World Energy Markets Outlook

How are AI and sovereignty driving a new energy paradigm in an uncertain world?

Welcome to the 27th edition of the World Energy Markets Outlook.

Capgemini's World Energy Markets Outlook (WEMO) is back, offering an unflinching look at the opportunities, contradictions, and breakthroughs shaping the global energy system.

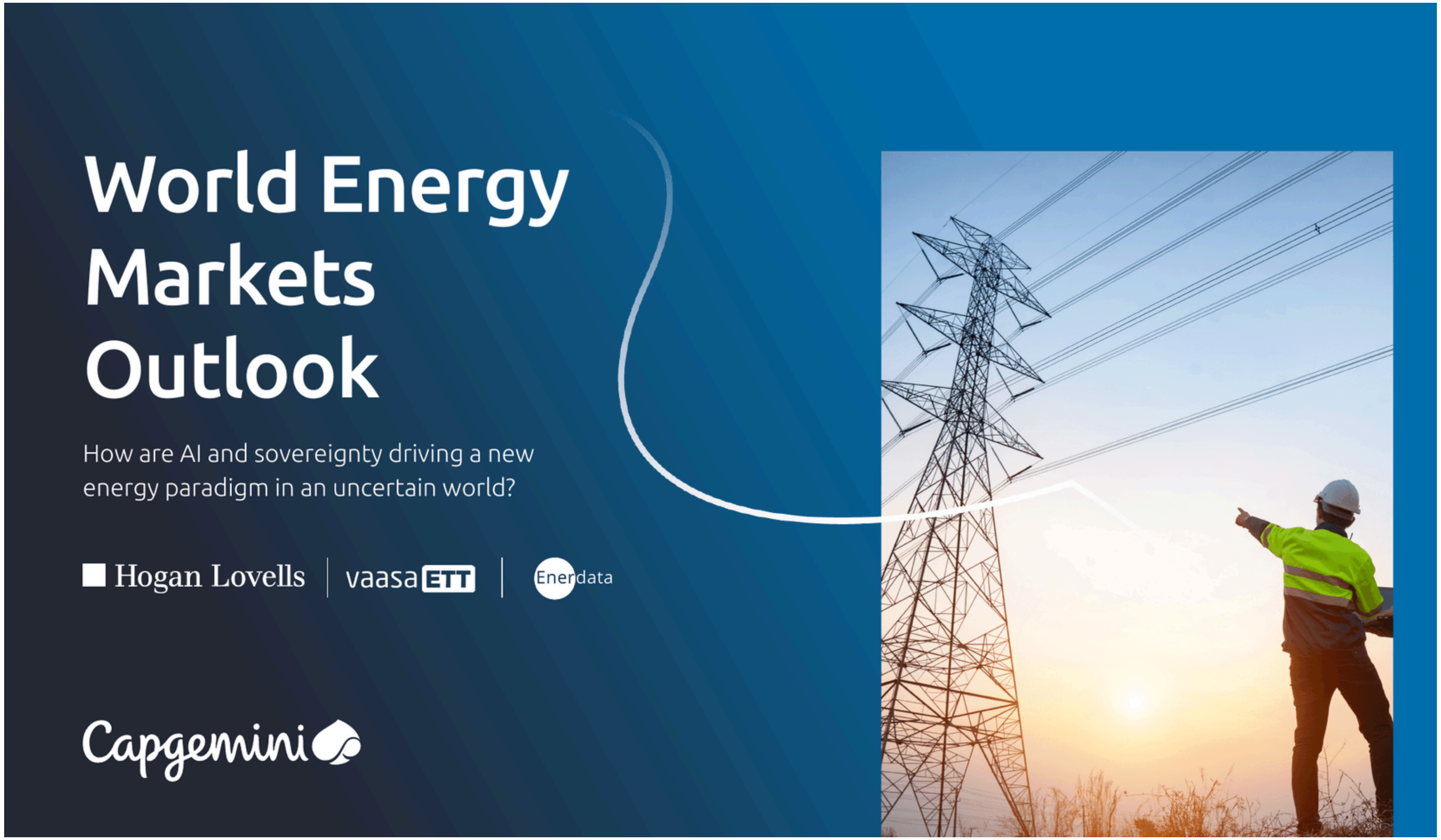
From the acceleration of clean investments and the rise of energy demand, to the persistent climate gap and shifting resource dynamics, the report dives deep into the forces redefining energy security and sustainability.

With insights on energy transition, critical resources, and consumption flexibility, WEMO 2025 equips leaders with the perspectives needed to act at speed and scale.

We hope you enjoy reading it, and would love to hear what you think.

01
Global outlook

A Global Outlook



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02
Critical resources

Introduction

How does the criticality of resources put low-carbon technologies at risk?

All resources used in the energy sector are critical - including the most commonly used ones. While rare materials often dominate the conversation, they can overshadow more abundant yet equally essential resources that underpin every energy technology, regardless of the chosen pathway.

Key questions to explore in this article:

- What defines a resource's criticality, and what risks does it entail?
- How do resource constraints impact low-carbon and carbon-intensive technologies?
- Why are some critical resources still overlooked, and what are the consequences?
- What levers can mitigate resource scarcity risks - and under what conditions?
- How can countries or companies leverage supply chain advantages for critical resources?

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What is criticality of resources?

- Some resources, such as lithium and rare earth elements, are essential for critical components like permanent magnets. Although typically required in relatively small volumes, they are non-substitutable. Conversely, materials like sand and aggregates are abundant but demanded in very large quantities, presenting different types of sustainability challenges.
- Energy-intensive mining and processing activities lead to environmental damage, including CO_2 emissions (e.g., from steel and copper), impacts on biodiversity, high water consumption, depletion and pollution, land use change, and water and waste-related contamination (e.g., lithium, cobalt, rare earths, and silicon).

Criticality must be assessed across five interconnected dimensions:

Dimensions	Key factors	Implications
Resource Availability	Global geological reserves Geopolitical concentration of supply Dependency & disruption risks	• Dependency • Adequacy of supply • Strategic sourcing • Risk mitigation
Economics	Short-term price volatility Long-term price elasticity to demand	• Market stability • Investment planning/signals to investment
Environmental Impact	Beyond carbon emissions Biodiversity loss Water usage Waste Land degradation (...)	• Environmental compliance • Stricter compliance requirements

Open full table in browser:

https://capgemini.turtl.co/story/world-energy-markets-outlook-2025-chapter-2/page/3/2

Source: ?

Rare earths are not geologically rare, while some seemingly abundant resources face growing supply risks

Resources	Projected Years of Reserves by 2040	Demand Growth Rate by 2040 (%)
Aggregates	Not reliable	143%
River sand	Not reliable	55%
Nickel	20-25	135%
Iron Ore & Steel	60-70	20%
Copper	30-35	30%
Bitumen	40-50	75%
Rare Earths	20-25	195%
Lithium	15-20	410%

Source: Capgemini Invent 2025 analysis, IEA – Global Critical Minerals Outlook 2025; Global Energy Association – Lithium and Cobalt Outlook (2025), Mining Weekly – Copper, Nickel, Rare Earths, Lithium (2025)

- Reserves of copper, cobalt, and bitumen (linked to oil reserves) are expected to decline by 2040, with projected reserve lifespans from that year estimated at 100 years for copper, 60 years for cobalt, and 120 years for bitumen.
- For rare earth elements and lithium, the main challenge is not the volume of reserves but rather the economic and environmental feasibility of extracting them at viable concentrations. This highlights the need to develop new mining capacities and processing technologies, rather than relying solely on current reserve estimates.
- Contrary to popular belief, sand and aggregates that are incorporated in concrete, are not easily accessible. In fact, the sand used for roads and civil engineering projects must meet very specific criteria such as grain sizes, cleanliness, and composition to ensure structural integrity and durability.
- Huge volume requirements are already causing regional shortages due to overexploitation, environmental degradation (for the record, sand & aggregates extraction and production require 0.059 m^3/kg of water), and subsequent regulatory constraints and restrictive policies.

All resources are critical to their own extent and this has nothing to do with planetary boundaries

	Degree of criticality				
Resources	**Resources availability**	**Economics**	**Environmental impacts**	**Human rights**	**Technology (recyclability/substitutability**
Aggregates	++	+	++	+	+
River sand	+++	+	+++	+	++
Nickel	+++	+++	+	++	++
Steel	+	+++	+	+	+
Copper	++	+++	+	++	+
Bitumen	+	++	++	++	++
Rare Earths	+++	++	++	+++	+++
Lithium	+++	++	++	+++	+++

Source: Capgemini Invent 2025 analysis

China's strategic preemption over key resources significantly constraints global availability

- Initial assessments of global supply chains reveal a significant concentration of production among a limited number of countries, with China occupying a dominant position - particularly in refining capacities.
- Crucially, the volumes available to the global market are what remain after China meets its own domestic demand and fulfills long-term contractual obligations. This further constrains supply for other countries and amplifies market tightness.
- Additionally, commodity markets (resources market) display limited liquidity. For instance, only about 40% of global copper production is traded on open markets, which restricts hedging options and reduces the market's ability to respond flexibly to demand fluctuations.
- Paradoxically, it is market prices - shaped by these very constraints - that determine production margins and signal future investment decisions.

