

World Energy Markets Outlook

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

■ Hogan Lovells | vaasa **ETT** | Enerdata

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GLOBAL OUTLOOK



WEMO 2025 OUTLOOK



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Dear reader,

Let me first present the Outlook of the 27th edition of WEMO.

In the first section, we review the main trends for 2024 regarding energy and climate change.

We then examine three important questions for the energy transition success:

- ✓ Will nuclear energy contribute enough to the greenhouse gas (GHG) reduction objectives?
- ✓ Will electrical grids be able to adapt to the energy transition challenges?
- ✓ What technologies will support the energy transition?

We go on to analyze the impact of geopolitics on the energy sector, and finally ask: has the energy transition reached a tipping point?

I wish you an enjoyable read.





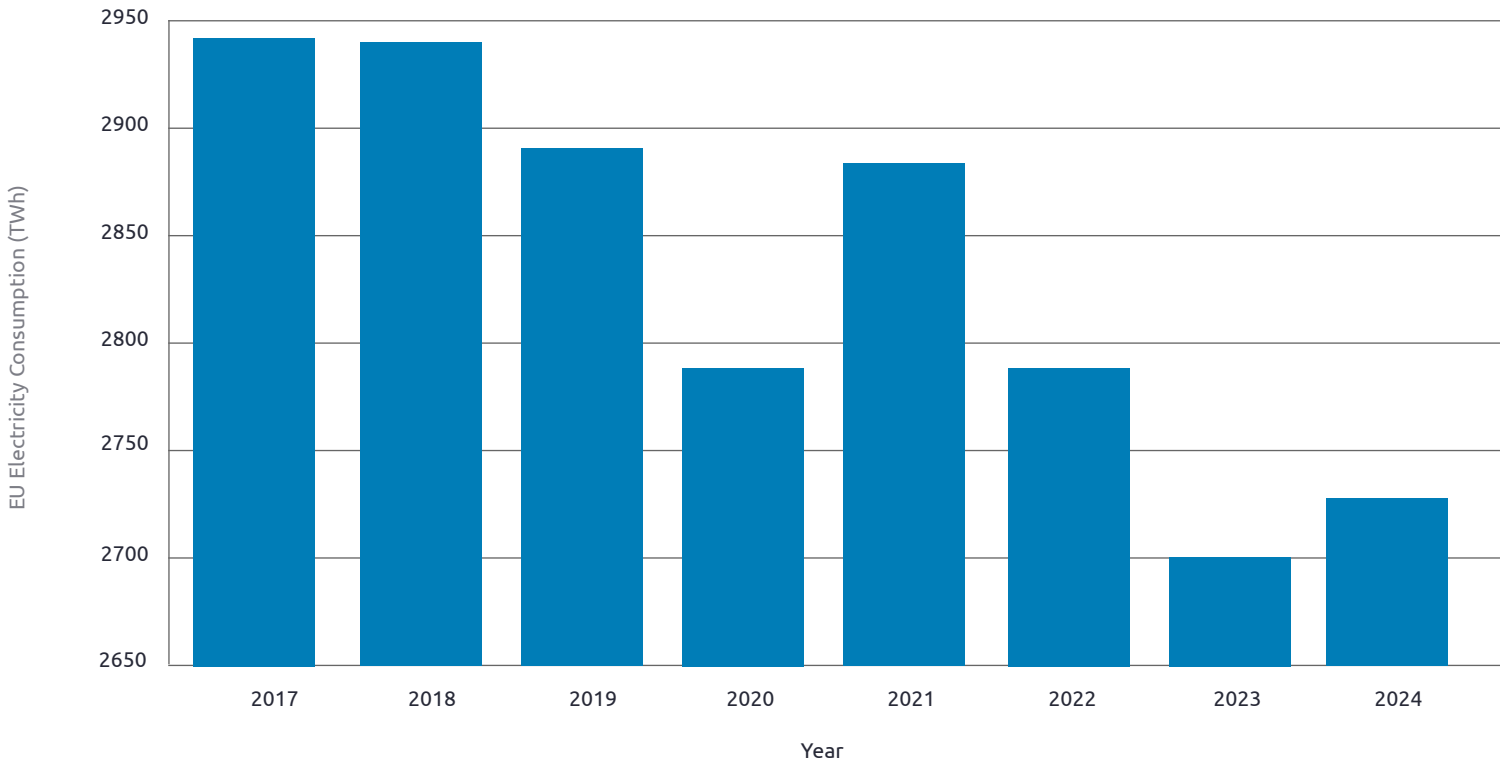
2024 Market Outlook

Global energy consumption grew:

- **Surge in global energy consumption** ^{1,2} Global energy consumption in 2024 rose by 2.2%, driven largely by a 4.3% surge in electricity demand. This growth outpaced the 2% increase in 2023. Emerging and developing economies accounted for over 80% of the 2024 electricity demand increase, with extreme weather, such as heatwaves in China and India, adding 0.3 percentage points to demand growth. Advanced economies saw a rebound in electricity consumption with nearly 1% demand growth reversing a 2% decline in 2023, led by the United States (+1.7%) and the European Union, which grew for the first time since 2021^{3,4} but is still lower than in 2017.

China’s energy demand growth slowed to under 3% from 6.6% in 2023, reflecting a post-Covid normalization, yet it remained a major driver. Renewables led the supply growth in global energy supply at 38%, followed by natural gas (28%), coal (15%), oil (11%), and nuclear (8%). Energy-related CO₂ emissions rose by 0.8% to 37.8 billion tonnes, slower than the 1.2% increase in 2023, mitigated by clean energy deployment avoiding 2.6 billion tonnes annually.

FIGURE 1
EU Electricity Consumption (2017 - 2024)



¹ <https://www.iea.org/reports/global-energy-review-2025>

² <https://www.iea.org/news/growth-in-global-energy-demand-surged-in-2024-to-almost-twice-its-recent-average>

³ <https://www.iea.org/reports/electricity-2025/demand>

⁴ <https://ember-energy.org/latest-insights/european-electricity-review-2024/eu-electricity-trends/#electricity-generation>

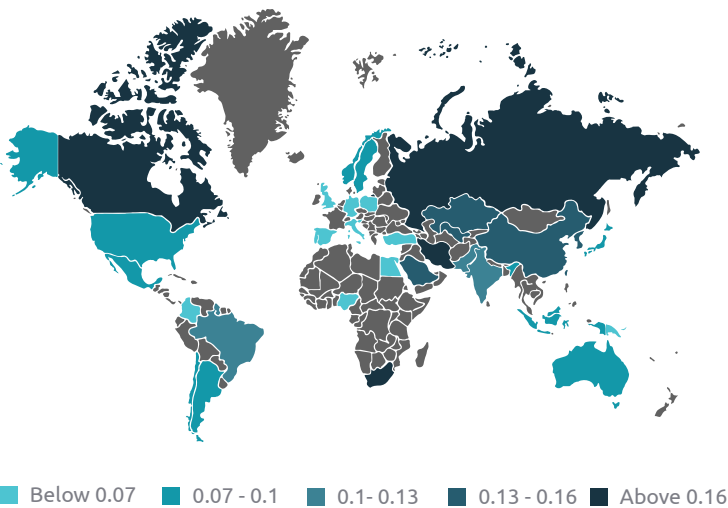


• **Weaker correlation between energy and Gross Domestic Product (GDP) evolutions^{5,6}** Historically, GDP growth and energy demand have been closely linked, with economic expansion driving higher energy consumption. However, from 2014 to 2023, a relative decoupling has been observed globally, where GDP growth has outpaced energy demand growth due to improvements in energy efficiency and shifts to service-based economies.⁷

This trend continued in 2024, with global energy demand rising by 2.2% compared to a GDP growth of 3.2%, suggesting that economic growth is less energy-intensive than in prior decades.

