;
- **Strategic Long-Term Diversification and Reserves.** Building upon the foundations of the Net-Zero Industry Act (NZIA) and the Critical Raw Materials Act (CRMA), the EU should prioritise the operationalisation of the targets set by these policy frameworks, ensuring that at least 10% of extraction, 40% of manufacturing and 15% of recycling occur within the Union by 2030 [84],[100]. Moreover, the EU should expand its network of sustainable raw materials partnerships with high governance jurisdictions that abide by international ESG and transparency standards. This is a selective mitigation strategy that can be exclusively actioned for CRMs with alternative viable sources (e.g. Canada, Australia, Chile), while prioritising materials whose global demand is projected to grow exponentially over the decade. To further mitigate the impact of global supply volatility, the EU should consider facilitating a coordinated strategic stockpiling initiative for the seventeen Strategic Raw Materials (SRMs) identified by the CRMA[84], [100], aiming to buffer the projected expansion of renewable energy production and storage capacity from external shocks, such as export bans, supply chain disruptions, tariffs or conflict;

Circular economy and innovation

As more countries push for decarbonisation, demand for CRMs and SRMs is bound to grow far beyond the current global supply over the next few decades [95], [97], [98], [100], [102], [103], [110]. To transition towards a 93 gCO₂eq/kWh grid while mitigating the risks linked to increased CRM demand and external dependencies, the EU must move from the current resource-intensive sourcing model to one of circular innovation. To achieve this, the EU should complement the operationalised targets with measures designed to encourage circularity, such as:

- **Circular Design Requirements.** To facilitate high-value material recovery, the EU should enhance lifecycle standards within the Ecodesign for Sustainable Products Regulation (ESPR) working plan. Said standards should promote the reversibility of technical assemblies and the purity of recovered material fractions for clean-tech components and storage systems, thus simplifying the recycling process, lowering the cost of secondary materials, and strengthening the resilience of EU clean-tech value chain [243];
- **Accelerating the Second Life Storage Market.** To optimise the lifecycle of existing battery assets, the EU should enhance the regulatory pathways for the repurposing of spent electric vehicle (EV) batteries. By leveraging the Digital Product Passport initiative (DPP) [108], the EU should explore establishing a harmonised "State of Health" (SoH) validation framework. Such system would provide standardised data to facilitate the re-certification of batteries for stationary grid storage application, allowing for increased grid stabilisation capacity and lower lifecycle emissions of storage projects, while partially mitigating demand for lithium and cobalt extraction;
- **Directed Innovation for Material Decoupling.** To reduce the risk of bottlenecks and structural deficits when expanding grid storage capacity, the EU should redirect the Innovation Fund and the SET Plan [120] to prioritise the mass commercialisation of Lithium-Iron-Phosphate (LFP) and Sodium-Ion (Na-ion) technologies. These would partially reduce the dependence on minerals such as nickel and cobalt, replacing them with more abundant materials;
- **Localised Clean-Tech Industrial Hubs.** To fulfil the NZIA's 40% domestic manufacturing target, the EU should aim to localise the value chain rather than the final assembly processes. To facilitate this, the EU should encourage the creation of "Clean Tech Industrial Valleys", clustered regional hubs where processes from refining to recycling can occur simultaneously. These clusters shall serve to reduce the logistics costs and carbon emissions linked to transcontinental supply chains, while preserving critical domestic sovereignty;

Social equity and market resilience

The energy transition acts as a partial stress test of the social contract, as energy prices are directly upstream of the rest of the economy. While high-governance countries are generally less susceptible to this dynamic, this paper found a statistically significant correlation between the volatility of energy prices and social stability, whereby moderate price fluctuations tend to spark ripple effects leading to civil unrest. There appears to be no specific price ceiling to trigger social disorders, that are instead dependent on a threshold of institutional trust below which even minor cost increases become socially unsustainable. Thus, according to our model, societal resilience to energy price shocks is a function of the government's response quality rather than mere price stability. To mitigate this risk, the EU should aim to prevent off-loading the costs linked to the energy transition to end consumers. In fact, as partially demonstrated by the *Jilet Jaunes* movement, climate transition strategies can be perceived as having a misaligned cost distribution, especially in peri-urban or rural environments characterised by insufficient public infrastructure and increased reliance on private means.