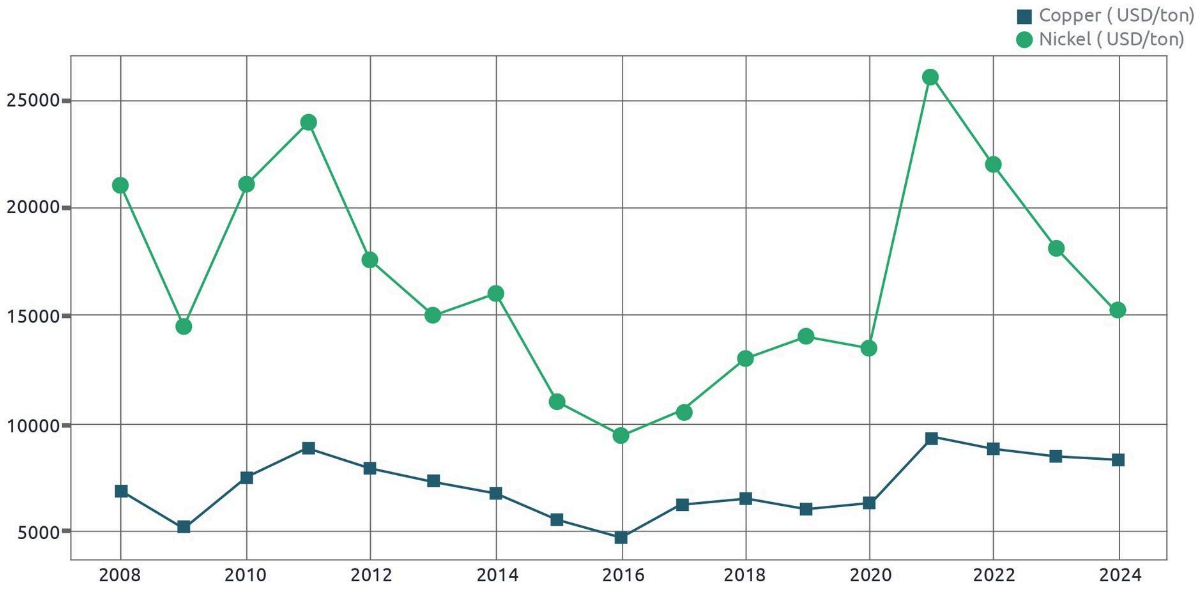
China's Share of Global Refining Production (%)	
Copper	40%
Steel	~54%
Nickel	65-70% (control and investment in Indonesia's refining capacity)
Aluminum	~60%
Rare Earths	90%
Lithium	60%
Cobalt	73%
Silicon	Over 70% (including ~67% of global polysilicon)

Source: IEA, Critical Mineral Outlook, 2024; USGS, 2025

Volatile market prices in the short term are sending mixed signals, discouraging long-term investment

FIGURE 1

Copper and Nickel Prices (USD per ton) from 2008 to 2024



Source: IEA, Critical Mineral Outlook, 2024; USGS, 2025

- Global resource prices remain volatile due to shifting supply-demand dynamics, rapid electrification, and competition of usages - especially affecting critical materials like lithium, rare earths, copper, nickel, and steel.
- This volatility is largely driven by external factors - port congestion and logistics delays, freight costs, geopolitical tensions, energy prices, regulatory barriers, and complex tax and tariff systems - rather than structural production issues.
- In response, market players are turning to speculative storage, hedging, and active trading in futures and options.
- However, current price levels do not support investment in new production capacity, which caps output and raises the risk of future shortages in both components and finished goods -ultimately threatening long-term supply security.

As a result, supply is consistently misaligned with demand

- There is a persistent misalignment between production capacity and a growing market demand.
- Even in sectors characterized by overcapacity - such as the European steel industry - shortages can still occur. This paradox is often the result of "stop-and-go" production strategies deliberately employed to influence market prices by restricting supply.
- This dynamic helps explain why steel shortages can arise despite an overall surplus in production capacity.

Estimates - annual growth rates (2025–2050) for estimated demand and production – depending on scenarios

Resources	Demand CAGR (%)	Production CAGR (%)
Steel	1.3	1.2
Copper	2	1.35
Nickel	4.5	3
Aluminum	1.6	1.5

Source: Capgemini analysis, IEA, Critical Mineral Outlook, 2024, RMG Consulting – Future Mine & Mineral 2024 Conference , 2024; International Energy Agency (IEA) – Global Critical Minerals Outlook 2024, Strategic Insights from World Steel Dynamics

Nickel is the most critical resource and is still under the radar

- Steel - particularly high-strength steel (incorporating crude steel and nickel) - is currently facing significant supply constraints and heightened price volatility. While metals markets were previously influenced mainly by geopolitical disruptions such as the COVID-19 pandemic and the war in Ukraine, today's volatility is driven by a broader set of factors. These include persistent geopolitical tensions and increasing competition among various end-uses, including strategic stockpiling.
- Nickel, a critical element in both stainless steel and high-strength steel alloys, has become especially pivotal. Its importance is further amplified by its essential role in battery production, making it a key material in the energy transition and electric vehicle sectors.
- Importantly, the risks associated with metals are not solely tied to the volume required.
- Instead, they stem from their strategic role as components in equipment - regardless of where they sit in the value chain.

Energy Technology	Steel Requirement (tons/GW)	Usage of High-Strength Nickel Steel
Nuclear Power	40,000–50,000	Used extensively in reactor pressure vessels, piping, fasteners, and structural components due to high safety and temperature requirements
Offshore Wind	120,000–180,000	Used in foundations, towers, and support structures exposed to harsh marine environments
Onshore Wind	100,000–120,000	Used in towers and nacelles; less nickel steel than offshore but still significant
Solar PV	35,000–45,000	Mostly structural steel for mounting systems

Source CleanTechnica – for steel requirements in solar and wind energy., Stainless Steel World –for nickel-containing steel usage in wind turbines.
World Nuclear Association and general nuclear engineering literature – for steel usage in nuclear power plants. Rystad Energy & WindEurope (2023).

Concrete (sand and aggregate) could be the next critical resource

- Concrete demand is increasingly driven by energy transition-related civil engineering needs, rather than traditional sectors like construction and road infrastructure. Specialized concretes - using aggregates such as barite, magnetite, serpentine, and hematite - are vital for niche applications like radiation shielding and thermal management, adding complexity to supply chains.
- Europe's current production capacity of 1.05 to 1.75 billion metric tons annually may suffice for conventional use but could fall short amid accelerated energy infrastructure deployment.
- The industry, characterized by capital-intensive operations and long investment cycles, faces a growing mismatch between existing capacity and emerging energy-related demand.

Technology	Concrete Demand (tons per GW)	Comments
Nuclear	~900,000 to 1.2 million tonnes per GW	Includes reactor buildings, cooling towers, and safety structures.
Offshore Wind	500,000 to 800,000	Driven by heavy foundations (monopiles, jackets, or gravity bases).
Onshore Wind	240,000 to 400,000	Mostly for turbine foundations and access roads (depending on turbine size, foundation design, and site-specific conditions)
Stationary Battery	1000 to 10,0000	Mostly for housing and site preparation.

Source: ADEME, Inventaire des besoins de la transition énergétique, 2020
CleanTechnica – for steel requirements in solar and wind energy., Stainless Steel World – for nickel-containing steel usage in wind turbines. World Nuclear Association and general nuclear engineering literature – for steel usage in nuclear power plants. Rystad Energy & WindEurope (2023): IEA Wind Task 37 – Reference Wind Turbines; NREL – Materials Quantification for Wind Energy Growth

Levers as industrial strategies enabled by digitalization

Procurement & hedging to mitigate shortage risks from competing demands

- Diversify supply sources and prioritize sustainable sourcing.
- Strategically stockpile critical materials (without incurring additional costs).
- Implement procurement and hedging strategies to secure essential supplies.
- Continuously monitor key component storage levels in line with market trends and forecasts.
- Negotiate fixed-price contracts for essential components (e.g., through bookings or options).
- Prioritize high-risk materials and components.

Circularity to enhance sustainability and resource efficiency

- Leverage urban mining by reusing spare parts and production scraps and systematically applying circular economy principles while ensuring economic viability.
- Incorporate recycled materials into production processes to reduce dependency on virgin resources.
- Develop dismantling processes to recover valuable materials, integrating transformation costs into the overall economic model.
- Build a global recycling value chain, including the management of offtakers to ensure consistent material flow and value recovery.

R&D & process

- Favor components with lower resource intensity or those incorporating recycled materials.
- Promote safe substitution strategies, considering potential negative externalities.
- Integrate eco-design practices throughout product lifecycle.
- Extend equipment lifespan through advanced maintenance strategies.

Digital tools to support mitigation levers

- Enable intelligent supply chain capabilities incorporating resource constraints into planning algorithms.
- Utilize modeling tools for scenario planning.
- Use e-procurement systems aligned with market scenarios
- Deploy data platforms to enable circularity strategies
- Implement Life Cycle Asset Management systems to optimize resource use.

Our convictions

1 All resources are critical, yet some are being overlooked - leading to unexpected shortages and price spikes.

2 Resource criticality is increasingly driven by short-term market dynamics - such as price volatility and strategic behavior by key players (e.g., organized shortages aimed at driving up prices) - rather than by planetary boundaries or absolute scarcity. The persistent mismatch between supply and growing demand is further intensified by geopolitical tensions and the evolving economic outlook in Asia, with China remaining central and India playing an increasingly significant role. This creates a 'pendulum effect' that disrupts predictability and complicates long-term planning.

3 Even industries with relatively low resource consumption are exposed to risks due to the strategic importance of certain materials. This calls for a systemic approach to resource security across sectors.

4 Tariff pressure remains a key concern and must be factored into resource strategies. Identifying and mastering bottlenecks in global supply chains - especially in proprietary access to resources and control over equipment value chains - can unlock competitive advantage.

5 While mitigation strategies exist, they often come with added costs and uncertainties. These must be carefully assessed to ensure resilience without compromising economic viability.

6 Resources must be managed through a global, value-chain-oriented lens that integrates circularity. This includes urban mining, recycling, and dismantling strategies that recover value while reducing dependency on virgin materials.

7 Digital tools - such as modeling platforms, life cycle asset management systems, and e-procurement - are essential to enable a systemic resource strategy and support informed decision-making.

8 Anticipating and modeling resource risks is crucial to guide today’s technological and industrial choices - decisions that will shape competitiveness and sustainability over the next 50 years.

03

Energy transition: countries perspective

Introduction

The energy transition is still far from expected targets: countries perspectives.

Let's follow the carbon to understand the net zero question.