In China and India, the correlation remains stronger (e.g., China’s energy demand grew 3–6% annually, closely tracking its 4–6% GDP growth), driven by industrial and infrastructure expansion. In contrast, advanced economies, such as the EU and U.S., showed weaker correlations due to energy efficiency and service-sector dominance (e.g. advanced economies saw in 2024 a 1% rise in energy demand but a 1.7% GDP growth.)

FIGURE 2
Energy Intensity - 2024⁸



¹¹Methane (CH₄) is more than 28 times as potent as carbon dioxide (CO₂) at trapping heat in the atmosphere
¹²Source: IEA, Methane Abatement¹³

GHG emissions reached a record level in 2024⁹:

Global greenhouse gas (GHG) emissions in 2024 reached a record high of approximately 53.8 billion metric tons of CO₂ equivalent (GtCO₂e¹⁰), a 1.5% increase from in 2023. Fossil CO₂ emissions, the primary driver, rose by 0.8% to 37.4 Gt CO₂. Land-use change emissions, including deforestation and wildfires, surged by 11.9% to 4.2 Gt CO₂, largely due to extreme wildfire activity in South America during the 2023-2024 El Niño event.

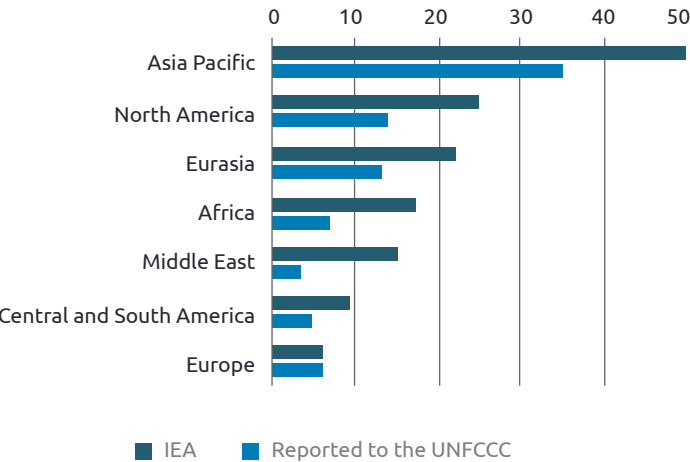
This GHG emissions increase shows insufficient progress toward the Paris Agreement goals, with emissions still far from the 42% reduction needed by 2030 for a 1.5°C pathway.

Curbing methane emissions is essential to reaching climate goals as methane is a very potent GHG¹¹. The energy sector contributes around 37% of the global methane emissions from human activities. In 2024 they reached 145 Mt a slight increase from 2023) driven notably by oil and gas leaks and flaring¹².

Graph - Source: Enerdata World Energy & Climate Statistics – Yearbook 20258
⁵<https://ourworldindata.org/energy-gdp-decoupling>
⁶<https://ourworldindata.org/energy-production-consumption>
⁷<https://www.statista.com/statistics/273951/growth-of-the-global-gross-domestic-product-gdp/>
⁸World Energy & Climate Statistics – Yearbook 2025
⁹<https://globalcarbonbudget.org/fossil-fuel-CO2-emissions-increase-again-in-2024/>
¹⁰CO₂ equivalent (CO₂e) is a unit of measurement that is used to standardise the climate effects of various greenhouse gases. In this outlook we will use indifferently CO₂ and CO₂e



FIGURE 3
Energy related methane emissions reported to the UNFCCC and IEA estimates, 2025¹³



Remedies include mandatory leak detection and repair programs, banning routine venting and flaring, and deploying vapor recovery units. Over 75% of fossil fuel methane emissions can be abated cost-effectively using existing technologies.¹⁴

Policies include the EU’s Methane Regulation¹⁵ and the US \$1.6 bn incentive¹⁶ under the IRA. Global cooperation via the Global Methane Pledge¹⁷ aims for a 30% reduction by 2030. To achieve these ambitious goals there is a need to thoroughly report all methane emissions and to scale up existing solutions. These solutions usually allow for the recovery of additional tradable gas quantities.

- **Partial decorrelation between GHG emissions and GDP:** Over the last decade (2014–2024), GHG emissions and energy consumption have shown a positive correlation globally, though the relationship is weakening due to energy efficiency and renewable energy adoption.

Energy accounts for over 75% of global GHG emissions, with fossil fuel combustion driving most of CO₂ emissions. In 2024, the rise of energy-related CO₂ emissions (by 0.8%) was less than the 1.2% increase in 2023, mitigated by clean energy deployment, avoiding 2.6 Gt CO₂ annually.

GHG emissions growth has been slower than GDP growth (3.2%), indicating partial decoupling.

The accelerated growth of electricity demand was met at 80% by low carbon sources¹⁸

- **In 2024, the global electricity demand increased by 4.3%** compared to 2023. This is more than the 2.5% YoY growth in 2023, and adds approximately 1,080 TWh, nearly double the average annual increase of 550 TWh from 2013 to 2023. This surge was driven by electrification in buildings, transport, and industry, alongside rising demand for air conditioning (due to severe heatwaves) and the expansion of data centers for AI. Emerging economies accounted for over 80% of this growth, while in Europe electricity consumption grew again after years of decrease.
- **Renewable contribution to electricity generation growth outpaced fossil fuels’ contribution.** Solar Photovoltaic (PV) led the increase in electricity generation, adding 474 TWh in 2024, reaching 7% of global electricity supply (up from 5% in 2023). Wind contributed 182 TWh, maintaining steady growth, while hydropower added 182 TWh, rebounding from 2023 drought-related declines in some regions. Nuclear power grew by 69 TWh, driven by new plants in Asia and increased output of existing plants in Europe. Wind and solar PV are expected to cover over 90% of the increase in global electricity demand in 2025.¹⁹

¹³ - [IEA, Methane Abatement](https://www.iea.org/energy-system/fossil-fuels/methane-abatement)
¹⁴ <https://www.iea.org/energy-system/fossil-fuels/methane-abatement>
¹⁵ <https://eur-lex.europa.eu/eli/reg/2024/1787/oj/eng>
¹⁶ <https://www.epa.gov/inflation-reduction-act/methane-emissions-reduction-program>
¹⁷ <https://www.globalmethanepledge.org/>
¹⁸ <https://www.iea.org/reports/electricity-2025/demand>
¹⁹ <https://www.iea.org/reports/electricity-mid-year-update-2025/executive-summary>



Natural gas generation increased by 103 TWh, particularly in the US and Middle East, while coal added 149 TWh, with 90% of this rise in China and India.

The buildings sector, driven by air conditioning, accounted for nearly 60% of demand growth (600 TWh), while industry contributed 40% (400 TWh), and transport, boosted by electric vehicle (EV) sales rising over 25%, added 8% to demand.

- **The rapid growth in data centers' electricity consumption is triggered by AI.** In 2024, data centers^{20,21,22} contributed to global and regional electricity demand, mainly driven by the rapid expansion of Artificial Intelligence (AI) but also by cloud computing, streaming and cryptocurrency mining. Globally, data centers consumed approximately 415 TWh of electricity, accounting for about 1.5% of total electricity consumption. The United States accounted for the largest share of global data center electricity consumption in 2024 (45%), followed by China (25%) and Europe (15%). While data centers remain a small fraction of global electricity growth (less than 10% of total demand increase), their concentrated nature strains local grids, particularly in regions with high data center density, such as Ireland where they account for 20% of total electricity consumption. This is prompting the government

to draft a new “private wire” policy enabling private operators to build and run direct power links to data centers.²³

In the United States,²⁴ data centers consumed around 4.4% of total electricity in 2023,²⁵ rising to an estimated 6% in 2024. This surge was driven by AI, cryptocurrency mining, and cloud services, with hyperscale data centers in states like Virginia and Texas leading consumption. The US Department of Energy projects that data center demand could reach up to 12% of US electricity by 2028.