Consumer protection

To reduce the likelihood of social disorders, the EU needs to relieve, within reasonable constraints, the end consumer from the financial burden of the energy transition. In this case the objective is twofold, to ensure price stability and to keep costs relatively contained. This is a challenging endeavour that requires a combination of integrated planning, distribution-cost-shifting, strategic communication and crisis management frameworks. Assuming the objective is to achieve the conditions presented under the Storage Diffusion scenario, this paper suggests the adoption of the following measures:

- **The Energy Equity Dividend & Social Stability Buffer.** To ensure a socially equitable energy transition and to mitigate the risk of regressive fiscal impact, the EU should consider establishing a coordinated framework for revenue recycling linked to systemic grid efficiencies. More specifically, this document identified €158 billion in cumulative annual systemic savings under the Storage Diffusion scenario, providing room for Member States to explore the implementation of a “Counter-Cyclical Solidarity Contribution”. During the progressive transition away from the current grid layout, this mechanism would capture a portion of the valuation gains from inframarginal generation during periods of documented volatility.

These resources could be used to contribute to the Social Climate Fund (SCF) and the Just Transition Mechanism [1] [2] in order to provide a fiscal buffer to offset the initial cost increases associated with the phase-in of ETS II for transport and heating, proactively mitigating the energy and mobility poverty risks for vulnerable households and micro-enterprises [32], [33], [34], [35], [195];

- **Facilitating Residential Demand-Side Flexibility (DSF).** To stabilise the alpha coefficient at 0.8, the EU should strive to mobilise at least 160 GW in DSR. Achieving this significant milestone requires complementing industrial flexibility with the deployment of residential flexibility frameworks. By promoting the interoperability of Distributed Energy Resources (DERs), such as EV chargers, heat pumps, and home battery systems, within the integrated grid, the EU can empower consumers to more efficiently manage their energy use. By promoting transparent and voluntary dynamic pricing models, residential consumers could be incentivised to align their consumption with periods of high renewable availability, curbing the marginal emission factor while effectively contributing to price stability. This approach would, in fact, turn residential consumers from passive subjects to prosumers, granting them tangible economic incentives for partaking in the energy transition;
- **Credibility Framework for Crisis Management.** Considering the inevitability of friction points throughout an energy transition of this scale, the EU should consider adopting a “Credibility Framework” to govern institutional responses from Member States. This paper highlighted that the quality of the institutional response is determined by consistency, predictability, transparency and timeliness. Such a framework would require Member States to pre-identify and define the conditions under which emergency market interventions would be triggered, preventing improvised ad-hoc policy responses that erode public and investor confidence;
- **Adaptive Policy Flexibility.** The energy transition is a dynamic process, thus the EU should explore incorporating responsive calibration mechanisms within its core climate legislation to handle unforeseeable socio-economic stresses more effectively. By introducing harmonised compensatory mechanisms, in the form of “review and adjustment” protocols, the EU could allow for the temporary modulation of implementation timelines, or fiscal measures, during periods of exceptional price volatility or persistent inflation.

Such approach would require embedding predictable adjustment triggers, allowing policymakers to respond to national socio-economic challenges without compromising the overall trajectory towards net-zero, while preventing the systemic erosion of public support that could lead to the repeal of essential climate policies;

- **The Green Transition Transparency Initiative.** To strengthen public trust and demonstrate the tangible benefits of the transition, the EU should evaluate establishing a “Green Transition Transparency” framework. This initiative would imply codifying a “transparency dividend” by providing citizens with clear and standardised, data on the impact of climate policies on their energy costs. By establishing a framework to clearly communicate to the broader public the direct benefits of enacted or planned climate policies, the EU can ensure better long-term institutional trust.