- Global progress in reaching net zero targets is slow, with only minimal improvement-though China has shown good progress.
- Europe has finalized its strategy, adding a competitiveness boost, signaling that economic prosperity is essential to achieving net zero.
- China treats net zero as both a planned economic project and a business model, flooding the markets with clean-tech products such as EVs, batteries, rare earth and metals and of course solar panels.
- Saudi Arabia invests in net zero using oil revenues, funding projects in renewables and carbon capture.
- The United States has abandoned its federal-level net zero aspirations under Trump II, signaling a more conservative path - though some states may pursue different approaches.
- European countries are becoming increasingly supportive of nuclear energy as part of their decarbonization strategy.
- Worldwide the required investment in the energy transition exceeds $3.5 trillion per year (vs $2.000tn today).

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Philippe has led the Capgemini Energy sector and now serves as an advisor for Capgemini, as well as large utilities or equipment suppliers. Philippe has been observing the market for many years and has sponsored the WEMO survey for more than a decade.

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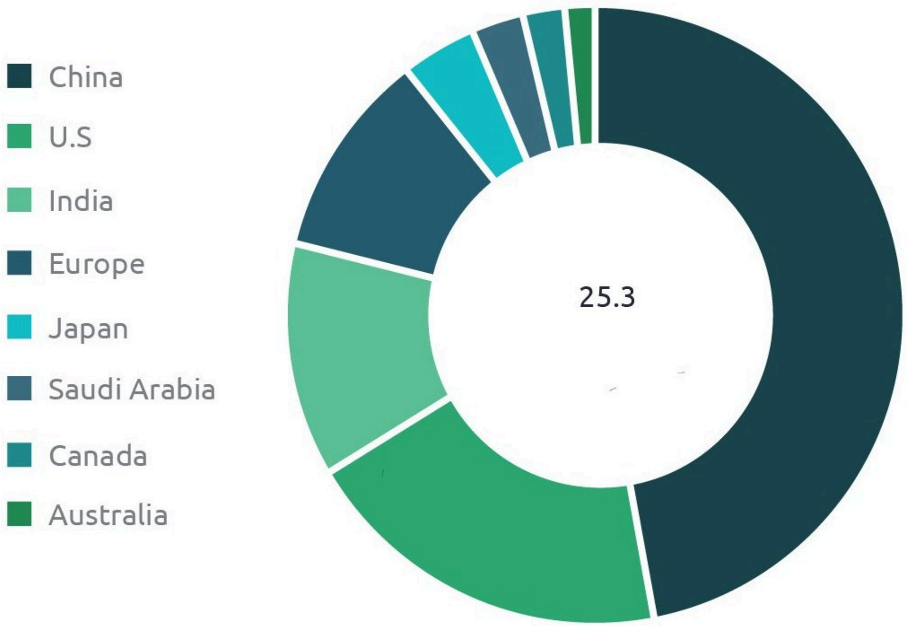
Manager - Invent Energy Transition & Utilities Germany
With experience in the Dutch and German energy sectors, Any advises international energy players on shaping operating models, addressing flexibility challenges, and navigating regulatory developments.

Every nation matters

US and China remain the top global carbon emitters by far driven by their emphasis on economic growth. Emission reductions in the near future appear uncertain, notably in the US. China plans to peak emissions before 2030 and to be net zero by 2060, while the US has reversed previous net zero commitments. Despite their outsized impact, focusing solely on these two nations is insufficient. Achieving global net zero goals demands collective action from all countries, including funding developing countries efforts.

FIGURE 1

Carbon emissions of selected economies 2023 (tons bn)



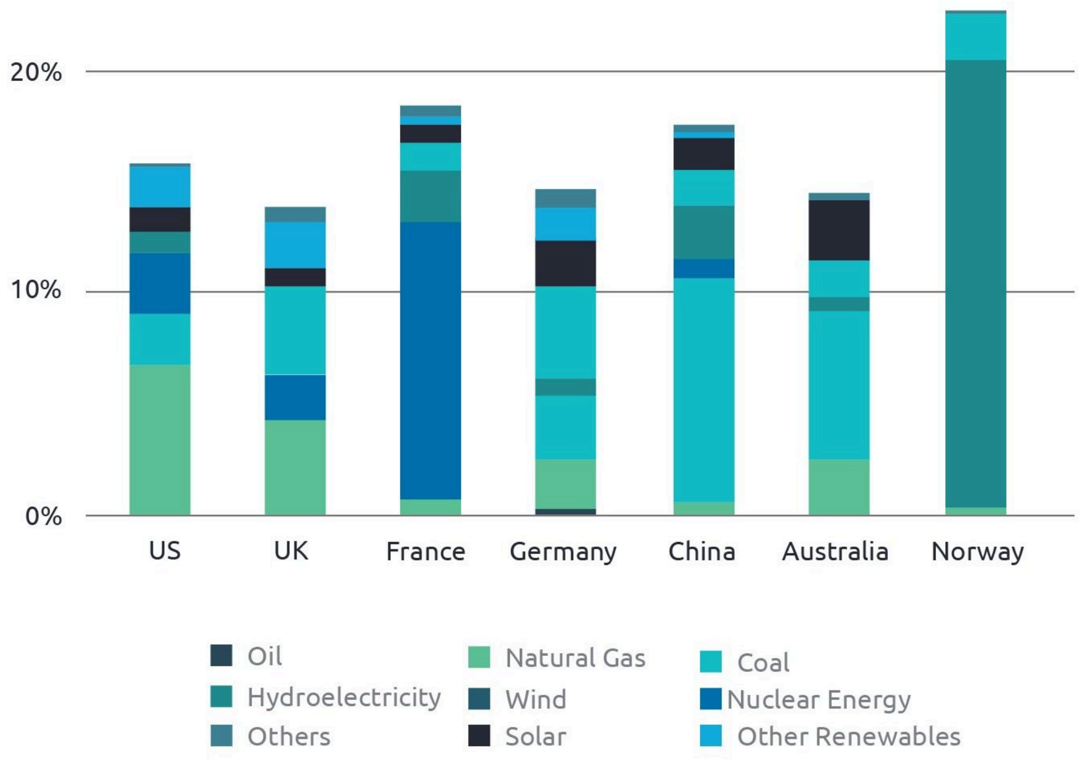
Sources: ourworldindata; Enerdata

One component for reducing emissions is **electrification**, but this requires **modernization of the grid as well as decarbonized electricity**. By now, electrification rates among major industrialized nations range from 13% to 25% (target being 50%), with Norway leading due to its reliance on hydroelectricity.

In contrast, countries like China, Australia, and the United States still depend heavily on fossil fuels, particularly coal and natural gas.

FIGURE 2

Electrification rate and electricity mix 2024



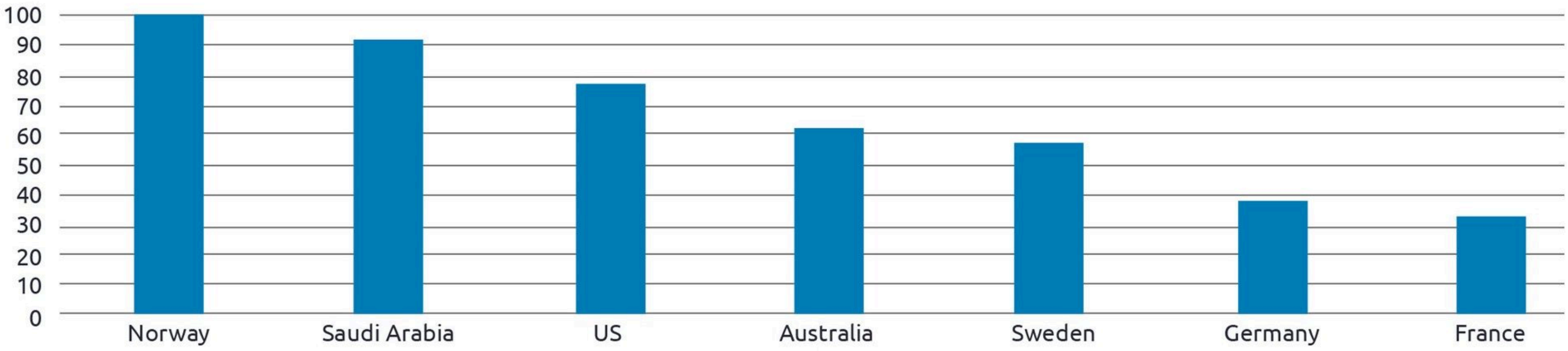
Sources: ourworldindata; Enerdata

The global struggle to achieve net zero

European countries, although leading the net zero race, face slow progress due to complex regulations, limited subsidies, and for few, a congested grid. Draghi's report highlights that European companies have ambitious net zero targets but receive limited government support, making it more difficult for them to compete with countries like China dominating the energy market thanks to a huge domestic market and lower labor and supply costs.