According to the IEA report,²⁶ data center electricity consumption is set to more than double, reaching approximately 945 TWh by 2030 (slightly more than Japan's total electricity consumption today).

The energy-intensive nature of AI, with ChatGPT queries requiring nearly 10 times the power of a Google search (2.9 Wh vs. 0.3 Wh), has amplified data center electricity demand. Additionally, streaming platforms like Netflix and YouTube consume over 200 TWh annually, further boosting data center loads. Moreover, Large Language Model (LLM) training requires thousands of GPUs to operate in lockstep and perform the



same computation on different data. This synchronization results in power fluctuations at the grid level. Unlike traditional data center workloads, where uncorrelated tasks smooth out the load, AI workloads cause abrupt transitions between idle and high-power demand. Those transitions are likely to become increasingly abrupt as more LLMs come online, and more difficult for grids to balance demand and supply under those conditions. To address this, the new Nvidia AI system²⁷ uses several mechanisms across different operational phases,

²⁰<https://www.iea.org/news/ai-is-set-to-drive-surging-electricity-demand-from-data-centres-while-offering-the-potential-to-transform-how-the-energy-sector-works>

²¹<https://www.jeffries.com/insights/the-big-picture/how-data-centers-are-shaping-the-future-of-energy-consumption/>

²²<https://www.iea.org/reports/energy-and-ai/executive-summary>

²³<https://www.datacenterdynamics.com/en/news/ireland-plans-legislation-for-data-centers-to-build-and-run-own-power-lines-report/>

²⁴<https://escholarship.org/uc/item/32d6m0d1>

²⁵<https://www.energy.gov/articles/doe-releases-new-report-evaluating-increase-electricity-demand-data-centers>

²⁶<https://www.iea.org/reports/energy-and-ai/executive-summary>

²⁷<https://www.eenewseurope.com/en/nvidia-details-ai-power-supply-adds-innoscience-gan/>

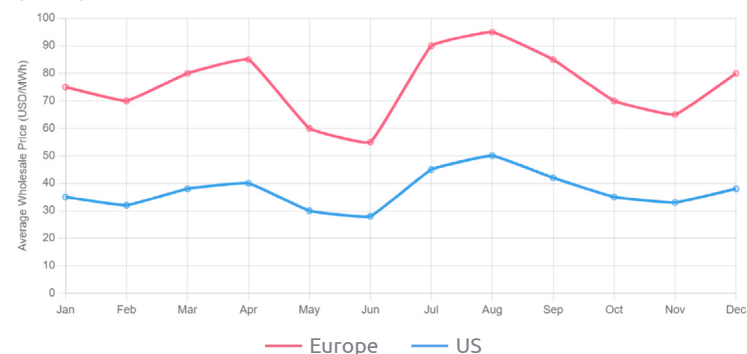
combining power cap, energy storage, and GPU burn mechanisms. The first experimental results show that this new design eliminates the power variations and the peak power demand seen by the grid is reduced by 30%.

In parallel, Google has introduced a new methodology to measure the environmental impact of AI inference with greater granularity, factoring in hardware type, location, and workload. This enables operators to pinpoint inefficiencies, optimize deployments, and improve sustainability.²⁸ Efficiency improvements and innovations like liquid cooling for data centers are underway, but the rapid growth of AI and hyperscale facilities continues to outpace these efforts, posing challenges for low carbon electricity supplies, GHG emissions reduction and electrical grids resilience.

However, AI also has the potential to enable emission reductions in data centers and elsewhere and its usage could accelerate innovation in energy technologies such as batteries and solar PV (see below the chapter on technologies).

FIGURE 4

Average monthly wholesale electricity prices in Europe and US (2024)



- **While electricity wholesale prices declined in Europe, they remained much higher than in the US^{29,30,31}:**

In 2024, European wholesale electricity prices continued to decline driven by falling natural gas prices and increased renewable output, averaging €74/MWh. They dropped by 22% from 2023 (€95/MWh) and fell sharply from 2022's €150–300/MWh peak during the energy crisis triggered by Russia's invasion of Ukraine and high natural gas prices.

However, 2024 prices remained 2.5 times higher than pre-COVID levels of €30–35/MWh in 2019–2020.

In the U.S., wholesale prices in 2024 were lower and less volatile, averaging \$36/MWh, down from \$63/MWh in 2022 and slightly below 2023's \$37/MWh, due to low natural gas prices (\$2.21/MMBtu) and solar and wind generation growth. Europe's 2024 wholesale electricity spot prices were significantly higher than the United States', driven by Europe's reliance on imported natural gas, especially more expensive LNG (Liquified Natural Gas), and more stringent environmental constraints such as ETS (Emissions Trading System) obligations.³² The US benefited from abundant domestic gas and a 45% increase in renewable generation since 2020, keeping prices closer to pre-crisis levels (\$40–50/MWh in 2019).

The divergence explains European high-electricity-consuming industries' competitive challenges towards their American peers.

²⁸ <https://cloud.google.com/blog/products/infrastructure/measuring-the-environmental-impact-of-ai-inference?hl=en>

²⁹ <https://www.iea.org/reports/electricity-2025/prices>

³⁰ <https://ember-energy.org/data/european-electricity-prices-and-costs/>

³¹ <https://www.eia.gov/todayinenergy/detail.php?id=64284>

³² https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

³³ <https://www.iea.org/reports/electricity-mid-year-update-2025/prices-trends-in-wholesale-markets-differ-across-regions>



Natural gas markets returned to growth in 2024^{34,35}

Following the supply shock of 2022, natural gas markets moved towards gradual rebalancing and returned to structural growth in 2024 (+2.8% compared to 2023³⁶). Global gas consumption exceeded 4,200 billion cubic meters (bcm), with the Asia-Pacific region accounting for nearly 45% of the growth due to industrial expansion and decarbonization efforts.

Asia-Pacific led the growth, with China's consumption rising by 7% due to coal-to-gas switching and power sector demand growth, and India's by 10% fueled by industrial and cooling needs.

North America's gas consumption grew by 1.8% notably driven by power generation needs. Europe's consumption remained flattish (+1%), due to high gas storage levels, renewables growth, and EU demand-reduction policies extended through March 2025.

The global LNG market tightened due to limited new capacity, with prices rising but remaining below 2022–2023 peaks. It will likely change in 2025–2026 with mega LNG projects entering production, such as Plaquemines LNG, Copus Christi Stage 3 and Golden Pass LNG. These three projects are projected to increase U.S. LNG export capacity by nearly 50% from 2024 levels.³⁷

In 2024, Liquefied Natural Gas (LNG^{38,39}) accounted for approximately 13% of the global natural gas market. The U.S. led exports with a 21% share, followed by Qatar (20%) and Australia (19%).

On the demand side, Asia-Pacific dominated LNG imports, contributing 70% of global demand. Europe's LNG imports remained stable at 150 bcm representing 45% of its gas supply, with the US supplying 46% of EU LNG.

Over the next five years, LNG supply capacity is projected to grow at an 8.35% CAGR driven by U.S. and Qatar expansions. Asia, particularly China and India, will drive demand growth, while Europe's demand may peak due to decarbonization efforts.

• **As for electricity, gas prices showed significant regional disparities.** Europe faced higher prices and the US benefited from abundant domestic production.