In practice, National Regulatory Authorities (NRAs) should introduce a standardised “Social Climate Credit” line item on the electricity bills of households and SMEs electricity bills, transparently stating the deductions applied thanks to the theoretical Counter-Cyclical Solidarity Contribution mechanism. Alongside this, energy providers should provide annual “Comparative Energy Statements”, contrasting current costs against a benchmark based on a fossil-fuel-dependent system. Lastly, the EU should deploy localised impact dashboards to target the trust gap in susceptible rural and peri-urban areas by creating real-time, public facing, maps to showcase the investment of transition funds into local infrastructure, renovation, and mobility projects;

5. The role of Italy and the UK within the energy transition

The role of the UK within Europe's energy transition

In times of renewed volatility, the UK and the EU stand to mutually benefit from continued, holistic engagement as continental partners. Especially in the energy sector, the UK possesses a series of structural advantages that uniquely position it to support, and benefit from, the EU's energy transition, rendering it a strategic pillar for a sovereign and resilient energy framework. This paper identified three main characteristics that make the continued pursuit of closer ties mutually advantageous: its role as a physical power hub and the ongoing UK-EU financial and technical recoupling. By leveraging these factors, the UK stands to play a twofold role in Europe's energy transition: as a crucial renewable energy exporter and energy price stabiliser and as a technological leader and regulatory-aligned financial centre.

The North Sea power hub

The Hamburg Declaration of Energy Ministers, signed on the 26th of January 2026, presents the primary roadmap for transforming the North Sea from a collection of national fossil fuel extraction sites to one of Europe's primary engines for renewable energy production. In this convening, seven EU Member States, the UK, and Norway committed to deploying 100 GW of cross-border off-shore wind capacity aimed at delivering a new generation of Offshore Hybrid Assets (OHAs), while enhancing cooperation within the North Seas Energy Cooperation (NSEC) and the Greater North Sea Basin Initiative (GNSBI) [59], [60], [61], [62] [244].

The inclusion of NATO in the Hamburg proceedings marked a consequential shift in energy policy, recognising that subsea cables and offshore wind farms are strategic sovereign assets requiring collective defence [244]. By anchoring this infrastructure to a shared security umbrella, both the UK and the EU stand to benefit from a "Secure By Design" and collaborative architecture that curtails resource weaponisation strategies by foreign powers, as well as reducing the systemic risk of sabotage in a strategic maritime region [250].

The technical cornerstone of this North Sea hub is the Multi-Purpose Interconnector (MPI), representing a departure from traditional point-to-point cables [245]. Under the previous model, electricity generated by a wind farm in the North Sea could only flow to the country of origin of the infrastructure. Instead, these assets directly connect offshore wind farms to multiple national energy markets simultaneously, giving rise to a hub of engineered interdependence. Under this configuration, the North Sea can become a physical valve for the Storage Diffusion scenario modelled in the early chapters of this paper, acting as an energy price stabiliser to mitigate the spikes seen in isolated national grids. For the UK, this significantly reduces the £1.9 billion in constraint costs experienced in 2024/2025 by allowing surplus wind to be exported rather than curtailed, while providing an influx of zero-marginal-cost energy to the EU [246]. This reciprocity ensures that both parties can operate their respective grids more efficiently, lowering energy costs for end consumers on both sides of the Channel.

The financial and technical recoupling

The rationale behind closer UK-EU energy cooperation is centred around the progressive elimination of congestion and trading inefficiencies that characterised the post-Brexit energy relationship between these two regions. Following the May 2025 UK-EU Summit, both parties agreed to a Common Understanding to explore the full recoupling of their electricity markets [183], [184], [240], [241], [247], [251]. By moving towards reintegration of the UK into Single Day-Ahead Coupling (SDAC) and Single Intraday Coupling (SIDC) platforms, both markets would transition towards implicit auctioning, where electricity and cable space are sold as a single package. Under this model, the EUPHEMIA algorithm calculates energy prices and allocates connectors capacity across the English Channel, ensuring that energy flows from the lowest to the highest price zone [52], [121], [198]. This efficiency constitutes a valuable tool to achieve the energy price stability modelled in the Storage Diffusion scenario, effectively rendering the UK a strategic flexibility partner for Northern Europe. By sharing the burden of system balancing across the English Channel, both regions can reduce marginal fossil fuel consumption, mutually stabilising energy prices and reducing non commodity costs [183], [184], [195], [247].

Perhaps more critical to the survival of heavy industry is the prospect of an ETS linkage agreement. At the time of writing, the British government committed to dynamic alignment to EU emission trading rules, progressively merging both regions' carbon price signals into a single high liquidity market [248], [252]. Under the previous configuration, UK ETS often proved to be too small to prevent price volatility, seeing carbon prices drop in relation to those of the EU, only for them to spike unpredictably when liquidity dried up [249], [252]. This linkage, which is in its negotiation and technical alignment phase, would provide a mutual exemption from the Carbon Adjustment Mechanism (CBAM), preventing an up to £800 million annual carbon tax by 2030 [247], [248]. Moreover, by establishing a unified carbon zone, the UK and EU could mitigate the threat of carbon leakage, or the phenomenon that leads to industries relocating to countries with lower environmental standards, and deindustrialisation in their respective pursuit of decarbonisation.