FIGURE 3

Energy consumption per capita (2024) [MWh/capita]



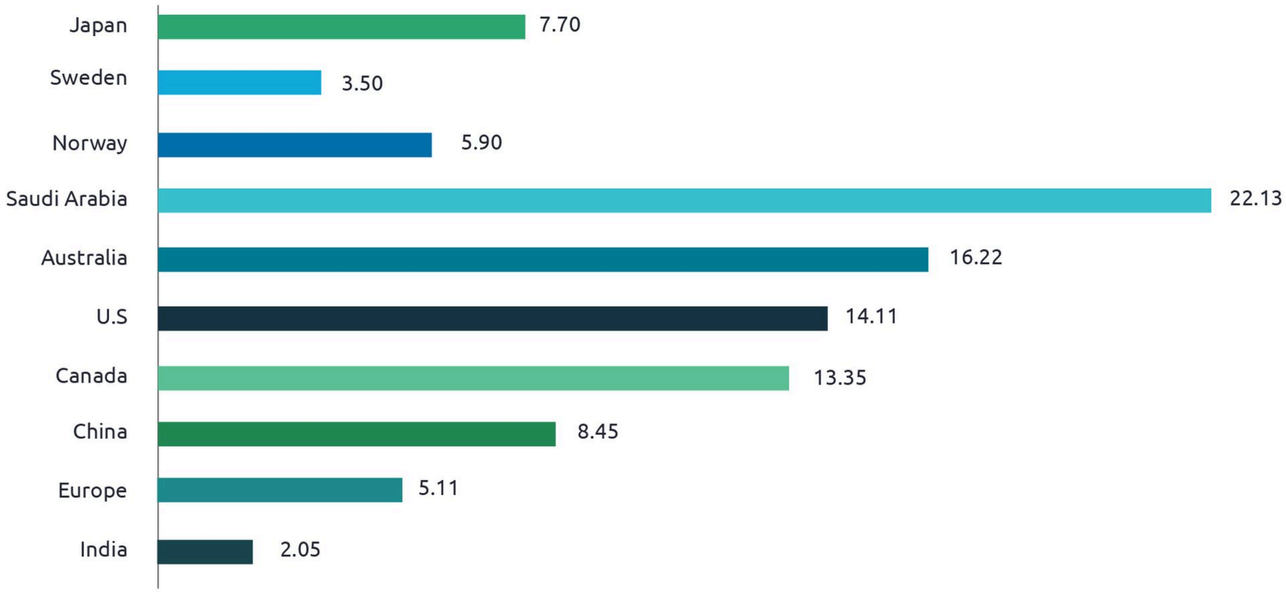
Source: Enerdata

Other countries, such as the United States and Australia, remain among the top global and per-capita polluter. US carbon emissions have declined slightly, by about 8% since 2019, but under Trump, the country shifted away from its net zero policy. Australia has even seen a slight increase in emissions since 2019, as it continues to rely heavily on coal.

Progress in CO_2 reduction in Norway and Sweden has stagnated since 2019, with Norway's per-capita CO_2 emissions close to China's and its per-capita energy consumption being the highest.

FIGURE 4

CO_2 emissions per capita (2024) [tons/capita]



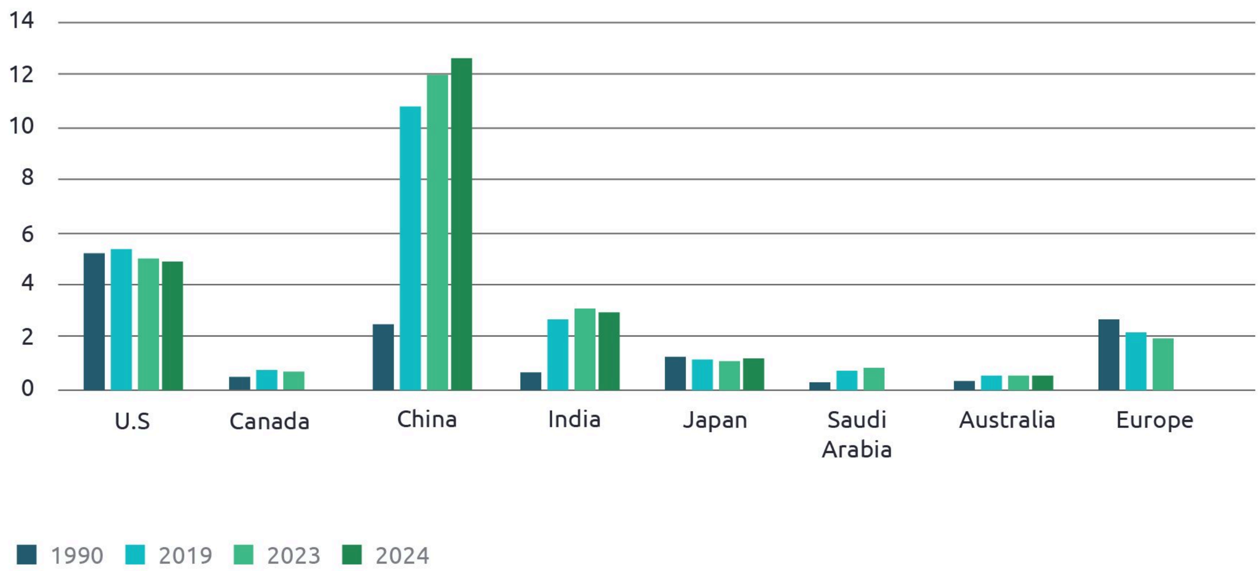
Source: ourworldindata

China, on the other hand, views also net zero as a business opportunity and is already a strong contender in the electrification market, However, China's CO_2 emissions have increased by an astounding 400% since 1990 and continue to rise, making China the largest carbon emitter by far.

Saudi Arabia, despite its reputation for its rapid modernization and cutting-edge technologies, has the highest CO_2 emissions and one of the highest energy consumption per capita as it continues to rely heavily on oil. The Kingdom's CO_2 emissions have been steadily rising since 1990.

FIGURE 5

Evolution of annual carbon emissions [tons bn]



Source: ourworldindata

FIGURE 6

Different paths to Rome: Each country has its own roadmap to net zero

Country	Renewables, Hydrogen	Nuclear	EV	Electrification	Investments	Political ambition
2060	Highly ambitious in building renewables fast	World leader in nuclear builds	Goal to make **45%** of new vehicles to be NEV by 2027	Grid expansion & industry electrification	Heavy state-led funding in all sectors	First-ever energy law effective in 2025
2050	High ambitions rolled back under Trump's policy	**200GW** of nuclear power to be added in next 25 years	Strong private sector but policy uncertainty	Trumps policy deprioritizes electrification	Inflation Reduction Act reversed under Trump's policy	Trumps policy deprioritizes Net Zero
2045	Strong push for solar, wind and partly hydrogen	Policy strictly against nuclear power	Goal of **15 million** EVs on German roads by 2030	Very high ambitions by international standards	Major share of debt package goes to energy	Ambitious targets, but complex implementation
2050	Ambitious, especially hydrogen leadership goal	Legally banned and policy remains against it	Growing, also due to supportive policies	High political ambitions for clean electricity	Rising, especially in hydrogen and renewables	Current government more ambitious
2050	Ambitious, aligned with global norms	Policy shift back toward nuclear	New passenger vehicles - **EV by 2035**	Moderate but strategic progress	Increasing investments	Strengthening with renewed political ambition
2050	Balanced renewable (solar, offshore wind), hydrogen	Nuclear energy as crucial part of low-carbon strategy	Goal of **800,000** annual PC-EV sales by 2027	High ambitions	€100bn investment plan by France's **TSO + €100bn DSO**	Roadmap revision still to be published - all aspects of the energy transition
2050	Strong targets, especially offshore wind and solar	Designated as critical national priority for net zero	Most ambitious regulatory EV framework	Decarbonized electricity grid by 2030	Serious commitment with high investments	Ambition to become "clean-energy superpower"
2060	Renewable targets and supporting initiatives	Former targets from 2013 were abandoned	Political targets on investments and EV share exist	Top-down push, but unclear national targets	Growing funding with Vision 2030 and more initiatives	Ambitious about increasing non-oil energy revenues

Source: ourworldindata

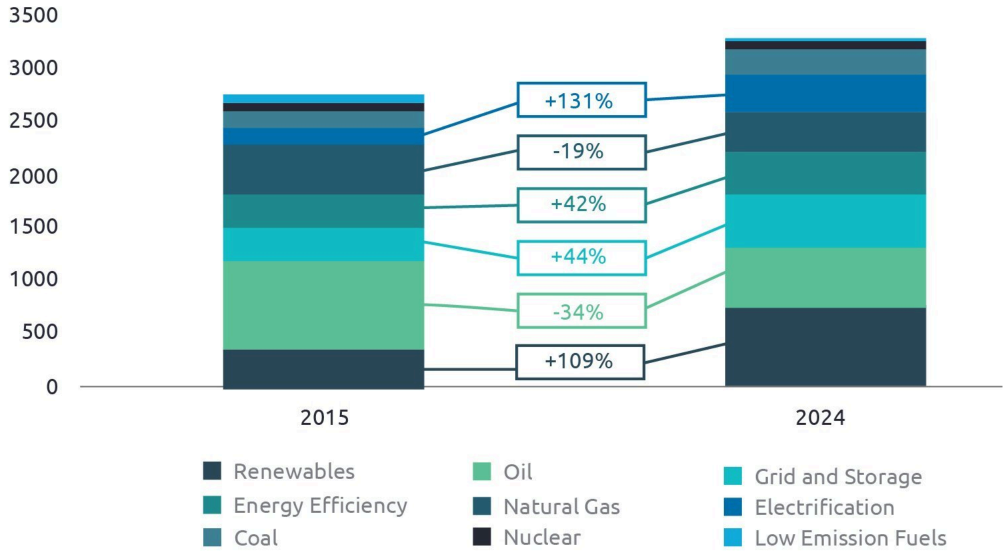
Energy transition investments haven't grown enough

The overall ambition of becoming climate neutral is reflected in global energy investments. Over the past decade, these investments have risen by more than 20%, with a major shift toward clean technologies such as renewables and grids. By 2025, they are expected to reach USD 3.3 trillion (approximately 3.3% of world GDP). In 2024, investments in low-carbon power, especially solar PV, were 50% higher than fossil fuel investments, reversing the trend seen in 2015. However, grid investment has not grown at the same pace, hindered by bureaucratic delays and supply chain challenges.

China is leading the global clean energy push, investing over $625 billion in clean energy in 2024 and achieving its 2030 wind and solar targets early. Yet, amid economic pressures and concerns over energy reliability, China has also increased investments in grid infrastructure and coal power for energy security. Over the past decade, the United States has significantly reshaped its energy investment strategy, reducing fossil fuel investments from 60% to 40% and, boosting investments in renewable manufacturing. However, under President Trump's current administration, recent cuts to clean energy spending and new tariffs on renewable imports have introduced uncertainty into the sector's future.