In 2024, LNG prices globally averaged \$10.05-\$14.23/MMBtu^{40,41}, significantly higher than pipeline natural gas due to liquefaction, shipping, and regasification costs⁴². Europe's TTF⁴³ hub⁴⁴ saw pipeline gas prices at \$10.37-\$13.98/

MMBtu, driven by supply constraints, while U.S. Henry Hub pipeline gas prices averaged \$2.21-\$3.26/MMBtu, supported by record production and high inventories.⁴⁵ Key drivers included Europe's reduced Russian gas and unplanned Norwegian facilities outages, contrasted with U.S. production strength.

LNG prices in Asia, notably Japan and China, were aligned with Europe's LNG prices.

• **The share of Russian gas in European Union imports has significantly declined from 2021 to 2024.**^{46,47}

This decline is driven by reduced Russian supply following Russia's invasion of Ukraine, diversification of supply, and reduced transportation pipeline capacity. In 2021, Russia supplied approximately 45% of EU gas imports (155 billion cubic meters), including both pipeline gas and LNG. In contrast, in 2024, Russian gas accounted for only 14% of EU imports (45 bcm, comprising 32 bcm pipeline and 20 bcm

³⁴<https://www.iea.org/reports/global-energy-review-2025/natural-gas>

³⁵<https://www.pwc.com/us/en/industries/energy-utilities-resources/library/future-of-lng.html#:~:text=In%202024%2C%20global%20natural%20gas%20consumption%20rose%20by%20growth%20due%20to%20industrial%20expansion%20and%20decarbonization%20efforts.>

³⁶This was above the 2% annual average growth rate from 2010 to 2019 and well above the rate of around 1% between 2019 and 2023.

³⁷<https://www.eia.gov/todayinenergy/detail.php?id=64884>

³⁸<https://www.mordorintelligence.com/industry-reports/global-lng-market-industry>

³⁹<https://www.grandviewresearch.com/industry-analysis/liquefied-natural-gas-lng-market>

⁴⁰<https://www.eia.gov/dnav/ng/hist/n9133us3m.htm>

⁴¹<https://www.statista.com/statistics/252984/>

⁴²[landed-prices-of-liquefied-natural-gas-in-selected-regions-worldwide/](https://www.statista.com/statistics/252984/landed-prices-of-liquefied-natural-gas-in-selected-regions-worldwide/)

⁴²LNG costs \$7-\$11/MMBtu more than U.S. pipeline gas and \$0-\$2/MMBtu more than European pipeline gas.

⁴³TTF is a Dutch gas trading hub operated by Gasunie. It is a reference for the European market prices

⁴⁴<https://www.oxfordenergy.org/publications/european-traded-gas-hubs-the-supremacy-of-ttf/>

⁴⁵<https://www.statista.com/statistics/252791/natural-gas-prices/>

⁴⁶<https://ember-energy.org/latest-insights/the-final-push-for-eu-russian-gas-phase-out/>

⁴⁷<https://www.statista.com/statistics/1021735/share-russian-gas-imports-eu/>



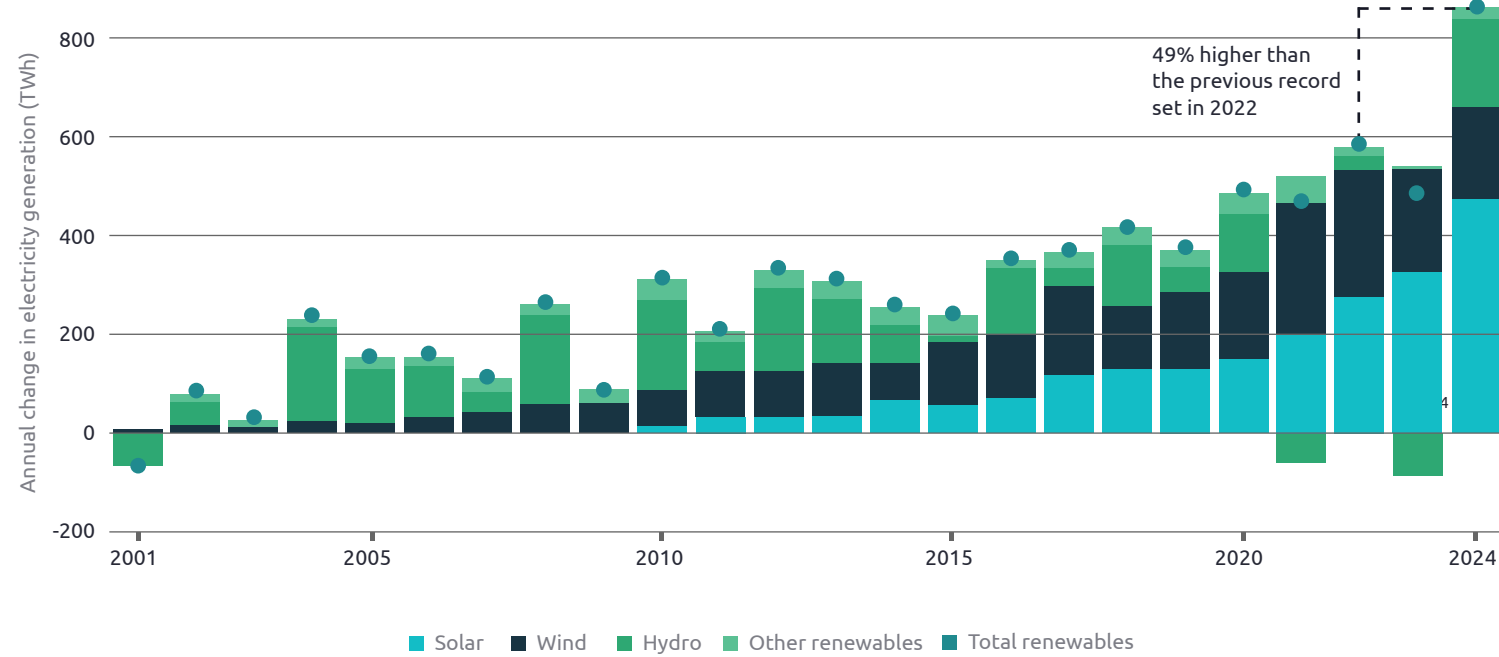
LNG⁴⁸). However, this share of imports increased by 18% from 2023 due to higher Russian LNG imports,^{49,50} driven by cheaper spot market sales. Pipeline import from Russia decreased due to Nord Stream closure, leaving Ukraine transit and TurkStream as primary routes. In 2025, transit through Ukraine stopped. *Despite this transit restriction and the EU sanctions on Russian oil and coal, the EU's imports of Russian fossil fuels reached €21.9 billion in 2024, exceeding the €18.7 billion in EU financial aid provided to Ukraine.* In 2024, the U.S. supplied Europe with about 55bcm⁵¹ of LNG supplies, (this accounted for 46% of Europe's total LNG imports⁵²) replacing a large share of Russian gas.

By 2030, LNG capacity increases notably in the US and Qatar⁵³ could result in a gas supplies exceeding demand by 26% triggering a price decrease.⁵⁴

- **EU is increasing sanctions against Russian gas:** A 17th EU sanctions package⁵⁵ was adopted in May 2025, focusing mainly on Russia's "shadow fleet" of oil tankers. In addition, the European Commission (EC) has proposed⁵⁶ a roadmap to phase out all Russian gas imports by the end of 2027, with legal measures to ban spot contracts by the end of 2025⁵⁷.