The positive effects of this renewed synergy can be amplified by the UK's financial and technical prominence. As the world's premier green finance hub, London excels at pricing First-of-a-Kind (FOAK) green technologies, such as Long Duration Energy Storage (LDES) and green hydrogen. This is complemented by the UK's prominent role in green R&D, driven by its university-led research clusters. Moreover, the UK's leadership in Green Gilts and private equity is key to providing the liquidity needed to fund the EU's €100 billion Industrial Decarbonisation Bank. Without London's capacity to aggregate capital, the EU's large infrastructure projects would face higher borrowing costs, negatively impacting the energy transition's economic viability. Conversely, the EU provides the industrial scale the UK lacks, as well as continued demand for British green exports. More specifically, the EU provides the volume of demand to make large scale energy projects, such as the North Sea Power Hub, financially sustainable; while British companies stand to benefit from regulatory alignment, as the EU provides the scale to de-risk the UK's energy transition, by providing a stable and predictable market for their exports.

The role of Italy within Europe's energy transition

Within the European Union's decarbonisation pathway, Italy is structurally positioned to operate as a strategic and infrastructural node across the Euro-Mediterranean energy system. This role is not predicated on infrastructural centrality as an end in itself, but on Italy's capacity to reinforce the feasibility, resilience, and strategic autonomy of the European transition during a phase of systemic reconfiguration. In particular, Italy's relevance can be conceptualised along three interrelated dimensions:

- As a Mediterranean gateway during the transitional phase, contributing to energy security and route diversification;
- As a Euro-Mediterranean interface for emerging low-carbon energy carriers, accompanying the shift from a gas-centred architecture toward hydrogen and its derivatives;
- As an industrial and technological enabler of network expansion and system integration.

These three structural dimensions map onto three system-level functions for the European transition: a stabilisation mechanism during the phase-down of fossil fuels, a corridor platform for decarbonisation-compatible energy vectors, and an industrial base for accelerating deployment while reducing external dependencies. Such a configuration does not imply a substitutive role vis-à-vis EU policy, but rather a reinforcing function aimed at mitigating supply-side risks, infrastructural bottlenecks, and technological vulnerabilities across the European decarbonisation trajectory.

Italy as a Mediterranean gateway and transitional stabilisation mechanism

During the transitional phase—characterised by rising renewable penetration alongside persistent requirements for flexibility, dispatchability, and security of supply—Italy’s geographical position and existing infrastructure confer a structural advantage in enhancing the resilience of the European energy system. Positioned at the intersection of continental demand centres and Mediterranean supply routes, Italy can contribute to the diversification of counterparties and entry corridors, thereby reducing exposure to geopolitical disruption, concentration risks, and infrastructure-related vulnerabilities.

In this context, Italy’s hub function should be interpreted primarily as a stabilisation mechanism within a period of structural reconfiguration. The strategic rationale is not infrastructural centrality per se, but the minimisation of transition-induced volatility capable of undermining economic competitiveness and social sustainability. By supporting continuity, redundancy, and operational reliability during the progressive phase-down of fossil fuels, Italy can help preserve the systemic stability required for decarbonisation policies to remain politically and economically viable.

More broadly, this transitional function reinforces the EU’s capacity to manage the sequencing problem inherent in the energy transition: renewable deployment and electrification must accelerate, yet system resilience must be preserved throughout the adjustment period. Italy’s contribution, in this sense, lies in reducing the probability that short-term shocks or bottlenecks compromise long-term decarbonisation outcomes.

Italy as a Euro-Mediterranean interface for low-carbon molecules

Concurrently, Italy may evolve into a Euro-Mediterranean interface for low-carbon molecules—including hydrogen, ammonia, and synthetic fuels—where technological maturity, infrastructure readiness, and economic viability permit. This role implies a pathway of gradual infrastructural repurposing rather than abrupt substitution. In the short term, gas-related assets continue to provide flexibility and security of supply; over longer time horizons, selected infrastructures may be technically adapted to support decarbonisation-compatible transport and storage corridors.