FIGURE 7

Global annual energy investments [USD bn]



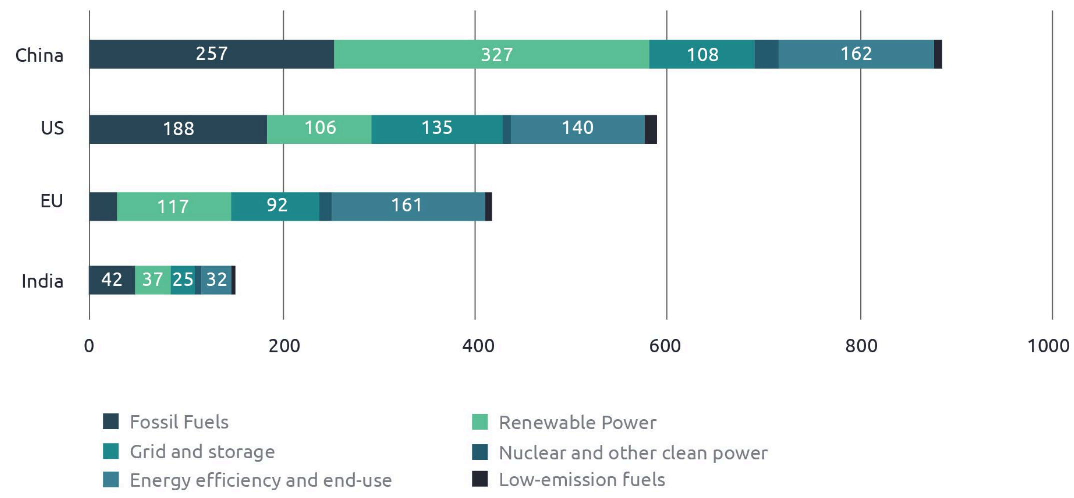
Source: iea

Meanwhile, the explosive growth of energy-intensive sectors like data centers and artificial intelligence has made energy security and grid efficiency a top national priority. Within the European Union, clean energy investments remain strong, supported by ambitious climate policies, but challenged by other nations' priorities. In Germany, total investment in renewables has more than doubled from €14.6 billion in 2021 to €38 billion in 2023, before slightly declining to €32 billion in 2024. However, lagging investment in grid (and related projects length) and storage infrastructure hinders further scale-up. Looking at an emerging economy, India has rapidly expanded clean energy investment, with 83% of 2024 power sector funding going to renewables (mainly solar PV), bringing non-fossil capacity up to 44% and attracting the world's highest development finance funding. Still, challenges like high financing costs, off-taker risk from indebted distribution companies, and inadequate transmission infrastructure continue to hinder projects viability and renewable integration in the country.

To meet global climate goals, the pace of the energy transition must accelerate. While growing investment in renewable power generation is essential and must even grow further, it's equally important that spending on power grids, storage, other cleantechs and energy efficiency keeps up. These areas are critical to managing the increasing share of renewables in the energy mix and ensuring a stable, reliable, and cost-effective energy system.

FIGURE 8

Annual energy investments per country and sector (2024) [USD bn]



Source: iea

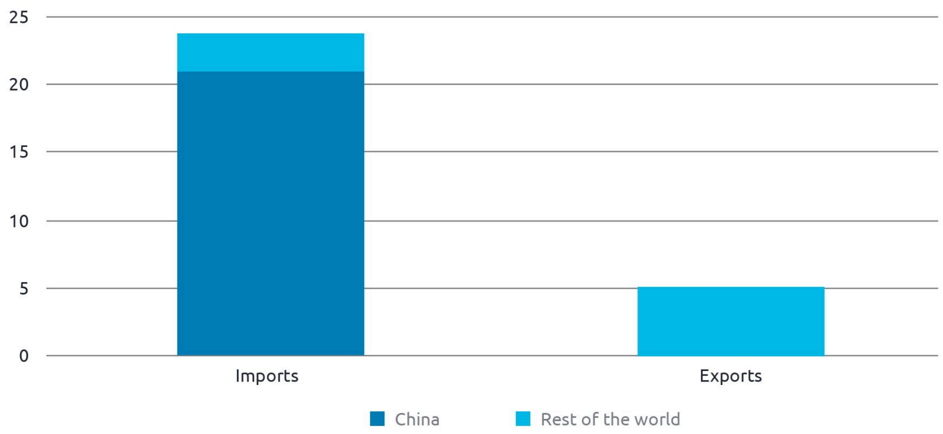
Economic prosperity matters to achieve net zero. Sovereignty has become critical with geopolitical troubles.

Recently, the European Union introduced the Competitiveness Compass following the Draghi report, which highlighted the contrast between the European and Chinese approach to net zero targets. China's policy has focused on boosting its economy to dominate the global economy, often at the expense of net zero progress. Nowadays, China's policy is ambitious on climate change and lands also on dominating the clean energy market by providing affordable materials and finished products such as batteries, EVs, solar panels, rare earths and metals, as well as wind turbines, gigafactories, and hydrogen electrolysers. Effectively, China has positioned itself as the world's primary supplier of clean technologies.

The EU, on the other hand (6.4% of world emissions), has been imposing much more ambitious decarbonization targets and wanted to be front-runner and example for countries. Still, high energy prices have made it difficult for European companies to remain competitive and invest in net zero. The Competitiveness Compass was therefore an extension of the old strategy: Instead of imposing strict targets, it aims to boost competitiveness and support businesses through lower energy prices, grid fees and subsidies.

FIGURE 9

EU imports vs exports of green energy products (2023) [EUR bn]



Source: Europe-data

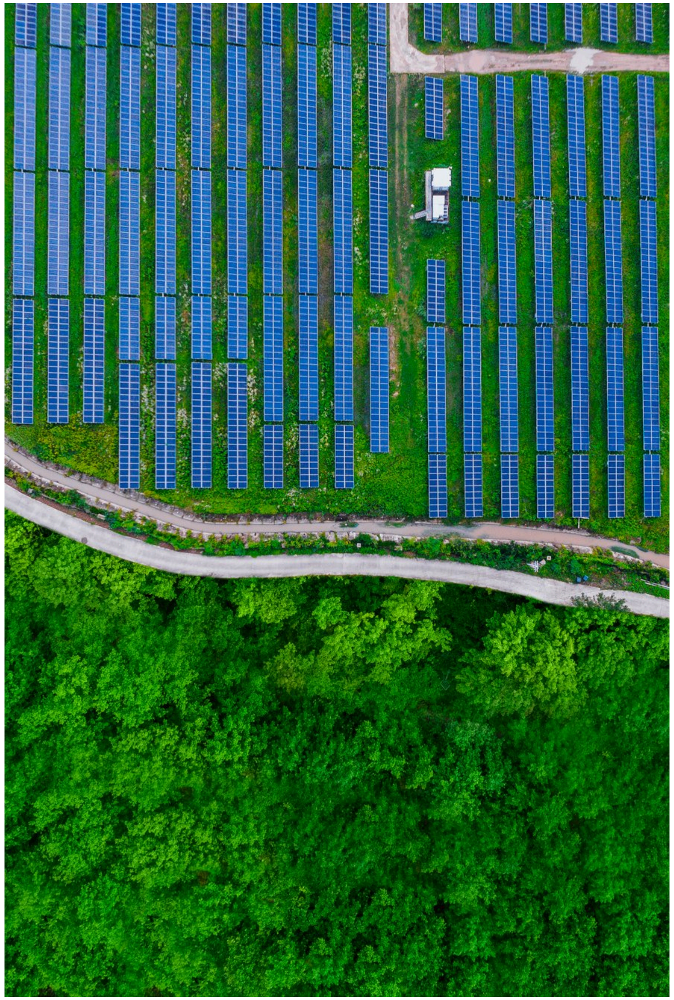
*Green energy products include solar panels, wind turbines and liquid biofuels

The new European strategy also focuses on re-industrialization, that includes modernizing the grid and accelerating investment permitting, as electrification can only add value when grid congestion is alleviated. But as energy grids become increasingly digital, safeguarding this critical infrastructure from foreign access and influence is essential. In this context, Europe's reliance on Chinese energy technology is considered a growing security risk. Reducing dependency and investing in domestic or allied production of key technologies will be crucial to ensure a secure and resilient energy transition. Europe faces a complex three-dimensional challenge: energy transition × sovereignty × competitiveness (affordable energy prices).

Moreover, there is increasing support for nuclear energy, with some countries (e.g., Denmark, Belgium) rethinking their positions and joining France, which produces roughly 70% of its electricity from nuclear and has much lower CO_2 emissions per capita than its neighbors.

The United States, caught in a trade war with China, had a more robust energy transition policy under President Biden, which was later reversed under President Trump. Trump's support for EVs (partly influenced by his relationship with Elon Musk) proved inconsistent, leaving the future of American energy policy uncertain and favoring fossil fuels. The latest spending bill proposes significant cuts to green energy incentives, including the early termination of tax credits for clean manufacturing and household technologies, if passed.

Saudi Arabia's policy, by contrast, is notably ambitious when it comes to net zero. The Kingdom has announced major plans to develop a comprehensive EV ecosystem, establish a civil nuclear power industry, and invest in carbon capture and storage. Interestingly, the same oil revenues that have fueled the Kingdom's economic success are now enabling greater freedom to experiment with renewable energy solutions.



Client story: Overcoming supply chain challenges to accelerate grid expansion

The supply chain challenge

By 2040, more than 80 million kilometers of power lines will need to be built or modernized worldwide. In Germany alone, around 25,700 kilometers of transmission grid are to be constructed by 2045 – with a substantial portion to be delivered by TenneT. This monumental task is triggering a global and intensifying race for raw materials, components, and highly specialized power electronics. But it's not just about supply chains – it's about energy security, economic strength, and Europe's role in a transformed global landscape.