⁴⁸[https://vleva.eu/storage/1459/COM\(2025\)-440-final_Roadmap-towards-ending-Russian-energy-imports.pdf](https://vleva.eu/storage/1459/COM(2025)-440-final_Roadmap-towards-ending-Russian-energy-imports.pdf)
⁴⁹<https://www.highnorthnews.com/en/eu-imports-more-russian-lng-2024-ever-mostly-arctic>
⁵⁰<https://www.bloomberg.com/news/articles/2024-12-20/europe-still-clings-to-russia-gas-with-record-lng-flow-this-year/embedded-checkout=true>
⁵¹based on the conversion factor of 1 MTPA ≈ 1.38 bcm
⁵²<https://www.fitchratings.com/research/corporate-finance/russian-gas-unlikely-to-return-to-europe-in-large-volumes-02-04-2025>
⁵³QatarEnergy is expanding LNG production capacity to 91bcm per annum by 2028 from 56bcm per annum currently. US LNG export capacity will grow by 100bcm per annum during 2024-2028

FIGURE 5
Global renewables growth in 2024 was 49% higher than the previous record



⁵⁴<https://ember-energy.org/latest-insights/the-final-push-for-eu-russian-gas-phase-out/>
⁵⁵https://finance.ec.europa.eu/news/eu-adopts-17th-package-sanctions-against-russia-2025-05-20_en

⁵⁶<https://www.euronews.com/my-europe/2025/05/06/eu-sets-2027-as-deadline-to-phase-out-all-russian-energy-including-lng>
⁵⁷Short-term contracts account for one third of Russian gas imports



Development of renewables⁵⁸

• Solar dominated the global renewable capacity increases:

While it is an impressive achievement, it is important to keep in mind that capacity factors are very different for wind or solar generation (around 23% for solar and 34% for wind⁵⁹) and dispatchable clean generation nuclear (around 90%). Consequently, 1 GW of solar installed capacity, produces roughly only 26% of the electricity generated by 1 GW of nuclear plants⁶⁰.

Solar and wind power account for 96.6% of these net renewable additions. Solar photovoltaic (PV) led with 451.9 GW of new capacity (77.3% of renewable growth), a 32.2% increase, bringing total installed solar capacity to 1,865 GW. Wind power added 113 GW (19.3% of renewable growth), up 11.1%, reaching 1,133 GW, with onshore wind dominating (93% of wind capacity) and offshore wind growing in selected regions.

China drove 64% of global additions, installing 277 GW of solar (up 45.2%) and 80 GW of wind (up 18%), surpassing its 2030 targets early. The US added around

50 GW of solar⁶¹ and 5 GW of wind, with total installed capacities of 179 GW and 153 GW, respectively. The clean energy generation represented 41.9% of the electricity generation while fossil fuels share decreased at 58.1%⁶²

The EU added 53 GW of solar and 17 GW of wind, with Germany, Spain, and France leading, bringing regional totals to ~90 GW (solar) and ~220 GW (wind). Consequently, the clean energy⁶³ share (including nuclear) of electricity generation, amounted to 71% as the fossil share declined to a historic low of 29%. The intermittent nature of wind and solar generation led to increased negative prices. This surge in negative price hours combined with long grid connection queues, highlights



⁵⁸ <https://www.weforum.org/stories/2025/04/renewable-energy-transition-wind-solar-power-2024/>
⁵⁹ <https://www.energy.gov/ne/articles/what-generation-capacity>

⁶⁰ <https://www.stout.com/en/insights/commentary/understanding-capacity-factors-renewable-sources-fossil-fuels>
⁶¹ <https://seia.org/news/report-solar-adds-more-new-capacity-to-the-grid-in-2024-than-any-energy-technology-in-the-past-two->

⁶² In absolute value fossil generation increased as gas rose almost three times more than coal fell

⁶³ <https://ember-energy.org/latest-insights/european-electricity-review-2025/>

⁶⁴ <https://www.irena.org/Publications/2025/Mar/Renewable-capacity-statistics-2025>

⁶⁵ <https://about.bnef.com/insights/clean-energy/new-energy-outlook/>

⁶⁶ <https://www.woodmac.com/blogs/energy-pulse/questions-over-trump-plans-solar-wind/>

⁶⁷ Capacity factors for offshore wind are higher than for onshore wind due to more consistent and stronger winds at sea.

renewables' grid integration challenges (see chapter on electrical grids).

• While growing, wind development will not catch up with solar:

In 2024, new wind capacity additions significantly trailed solar⁶⁴. This gap stems from solar's lower costs, and faster installation time⁶⁵. Wind faces challenges like longer permitting processes, supply chain bottlenecks for turbine components, and higher upfront costs, especially for offshore projects. In the IEA Net Zero Roadmap, wind triples to reach 2,742 GW in 2030. Solar, by comparison, rises five-fold.

In addition, the Trump administration's energy policy, implemented in early 2025⁶⁶, significantly increases difficulties for wind energy, particularly offshore wind⁶⁷ (see below).

However, while wind installed capacity by 2030 should be less than half of solar capacity, its electricity generation should be only slightly lower, because the wind capacity factor is higher than solar's.⁶⁸

⁶⁸ <https://ember-energy.org/latest-insights/wind-targets-are-achievable-but-fall-short-of-a-tripling/#:~:text=In%20the%20IEA%20Net%20Zero%20Roadmap%2C%20wind%20triples%20from%20901,hours%20per%20year%20than%20solar>



- **China was the largest investor in wind and solar new capacities and should continue to be dominant:** In 2024, global investments in clean energy (renewables, grids and storage, nuclear power and energy efficiency) reached \$2000bn.⁶⁹ nearly double the investments in fossil energies (\$1116 bn). China⁷⁰ was the largest investor with around \$650bn. Renewable energies investments totalled \$771bn, out of which China contributed for \$350 bn, with solar photovoltaic investments exceeded \$500 billion globally, surpassing all other generation sources. During the first three months of 2025⁷¹, China produced 951 TWh of clean electricity which is 19% more than during the same period in 2024, accounting for 39% of all electricity produced in China. Despite the new wind and solar pricing policy that went into effect in June 2025, the growth in wind and solar energy will likely continue throughout the year.⁷²

⁶⁹<https://www.iea.org/reports/world-energy-investment-2024/overview-and-key-findings>

⁷⁰<https://www.power-technology.com/news/china-clean-energy-investments-7cf-view>

⁷¹<https://carboncredits.com/china-sets-clean-energy-record-in-early-2025-with-951-twh/>

⁷²<https://www.carbonbrief.org/analysis-clean-energy-just-put-chinas-CO2-emissions-into-reverse-for-first-time/>

⁷³LCOE: Levelized Cost Of Electricity

- **In 2024, LCOEs⁷³ for renewables declined with strong variations by regions and technologies:** Solar PV in China being the most competitive⁷⁴. Altogether, renewables LCOE dropped the most in China, compared to other regions (-16% in China compared to -4.2% in the US and only -0.2% in Europe). For solar PV, fixed-axis system LCOE was \$66/MWh globally while single-axis tracking PV systems averaged lower at \$60/MWh, reinforcing their growing role in utility-scale projects.

In contrast, onshore wind global average LCOE amounted to \$75/MWh. Offshore wind, particularly floating systems, remains expensive, with fixed installations averaging \$230/MWh and floating systems at \$320/MWh. These costs are expected to fall over time.