These governance and technical conditions are essential to avoid fragmentation, reduce transaction costs, and enable the emergence of scalable Euro-Mediterranean value chains.

This positioning also supports decarbonisation on the demand side, particularly in hard-to-abate sectors where direct electrification remains technologically constrained or economically inefficient in the medium term. In this respect, Italy's role as an interface for low-carbon molecules can help reconcile short-term security-of-supply imperatives with long-term climate objectives, while contributing to a more diversified and resilient European decarbonisation architecture.

Italy as an industrial and technological enabler of network expansion and system integration

Italy's structural relevance within Europe's transition ultimately depends not only on its transit and interface functions, but also on its capacity to act as an industrial and technological enabler of deployment. The European decarbonisation agenda is contingent upon the timely expansion and reinforcement of electricity grids, cross-border interconnections, digitalised transmission and distribution systems, and advanced system-management technologies. These processes require strong domestic engineering capabilities, manufacturing capacity, and resilient supply chains able to support implementation at scale.

A strengthened industrial base performs a strategic function beyond production alone. It reduces exposure to external dependencies for critical components and technologies, mitigates deployment delays associated with supply-chain fragility, and internalises value creation within the European economy. In this sense, infrastructure investment acquires a dual character: it enables decarbonisation while simultaneously reinforcing industrial competitiveness, technological capability, and strategic resilience.

For Italy, the strategic opportunity lies in moving beyond a passive transit-centred role toward an integrated platform combining infrastructure deployment, industrial upgrading, and technological innovation. Such an evolution is increasingly necessary to prevent the emergence of new forms of dependency in the decarbonised economy and to transform geographical centrality into a structurally embedded competitive advantage within the future architecture of the European energy system.

The effectiveness of these functional roles depends on a coherent multilevel governance architecture. Italy's strategic value as a European node is contingent upon its ability to align national energy planning with EU financial instruments, internal market regulation, and common industrial policy priorities. Regulatory fragmentation or policy misalignment would risk diluting the systemic impact of infrastructure deployment and reducing the credibility of long-term investment signals. Accordingly, Italy's strategic relevance derives not only from geography or infrastructure endowment, but from its capacity to contribute to EU-level agenda-setting through an integrated framework reconciling energy security, industrial competitiveness, and climate mitigation objectives.

Taken together, these elements position Italy as an enabling structural component of the European energy transition. By combining transitional stabilisation, infrastructural adaptation to low-carbon vectors, and industrial capacity expansion, Italy can contribute to a decarbonisation pathway characterised by greater systemic stability, reduced exposure to external shocks, and enhanced European strategic autonomy. Over the medium to long term, Italy's strategic relevance will therefore depend not solely on its transit function, but on its ability to evolve into an integrated Euro-Mediterranean platform for energy, industry, and technological innovation.

Declaration of generative AI in the writing process

During the preparation of this work, the authors used generative AI tools in order to improve the clarity, grammar, and readability of the manuscript. Additionally, generative AI was used to harmonise the citation style of the bibliography. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of this publication.

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The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. Neither AWARE Think Tank nor the Bloomsbury Intelligence and Security Institute has a financial stake in the specific outcomes or recommendations presented in this report.

Note on scope and data limits

This analysis utilises data and policy developments documented through February 2026. Consequently, recent shifts in the energy landscapes of Venezuela, Iran and Gulf Cooperation Council (GCC) countries are not reflected in this report. These developments occurred after the primary data collection and analysis phases were finalised; therefore, they fall outside the current temporal scope of this study. Future iterations of this research may seek to integrate these markets as more standardised data becomes available.

Data availability

The datasets generated and/or analysed during this study are available from the authors upon reasonable request. Interested parties should contact the lead researchers at AWARE Think Tank or the Bloomsbury Intelligence and Security Institute. Some data may be subject to confidentiality agreements or institutional privacy policies.

Review status disclaimer

This report has undergone internal institutional review by AWARE Think Tank and the Bloomsbury Intelligence and Security Institute to ensure quality and accuracy, but has not been subjected to external formal peer review. It is intended to stimulate discussion and provide timely analysis on European energy security.

Disclaimer of liability

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