What we need from policymakers

What we need now is an industrial policy framework that enables action and ensures investment security. The expansion of European production capacities – for instance in power electronics, transformers, or direct current technology – must be politically supported through demand-oriented planning, faster permitting processes, clear market conditions, and targeted incentives. This is how we ensure value creation in Europe, reduce dependencies, and strengthen the resilience of our energy infrastructure.

Anyone investing billions in strategic industries needs reliability. In times of geopolitical uncertainty, stable framework conditions are the most valuable currency. Europe must actively promote key technologies for the energy transition – from high-voltage systems and AI to semiconductor manufacturing. This requires a strong European alignment, lean structures, and investments in our technological sovereignty.

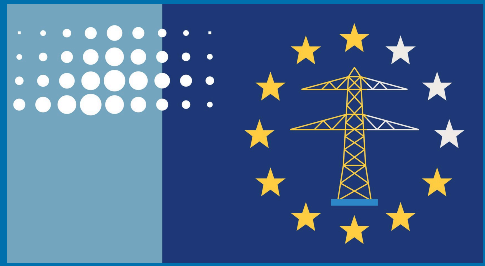
What TenneT is doing

TenneT has long relied on strong European procurement. Around 75 percent of our directly sourced components and services originate in Europe. This also has a direct impact on domestic value creation. Many of our investments flow back into Germany, as many components are "Made in Germany."

To counter market price pressures, we rely on long-term framework agreements with selected suppliers. Through strategic partnerships, we share commercial risks. Innovation drives the energy transition – but only if it can scale. The key to this is standardization. Together with our partners, we have developed cables and converter platforms that can transmit two gigawatts – the equivalent of two conventional power plants. What began as an innovation project is now setting the technical standard for grid expansion in Europe. This enables economies of scale, accelerating progress and reducing costs.

75%+

of the materials and services are to be sourced from Europe*



*Based on internal estimates, factoring in direct supplies and contractors.

Tim Meyerjürgens
CEO TenneT Germany

Supply chains are a key bottleneck in the energy transition – and often underestimated. Our energy future hinges on the availability and affordability of critical resources. Insights from Tim Meyerjürgens on current challenges and strategic answers.

FIGURE 10

We are still far from expected targets, globally

Technologies	Today (Fleet/ Production) 2024 YE	2030 pace / objective	2050 pace / objective	Are we on track?
Wind	**2024 total capacity: 1,133 GW** (fleet) **2024 added: 114.0 GW**	**150 GW / y**	**500 GW / y**	
Solar PV	**2024 total capacity: 1,859 GW** (fleet) **2024 added capacity: 452 GW**	**550 GW / y**	**615 GW / y**	
Nuclear	**2024 total capacity: 398 GW (439 units)** (fleet) **2024 added capacity: 452 GW**	**541 GW** (fleet)	**1,160 GW** (fleet)	
Low carbon Hydrogen	**2024 total production capacity: 1.7** Mt / y **2024 added capacity: 0.8** Mt / y	**125 Mt / y**	**523 Mt / y**	
Storage	**247 GWh** stationary (fleet) **Capacity - 94 GW / 247 GWh (2025)** **189 GW / 3,000 GWh (2025)** pumped (fleet)	Up to **1,600 GWh** stationary (NZS)	**6,000 GWh** stationary **10,000 GWh** pumped	
Electric transportation	**57 M** (fleet) **17 M** (2024 sales +25% YoY)	**360 M** (fleet)	**2180 M** (fleet)	
Heat pumps	**213 M units** (fleet) **+ 13 M pa / +6.5% YoY**	**450 M** (fleet)	**800 M** (fleet)	
CCUS	**0.6 GT** capture / y (production) +7% from 2023	**1.7 GT / y**	**3.3 GT / y**	
Energy intensity progress	**1.0% / y**	**3.3% / y**	**2.8% / y**	

Sources: IRENA-2025, IEA, Statista, World Nuclear Industry Status Report, European Heat Pump Association, Global Heat Pump Market Report 2024, Statistical Review of World Energy-2025, Enerdata, IHA, BNEF, and other secondary sources

Our convictions

1 **The world is not on track to meet the net zero target by 2050. Countries and regions are balancing climate targets with sovereignty and economic growth (energy competitiveness).**

2 **Each country has its own net zero journey with local priorities** and quite different sets of pillars: be it renewables, nuclear energy, or electrification. This is not a problem if net zero is achieved as soon as possible, and no later than 2050, while also meeting regional conditions (e.g., markets fluidity). But the question is which strategy is the fastest and most effective?

- China: High investments to economically dominate clean tech worldwide and subsequently transform its own economy to net zero.
- Europe: Renewables or nuclear strategies often combined with complex discussions how to balance priorities best (energy transition vs. industrial strength vs. affordability of energy).
- US: Clear focus on industry strength and de-prioritization of net zero ambition.
- Rest of the world: use energy transition re-structure and strengthen their own economy (e.g., Australia, Saudi-Arabia).
- Developing countries economic growth – THE priority - boost energy demand and emissions.

3 **From a technological point of view only PV/ solar power and heat pumps are the only dimensions to be almost on track with ambitions.** This indicates a clear dominance of decentralized technologies, which in turn requires:

- Acceleration of grid expansion and modernization or
- New or more local/ regional energy market designs

4 **Economic forces often outpace regulation, especially when regulatory progress is slow, unstable or lacks global alignment.**

5 **There are great examples of how energy transition works out once right regulations and technologies are combined**, e.g., California. However, 2025 also highlighted the vulnerabilities and complexities of renewable energy markets, such as the blackout in Spain.

And a call to action...

1 **Each state, country, and region must elaborate and publish an ambitious decarbonation roadmap.** Related local regulation should enable the ambition, be stable over time, and mitigate barriers to adoption and deployment.

2 In these challenging budgetary times, **long-term funding** for the energy transition—whether **public or private—must be secured.**

3 **Climate tech competitiveness at scale matters,** to unlock profitable investments.

4 **Companies,** especially international ones, **need to redefine their business model to support energy transition,** and participate in the newly created business value streams.

5 **Active consumer participation in energy savings and efficiency programs should be elevated as a priority.**

6 **Finally, developed countries must treat funding for the energy transition in developing nations as a sacred commitment.**

Capgemini

04
Flexible consumption

Introduction

Anticipating and seizing the opportunities of consumption flexibility

- Flexibility is expanding beyond traditional upstream services, creating new roles for storage operators, renewable producers, and aggregators on both sides of the meter.
- Behind-the-meter flexibility is unlocking economic and regulatory transformation, requiring dynamic pricing models, new contractual frameworks (e.g., sleeving), and updated consumer - supplier relationships.
- To scale these models, regulatory adaptation, international benchmarking, and structured stakeholder engagement (including legal tools and market incentives) are essential.

The energy transition is accelerating across Europe and beyond, driven by the need to decarbonize power systems and integrate growing shares of variable renewables. In this context, system flexibility - the real-time ability to adjust electricity generation and use - has become central to energy policy and grid stability. While the focus has historically been on front-of-the-meter (FTM) or supply-side flexibility, demand-side flexibility is now emerging as a critical and underutilized lever.

Consumption-side flexibility includes actions such as shifting usage in response to price signals, storing electricity off-peak, or participating in grid balancing. These services involve a wide range of actors - from industrial users and households to aggregators and storage operators - and increasingly take place behind the meter (BTM), where digitalization and new technologies are transforming energy use. This shift is prompting suppliers, regulators, and consumers to rethink their roles in the energy system.




Authors : Christine le Bihan-Graf & Laure Rosenblieh, Partners in the energy transition department at Hogan Lovells LLP Paris. Maxime Gardellin & Edouard Olson, senior associates of the team, also contributed.

What we are seeing

International markets show growing divergence in the pace and scale of flexibility deployment - especially behind the meter. Countries like the UK, Germany, the Netherlands, and the USA are leading with supportive regulation, targeted storage incentives, and digital infrastructure enabling real-time grid interaction. These frontrunners are also integrating distributed energy resources (DERs) into wholesale markets and testing innovative tariffs to activate consumer-side flexibility.

In France, progress is underway, notably through RTE and Enedis initiatives to define the value of services like frequency regulation and demand response. Article 175 of the 2025 Finance Law reflects a shift toward linking renewable support schemes to flexibility participation. However, France still lags behind top performers in downstream flexibility. Key barriers include tariff design (e.g., dynamic pricing), limited aggregator access, and the incomplete contractual integration of BTM assets.

New opportunities in flexibility

Enhancing upstream flexibility services

Traditional flexibility services, such as primary and secondary frequency control (FCR, aFRR), are now increasingly provided by a wider range of market participants. Once dominated by large centralized generators, these services now include battery energy storage systems (BESS), renewable producers, and aggregators, diversifying the grid's balancing resources.

BESS offer fast response and modularity, making them well-suited for short-duration balancing. Their integration is supported through auctions and standardized contracts, offering day-ahead flexibility or multi-year visibility. Aggregators play a key role by pooling smaller flexible assets and enabling their access to balancing markets.

Capacity markets have also adapted, rewarding flexible assets not just for energy delivery but for their peak availability, with remuneration tied to certified capacity. Still, the legal framework must continue evolving - to guarantee technology-neutral access, clarify certification, and align rules across borders. Without this, flexibility potential risks being underused.

Developing downstream flexibility services

Behind-the-meter (BTM) flexibility is emerging as a game-changer. Once limited to industrial sites, it now extends to households, commercial buildings, and energy communities. Consumers are increasingly installing batteries, EV chargers, and energy management systems (EMS) to respond dynamically to price signals and grid conditions. Flexibility services like time-shifting, peak shaving, and self-consumption optimization help reduce energy bills and monetize flexibility. These models gain value when paired with dynamic tariffs, real-time metering, and smart technologies. New actors - aggregators, storage-as-a-service providers, and energy service companies - are stepping in to manage assets for end-users.

BESS are central to this model, enabling multiple revenue streams: system services (FCR, aFRR, mFRR), intraday trading, capacity payments, congestion relief, and enhanced self-consumption. The value of each stream depends on technical configuration (BTM vs. FTM) and market design.