LCOE for solar and wind varied across regions (China⁷⁵, the U.S., and Europe) due to differences in technology, labor, and policies. China's LCOEs were the lowest, with on average utility-scale solar at \$36/MWh, onshore wind at \$38/MWh, offshore wind at \$87/MWh.⁷⁶

⁷⁴<https://www.woodmac.com/press-releases/2024-press-releases/global-competitiveness-of-renewable-lcoe-continues-to-accelerate/>

⁷⁵<https://about.bnef.com/insights/clean-energy/global-cost-of-renewables-to-continue-falling-in-2025-as-china-extends-manufacturing-lead-bloombergnef/>

⁷⁶https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023_executive_summary.pdf

- **Grid system additional costs make renewables less competitive than standard LCOE suggests, emphasizing the need for schedulable generation to ensure grid reliability.** Intermittent renewables like solar and wind incur additional grid system costs⁷⁷, particularly as their share in the electricity mix grows. These “System LCOE” costs include additional storage for grid balancing needs, grid expansion, and backup generation. They increase strongly with higher renewable penetration. For example, in the U.S., solar with storage LCOE ranges from \$38–\$217/MWh and wind with storage from \$37–\$157/MWh, reflecting different “System LCOE” according to renewables penetration rates.

In China, curtailment rates of 20–40% in some regions due to grid constraints add to costs, though low battery storage prices⁷⁹ can help store excess electricity. Europe faces high transmission grids upgrade costs (e.g., Germany's having to invest €659 billion by 2045⁸⁰), increasing “System LCOE” at high penetration levels in the absence of dispatchable sources (like clean nuclear or gas plants).

⁷⁷<https://www.lazard.com/research-insights/levelized-cost-of-energyplus-lcoeplus/>

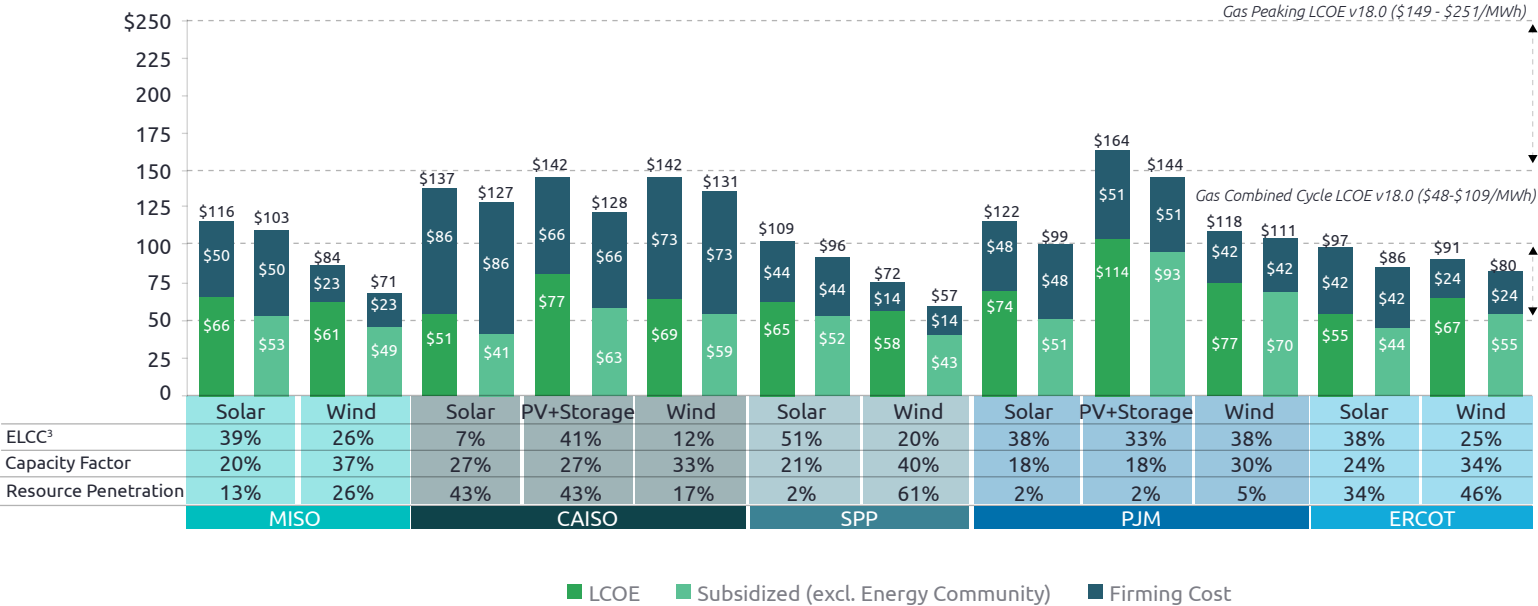
⁷⁸<https://www.lazard.com/media/voynhon/lazards-lcoeplus-june-2025.pdf#170>

⁷⁹\$296/MWh for a 4-hour system)

⁸⁰<https://www.cleanenergywire.org/news/electricity-grid-upgrades-will-cost-germany-650-billion-euros-2045-report>



FIGURE 6
LCOE including leveled firming cost (\$/MWh)⁷⁸



• **LCOE for nuclear power varies significantly between existing and new plants**, reflecting differences in capital costs, operational expenses, and regional factors. For existing nuclear plants, LCOE is relatively low due to amortized capital costs⁸¹: in the U.S., it averages \$70–\$80/MWh; in Europe, \$50–\$90/MWh (depending on refurbishment needs); and in China, \$40–\$60/MWh, driven by lower maintenance costs.

For new nuclear plants, LCOE is much higher due to substantial upfront capital costs and longer construction timelines: in the U.S., new plants range from \$142–\$222/MWh (averaging \$182/MWh); in Europe, \$150–\$350/MWh⁸² (e.g., France and UK EPR projects); and in China, \$70–\$100/MWh, benefiting from standardized designs and lower construction costs. These figures exclude additional grid system costs, which are minimal for nuclear thanks to its dispatchable nature.

Compared to renewables, existing nuclear often undercuts solar and wind when System LCOE are factored in, but new nuclear struggles to compete without subsidies or high enough carbon pricing.

⁸¹Capital cost accounts for 80% of the LCOE, maintenance and fuel for the remaining 20%

⁸²<https://www.ft.com/content/ee89bce2-a3e9-48ed-82eb-85916eb24777>



Hydrogen development is challenging⁸³ Let's recall that hydrogen is the smallest molecule and that it is flammable when mixed with oxygen.

This creates safety problems when hydrogen is produced and used as well as transportation difficulties because of its low density.

• **Green hydrogen development challenges in 2024:**

Green hydrogen is hydrogen gas produced through electrolysis of water, powered by renewable energy sources, resulting in zero carbon emissions during production. Low carbon hydrogen is the same with renewables and nuclear electricity sources. In both cases no GHG are emitted during hydrogen production. In this report we will use the terms green hydrogen or low carbon hydrogen interchangeably. In contrast fossil fuel-based hydrogen (grey hydrogen) generates a high level of emissions. Green hydrogen can serve as a clean energy carrier for decarbonizing sectors where direct electrification is challenging.

Demand for green hydrogen remains concentrated in traditional sectors like refining and chemicals and represents only 1.2% of the global hydrogen demand.⁸⁴ Emerging

applications as in steel, heavy transport, and synthetic fuel production are growing, particularly in Europe and the U.S., with favourable policies like the EU's Fit for 55 and U.S. tax credits.

However, in 2024, green hydrogen development in Western countries fell short of expectations^{85,86} due to the following issues that are detailed below:

- ✓ Technical and economic problems linked to the sustainability and limited lifetime of electrolyzers, difficulties in production scalability and high costs
- ✓ Infrastructure gaps: Insufficient pipelines and long-distance transportation issues.
- ✓ Demand-supply cycle: a classic chicken-and-egg problem between demand and production: low demand due to high costs and regulatory uncertainties deterring investment and, in turn, the lack of production growth deprived of the costs benefits of scale effects.
- ✓ Policy Efforts: EU's Hydrogen Bank and U.S. tax credits aimed to stimulate progress but faced delays and uncertainties in implementation.

However, three regulatory developments are expected to accelerate demand:

- ✓ EU SAF Mandate (ReFuelEU Aviation Regulation):
- ✓ Maritime Organization (IMO) approved global GHG regulations for shipping, mandating zero-emission fuels and GHG pricing by 2027. These measures could drive early investment in hydrogen infrastructure.⁸⁷
- ✓ RED III Directive (Renewable Energy Directive III) sets binding targets for renewable fuels of non-biological origin (RFNBOs), including green hydrogen.⁸⁸

• **Investments in electrolyzers are growing but only 7% of announced capacity were launched.**

In 2024, global investments in electrolyzers reached \$2.4bn, a 60% increase from 2023.⁸⁸ Clean hydrogen projects⁸⁹ that reached Final Investment Decision (FID) have increased from 102 committed projects in 2020, representing around \$10 bn in investment, to 434 in 2024, representing around \$75 bn⁹¹. Despite this growth, only 7% of announced capacity reached FID, with challenges such as technical difficulties, high production costs and lack of demand.

⁸³<https://www.iea.org/reports/global-hydrogen-review-2024>

⁸⁴In 2024 the global hydrogen demand (98.8% grey) was almost 100 Mt

⁸⁵<https://rmi.org/hydrogen-state-of-the-union-where-we-stand-in-2024/>

⁸⁶<https://www.ft.com/content/d3102a61-368e-4ec6-8de3-833f4c62e7ba>

⁸⁷<https://maritime-innovations.com/imo-net-zero-regulations-2025-shipping-impacts/>

⁸⁸<https://strategicenergy.eu/how-europes-oil-refiners-could-offer-a-route-to-scale-up-green-hydrogen/>

⁸⁹<https://www.hydrogeninsight.com/production/global-investment-in-clean-hydrogen-production-expected-to-grow-by-70-in-2025-iea/2-1-1829577>

⁹⁰Clean hydrogen includes green hydrogen and blue hydrogen (grey hydrogen installations with Carbon Capture and Storage)

⁹¹<https://hydrogencouncil.com/en/hydrogen-insights-2024/>



- **Electrolyzer installed capacity is growing led by China.**

In 2024, the global installed electrolyzer capacity for hydrogen production reached approximately 5 GW, a significant increase from 1.4 GW in 2023. China led with nearly 70% of the total, primarily in regions like Inner Mongolia and Xinjiang. However, China's electrolyzer production faced significant overcapacity, with 68% of the global 31.7 GW annual capacity (21 GW) located in China, far exceeding the 5 GW installed in 2024.

Europe followed with approximately 700 MW (14%), supported by initiatives like the European Hydrogen Bank and Germany's H2Global program. North America contributed about 500 MW (10%), with the U.S. leveraging in 2024 the Inflation Reduction Act incentives.

Electrolyzer's OEM market is facing overcapacity.⁹² Green hydrogen has been expected to grow fast and reliably, but project realization is largely lagging as many Oil and Gas Companies and Utilities are cancelling or delaying projects. For example: Shell cancelled the 400 MW⁹³ electrolyzers plant project aimed at shipping vast volumes of liquid green hydrogen from Portugal to the Netherlands. On the utilities side, Engie has delayed 4GW green hydrogen target by five years, due to slower-than-expected industry progress⁹⁴

Electrolyzer manufacturers have built out large production capacities to deliver the numerous announced projects. However, as only few projects have reached current FID stage and resulted in binding order, there is a large manufacturing overcapacity in the OEM market⁹⁵ undermining the industry's profitability.

⁹²<https://www.hydrogeninsight.com/electrolysers/severe-overcapacity-the-global-supply-of-electrolysers-far-outstrips-demand-from-green-hydrogen-projects-bnef/2-1-1618327>

⁹³<https://www.hydrogeninsight.com/production/exclusive-this-shell-backed-project-to-ship-vast-volumes-of-liquid-green-hydrogen-from-portugal-to-the-netherlands-has-been-scrapped/2-1-1621919>

⁹⁴<https://www.hydrogeninsight.com/production/engie-delays-4gw-green-hydrogen-target-by-five-years-due-to-slower-than-expected-industry-progress/2-1-1605256>

⁹⁵<https://www.strategyand.pwc.com/de/en/industries/energy-utilities-resources/electrolyzer-market/strategyand-electrolyzer-market.pdf>



- **Green hydrogen costs are falling in China:** Green hydrogen costs globally range from €3–8/kg, compared to grey hydrogen's €1–2.5/kg, varying by region due to renewable energy and natural gas prices⁹⁶. In China, green hydrogen is cheapest at €2–4/kg, sometimes undercutting grey hydrogen (€3–5/kg) due to low-cost renewables and electrolyzers.⁹⁷

In July 2025, China's Envision Energy launched the world's largest green hydrogen and ammonia plant in Chifeng (Inner Mongolia)^{98,99}. Powered entirely by the largest off-grid renewable energy system, the plant is also the first of its kind to be fully AI-enabled, achieving real-time optimization and stability at scale. The plant will deliver 320,000 tons of green ammonia annually with exports commencing in Q4 2025. Europe green hydrogen averages €4–6/kg, while grey is €1.5–2.5/kg¹⁰⁰. In the U.S., green hydrogen costs €5–7/kg, while grey is €1–2/kg, driven by cheap natural gas¹⁰¹. Scaling infrastructure (notably by building Mega factories), improving electrolyser efficiency, and cheaper renewables are key to making green hydrogen competitive, with electrolyzer costs expected to decline from \$600/kW to \$400/kW by

2030 mirroring solar and battery trends. However, in 2024 and early 2025, electrolyzers have faced technical challenges notably linked to their load-following capabilities. Contrary to forecasts, their costs - comprising 15–30% of the levelized cost of hydrogen (LCOH) - rose over 50% in 2024 in China, the U.S., and Europe compared to 2023¹⁰².

• **Technical issues and remediation**^{103,104}:

In 2024, electrolyzers for green hydrogen faced challenges like high material costs, membrane degradation, gas cross-permeability, and scalability, particularly for Proton Exchange Membrane Electrolysis (PEM) and Alkaline Water Electrolysis (AWE), systems. PEM systems struggled with costly noble metal catalysts (e.g., iridium) and gas crossover, while AWE systems had lower efficiency and slower response to renewable inputs.

Innovations included catalyst-coated membrane¹⁰⁵ reducing iridium use by 25 times and Toshiba's 90% iridium reduction technology. Membrane-free designs and advanced manufacturing, like 3D printing, are aimed to lower costs and improve scalability.