Capturing this value requires advanced EMS capable of real-time arbitrage. As flexible assets scale up, their coordination through standardized platforms will be key to achieving system-wide impact.

Deployment trends across Europe

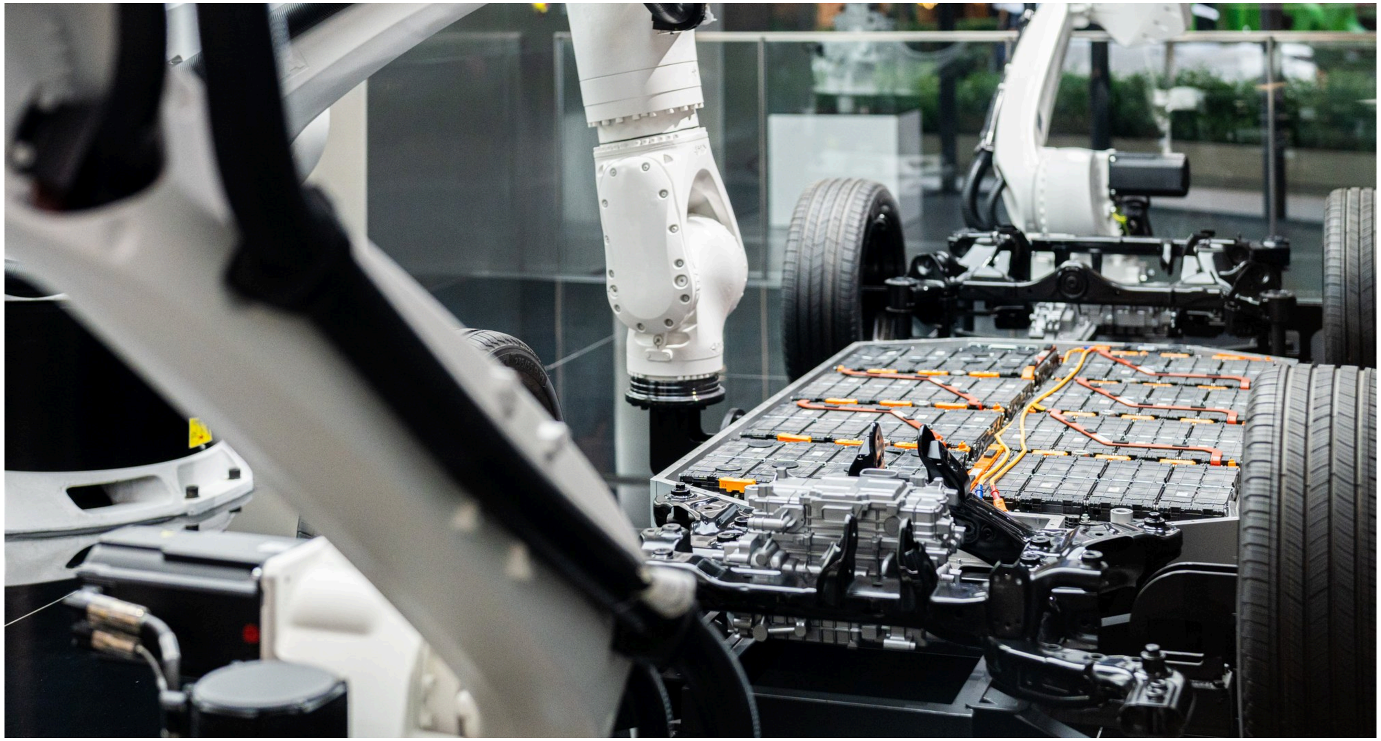
Battery storage deployment in Europe is progressing across both front-of-the-meter (FTM) and behind-the-meter (BTM) segments, each shaped by distinct drivers, project scales, and maturity levels.

By the end of 2022, around 4.5 GW of BESS capacity had been installed across Europe, with nearly 70% deployed in FTM applications. These systems —typically ranging from 5 to 200 MW - support grid services such as frequency regulation and balancing or are co-located with renewables to manage curtailment and price volatility.

BTM deployments, while currently representing a smaller share, are now accelerating, driven by consumer-facing incentives and the electrification of end uses. Though individually smaller - from 5 kW to 20 MW - they are rapidly scaling due to their distributed nature.

Their value lies in reducing supply costs and enhancing energy independence, particularly in segments where dynamic pricing and digital control systems are widely available.

Together, these deployment trends illustrate how BESS is being deployed across multiple levels of the energy system - from utility-scale grid support to decentralized consumer empowerment.



International benchmark: Lessons from advanced markets

Several countries are moving decisively to unlock consumer-side flexibility, offering valuable insights for France.

- **The United Kingdom:** The UK has built an advanced framework for residential flexibility. Nearly universal smart meter deployment, along with the Smart Export Guarantee (SEG) and the Capacity Market, allows households and aggregators to access grid services. DSOs have also launched local flexibility markets to monetize demand-side resources.

- **Germany:** Germany has been a pioneer in integrating decentralized energy systems, particularly hybrid PV + storage installations. Ongoing reforms aim to align grid tariffs with time-based energy value, encouraging off-peak consumption. Flexibility is also promoted to ease congestion in high-renewable zones.

- **The Netherlands:** The Dutch government has embraced digitalization and administrative simplification through tools like the "All-in-One Permit" - a unified platform designed to fast-track the approval of distributed energy projects. Combined with dynamic tariffs and demand response pilots, this approach supports rapid rollout of consumer flexibility.

- **USA:** Under FERC Order No. 2222, distributed energy resources (DERs) - including storage, demand response, and solar-plus-storage - can participate directly in wholesale markets across several U.S. regional transmission organizations (RTOs). Programs like SolarAPP+ streamline permitting for rooftop solar and storage, while Time-of-Use (TOU) pricing and demand flexibility programs have been widely adopted by utilities in states such as California, Texas, and New York.

> "Germany has been a pioneer in integrating decentralized energy systems, particularly hybrid PV + storage installations."

International benchmark: Lessons from advanced markets

Key success factors observed

- **Regulatory clarity and openness:** Simple, technology-neutral frameworks that reduce barriers to entry.
- **Market access:** Inclusion of DERs and aggregators in capacity and balancing markets.
- **Economic incentives:** Targeted support mechanisms for storage deployment, grid digitalization, and local flexibility.
- **Proactive system operators:** DSOs and TSOs actively developing local flexibility markets and congestion management platforms.

These international benchmarks show that clear rules, digital tools, and well-designed incentives are essential to unlocking flexibility at scale. France can draw from these examples to accelerate deployment, especially in the residential and commercial sectors where potential remains underutilized.

BESS capacity outlook in Europe and France

Battery energy storage capacity in Europe is expected to grow rapidly, from around 4.5 GW installed in 2022 to ~51 GW by 2030, and ~98 GW by 2050 (sources: *SolarPower Europe* and *Aurora Energy Research*).

These projections reflect the accelerating deployment of variable renewable energy, rising electrification, and the growing need for short-term flexibility and grid stability. Both front-of-the-meter (FTM) and behind-the-meter (BTM) storage solutions will contribute, supported by improved profitability and evolving market mechanisms.

France accounts for only 4% of installed BESS capacity in Europe (as of 2022), while the UK and Germany together represent nearly 70% of the market. However, a catch-up dynamic is expected, with France projected to reach approximately 20% of the European market by 2050. This progression will be driven by a combination of system needs and economic signals.

Two key factors underpin this acceleration:

- The rising share of intermittent renewables, which increases the need for storage to ensure grid stability; and
- The strong profitability demonstrated by early BESS projects, which is expected to attract further investment and scale deployment in the years ahead.

This deployment is also enabled by capacity remuneration mechanisms, targeted tenders, and regulatory incentives that facilitate both large-scale and distributed storage integration.

> France currently accounts for only 4% of installed BESS capacity in Europe (as of 2022), while the UK and Germany together represent nearly 70% of the market."

Legal and regulatory levers for enhancing flexibility

The evolving regulatory framework in France

A supportive legal framework is key to scaling flexibility - both upstream and behind the meter - in a fair and sustainable way. Today, most renewable producers lack incentives to contribute to grid flexibility, as feed-in tariffs and top-up payments shield them from price signals like negative market prices.

A turning point came with Article 175 of France's 2025 Finance Law, which allows supported renewable producers to be curtailed under specific conditions. This reform ties public subsidies to system needs, requiring producers above a certain capacity (e.g., 10 MW) to offer flexibility as part of their support package. It signals a shift toward performance-based models that better integrate intermittent renewables.

Looking ahead, additional legal tools could include:

- **Bonus-malus schemes** rewarding responsiveness;
- **Mandatory flexibility participation** for large RES in capacity or reserve markets;
- **Hybrid support models** bundling energy delivery and flexibility readiness.

Data access and interoperability

Access to real-time consumption, pricing, and network data is essential for effective flexibility services. Legal mandates ensuring data sharing between suppliers, network operators, and third parties - with strong privacy and cybersecurity safeguards - are needed to enable innovation and maintain trust. A neutral data hub or similar infrastructure could help deliver this interoperability.

Client story:

We advised a leading European operator of electric vehicle charging infrastructure, managing over 3,000 sites across the continent in partnership with major retail chains.

How we see this market / issue

The operator wanted to explore a strategic shift in their business model: moving from a pure EV charging player to a multi-service energy partner.

What we are doing

We conducted a comprehensive legal analysis covering French and EU energy law to assess the regulatory feasibility and constraints of these models.

Our work included a detailed review of licensing requirements, balancing responsibilities, participation in the French capacity mechanism (MECAPA), and the legal conditions for implementing sleeving and aggregation models.

We also advised on the structuring of energy contracts, data access rights, and compliance with French legal rules prohibiting unauthorized private grid connections.

Client story: NW

How we see this market / issue

A consortium of lenders led by Santander CIB and Rabobank approached us to legally structure and de-risk a €430 million financing package to support NW's second-generation JBox® systems across France and Finland.

What we are doing

We advised the consortium of lenders on the legal structuring of one of the largest private storage financings in Europe. The financing enabled NW to deploy more than 2 GWh of storage capacity by 2025, reinforcing its leadership in flexibility services.

Our role included a full legal and regulatory due diligence of NW's BESS activities in France and Finland, with a focus on electricity market participation, licensing requirements, compliance with EU energy law, and regulatory treatment of storage revenues.

We also assisted in drafting and negotiating the financing agreements.

NW is a French energy transition company and the national leader in battery electricity storage. Through its patented JBox® units, NW develops and operates large-scale storage infrastructure that supports grid stability in rural and peri-urban areas.

NW Réussir la transition énergétique

Contractual levers for enhancing flexibility

On the contractual side, new models are emerging to structure flexibility participation:

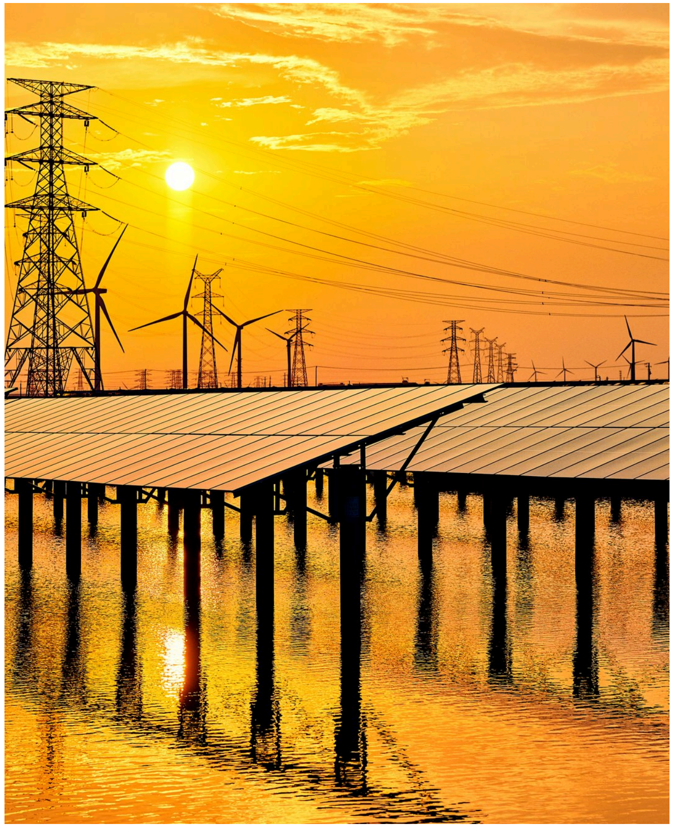
- **Sleeving agreements**, allowing third-party services to operate within a supplier's balancing perimeter without changing supply contracts.
- **Aggregation contracts**, pooling flexible assets into a unified offer in wholesale or balancing markets.
- **Performance-based or shared-savings models**, linking remuneration to measured results, particularly in commercial and industrial settings.

To scale these models, standardized templates, regulatory approval, and legal recognition of services like flexibility-as-a-service are essential.

The UK and Germany offer useful precedents, notably in aggregator-supplier rules and minimum transparency standards.

Public procurement and capacity mechanisms can also stimulate flexibility. Tenders with flexibility criteria or contracts-for-difference rewarding dispatchability would attract investment. Combined with time and location-sensitive tariffs, they would send clearer system-aligned price signals.

In sum, enabling flexibility requires not only market access but legal certainty, ensuring that all stakeholders, from prosumers to grid operators, can engage with clarity, confidence, and a shared understanding of rights and responsibilities.



The central role of grid operators

Transmission and distribution operators as active flexibility facilitators

One key factor in unlocking the value of consumption-side flexibility lies in the evolving role of grid operators — both transmission (RTE) and distribution (Enedis). While market participants and legal instruments are essential, flexibility also depends on how system needs are identified, signaled, and coordinated.

TSOs like RTE are taking on more dynamic roles. For instance, RTE has launched pilots testing geographically targeted flexibility incentives, guiding storage and flexible loads to areas with high solar output or grid congestion. These are early steps toward using flexibility as a localized grid management tool, not just a market mechanism.

DSOs like Enedis face increasing challenges from distributed generation and local grid stress. Yet, current regulations lack the mandates or tools to let DSOs procure or manage flexibility directly. Realizing this potential means creating local flexibility markets, empowering DSOs to contract services based on local needs, and clarifying their coordination with aggregators and suppliers.

Enabling tools: signals, platforms, and regulatory mandates

Grid operators are well placed to deliver granular, time and location specific signals - critical for guiding investment in flexibility assets. With smarter tariffs, transparent procurement platforms, and standardized data-sharing, TSOs and DSOs can become key enablers of a decentralized, resilient energy system.

But this requires strong regulatory support: clear mandates to procure flexibility when cost-effective, real-time asset visibility, and the ability to coordinate with aggregators and flexibility providers. Scaling flexibility won't depend solely on consumers or suppliers, but also on empowering grid operators.

Strengthening their role is essential to complete the value chain and ensure flexibility delivers both system-wide and local benefits.

Our convictions

1 Flexibility behind the meter must be fully recognized and integrated into market mechanisms.

2 Legal and regulatory frameworks must evolve to support hybrid actors and clearly define the roles of aggregators, storage operators, and consumers.

3 Creative contractual models - such as sleeving, aggregation, and dynamic pricing agreements - are key to unlocking new business models.

4 Market design must reward flexibility fairly, across energy, capacity, and ancillary service markets.

5 Digitalization and advanced EMS platforms are essential to orchestrating distributed resources effectively.

6 Anticipating flexibility means not just enabling the energy transition but making it economically viable, socially inclusive, and systemically resilient.

05
Infographic

Infographic

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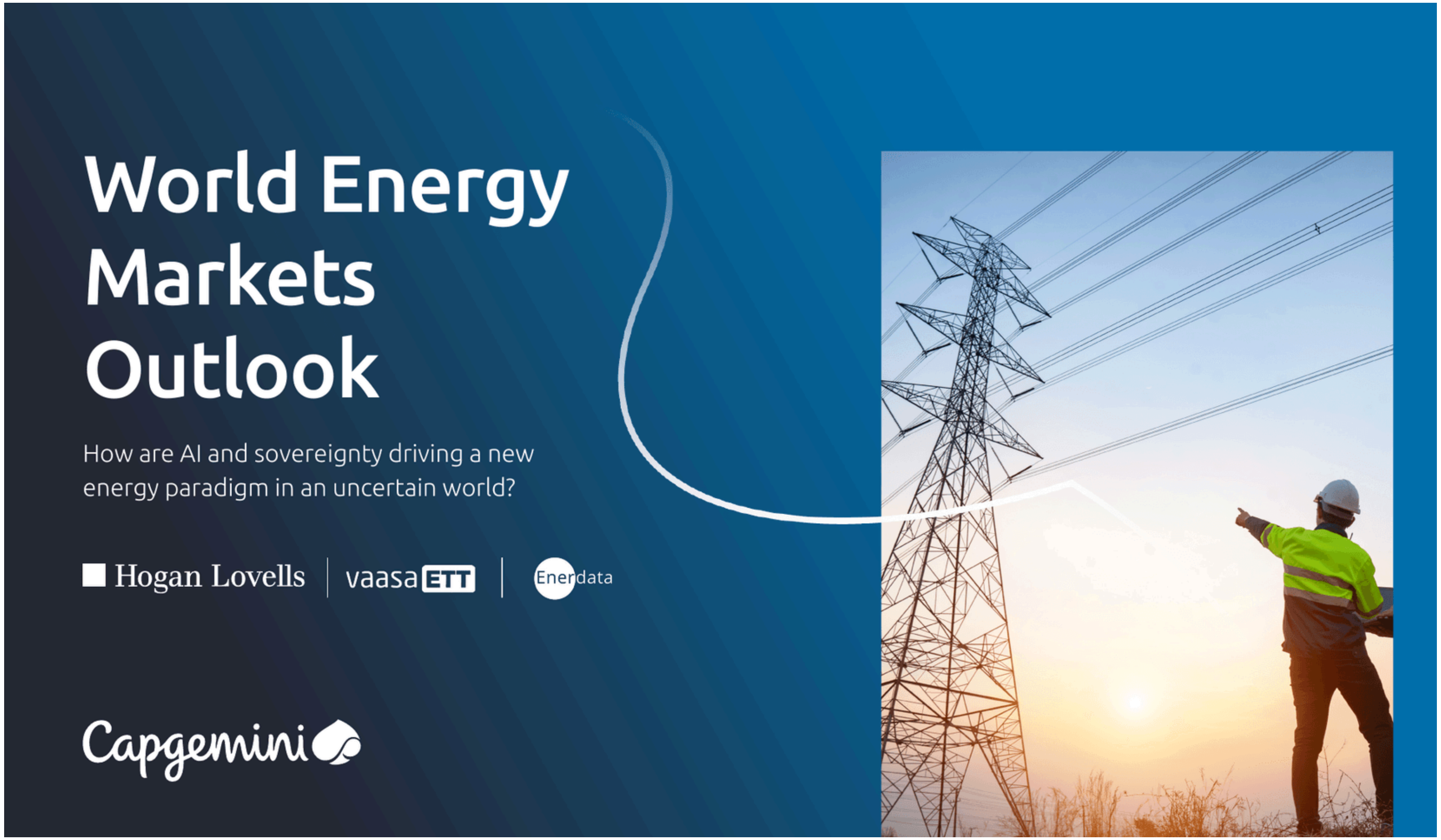
06
Data appendix

Data appendix



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Peter King, Lead Editor Peter King was lead editor on this chapter of WEMO. As Vice President, Energy Transition and Utilities at Capgemini Invent UK, Peter focuses on driving transformation by working with clients to define new ways of working, new operating models and the transformation programs that will deliver change.