• **Hydrogen transportation:**

- ✓ Short-distance issues include limited pipeline infrastructure (only 4,300 km of hydrogen pipelines globally¹⁰⁶) and storage inefficiencies due to hydrogen's low density. Solutions involve building hydrogen facilities near the utilization industrial assets or blending hydrogen into existing gas networks (up to 20% safely). However, hydrogen causes pipelines cracking and deforming through embrittlement limiting their transportation capacity.
- ✓ Long-distance hydrogen transport faces challenges like high costs and energy losses, with pipeline transmission costing \$1.5 to 2.5/kg per 1,000 km¹⁰⁷ and liquefaction for shipping requiring 30% of hydrogen's energy content¹⁰⁸

For transporting large quantities of hydrogen over long distances, liquid organic hydrogen carriers (LOHCs)¹⁰⁹ are a very promising alternative. However, there is a need to develop new and alternative LOHCs that fulfil several criteria, such as thermal and chemical stability, low toxicity, sustainability and high hydrogen storage capacity,

⁹⁶ <https://www.iea.org/reports/global-hydrogen-review-2024>

⁹⁷ https://about.bnef.com/insights/clean-energy/new-energy-outlook/?utm_source=google&utm_medium=paid_search&utm_campaign=emea_bnef_bssscorp_2025_a0&utm_content=text_bnef_emea-nonbrand-

⁹⁸ <https://carboncredits.com/chinas-envision-energy-launches-worlds-largest-green-hydrogen-and-ammonia-plant/>

⁹⁹ <https://www.prnewswire.com/in/news-releases/envision-delivers-on-worlds-largest-green-hydrogen-and-ammonia-plant-with-off-grid-renewable-system-302502294.html>

¹⁰⁰ https://www.irena.org/-/media/Files/IRENA/Agency/Publication/%202020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

¹⁰¹ <https://www.lazard.com/media/xemfey9k/lazards-lcoeplus-june-2024-vf.pdf>

¹⁰² <https://www.hydrogeninsight.com/electrolysers/cost-of-electrolysers-for-green-hydrogen-production-is-rising-instead-of-falling-bnef/2-1-1607220>

¹⁰³ <https://www.policycircle.org/environment/green-hydrogen-advancements/>

¹⁰⁴ <https://www.libertyspecialtymarkets.com/gb-en/article/green-hydrogen-scale-up-giga-projects-and-mega-challenges>

¹⁰⁵ <https://www.bspkl.co/>

¹⁰⁶ <https://www.rystadenergy.com/news/building-the-future-hydrogen-pipelines-start-to-materialize-in-europe>

¹⁰⁷ <https://www.eai.in/blog/2024/03/realistic-cost-for-green-hydrogen-transportation-in-pipelines-road-and-rail.html>

¹⁰⁸ <https://ieefa.org/resources/hydrogen-energy-supply-chain-project-viability-remains-uncertain-wake-hydrogen-headstart>

¹⁰⁹ <https://cicenergiguine.com/en/blog/tecnologias-liquid-organic-hydrogen-carriers-lohc-ekarrih2>

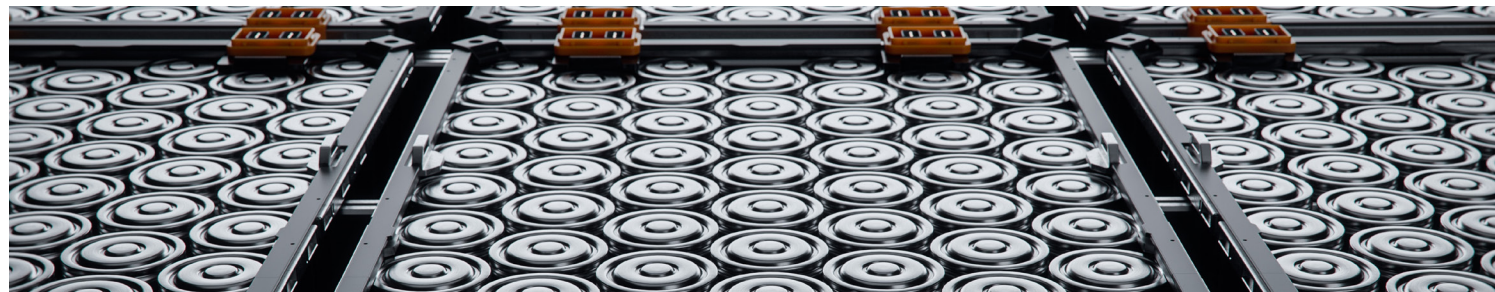


Green ammonia¹¹⁰ is a promising carrier for long-distance green hydrogen transport, offering higher energy density (15.6 MJ/L vs. 5.6 MJ/L for compressed hydrogen) and leveraging existing infrastructure. Ammonia is then either burnt to provide a direct source of energy or converted back into hydrogen by cracking. The latter reaction is energy-intensive, losing 30-35% of energy.

The transport of ammonia also presents a risk of leakage, with far more detrimental effects on the climate. Moreover, some of the compounds produced by the combustion of ammonia are powerful greenhouse gases, such as nitrous oxide, which has a warming potential 265 times greater than that of CO₂. Related studies¹¹¹ underscore the need for caution, as false solutions may cause more harm than good to the climate.

Solid-phase hydrogen storage¹¹², using metal hydrides or activated carbon, provides safer, compact transport¹¹³ but has lower storage capacity (25 kg/m³ vs. 108 kg/m³ for ammonia)¹¹⁴ and high energy costs for release.¹¹⁵

- **Conclusion¹¹⁶: Green hydrogen's limited resources should be allocated efficiently to maximize impact.** Green hydrogen development faces significant challenges requiring prioritized policy support and investment in sectors where it is the optimal or sole decarbonization solution.



Electrical battery demand grew while prices declined:

- **China dominated the battery market:** In 2024, the global Electric Vehicle (EV) battery market saw significant growth, driven by rising EV sales and advancements in battery technologies. Global battery demand reached 1TWh¹¹⁷, with electric cars accounting for more than 95% of the demand and stationary batteries for around 45 GWh. Demand for EV batteries grew by 25% compared to 2023.

Lithium-ion batteries, particularly lithium-iron-phosphate (LFP) and nickel manganese cobalt (NMC), remained dominant due to their high energy density and performance. Emerging technologies like sodium-ion and solid-state batteries gained traction, with sodium-ion batteries

(led by CATL) reaching commercial readiness in China and solid-state batteries advancing toward 2027–2028 commercialization. In 2024, China dominated the global EV battery market, producing 78% of batteries, driven by its EV market and cost-effective LFP batteries, with CATL (38% market share) and BYD leading the market.

Europe's battery demand grew to 200 GWh (up 35% from 2023), supported by EU climate policies, and the U.S. reached 220 GWh, boosted by the Inflation Reduction Act, though both rely on Asian firms. South Korea (20% market share) and Japan (6%) were focused on NMC and solid-state batteries, respectively. Overcapacity and mineral constraints drove recycling and alternative chemistries like lithium-sulphur.¹¹⁸

¹¹⁰<https://www.hfw.com/insights/nh3-news-is-ammonia-the-future-of-long-distance-hydrogen-transport/>

¹¹¹<https://www.polytechnique-insights.com/en/columns/energy/hydrogen-and-ammonia-the-risk-of-climate-damaging-leaks/>

¹¹²<https://link.springer.com/article/10.1007/s10311-024-01741-3>

¹¹³<https://onlinelibrary.wiley.com/doi/full/10.1155/er/6300225>

¹¹⁴<https://www.sciencedirect.com/science/article/pii/S0254058424008356>

¹¹⁵<https://www.sciencedirect.com/science/article/pii/S036031992401869X>

¹¹⁶<https://globalenergymonitor.org/report/europe-gas-tracker-2025-hydrogen-edition/>

¹¹⁷<https://www.iea.org/reports/global-ev-outlook-2025/electric-vehicle-batteries>

¹¹⁸<https://www.idtechex.com/en/research-article/lithium-sulfur-batteries-set-to-become-billion-dollar-industry/33026>



- **Prices continued to decrease:** In 2024, EV lithium-ion battery pack prices dropped by 20% to a record low of \$115/kWh, the largest decline since 2017, driven by lower metal prices (e.g., lithium price was down 20%), and wider use of cost-effective LFP batteries.¹¹⁹ On a regional basis, average battery pack prices were lowest in China, at \$94/kWh. Packs in the US and Europe were 31% and 48% higher, reflecting the higher production costs and lower volumes. Prices could fall to \$80/kWh by 2026, nearing cost parity with gasoline vehicles¹²⁰ thanks to technological advancements, like cell-to-pack designs and increased energy density.
- **Battery manufacturing supply chain vulnerabilities are triggering localization policies:** In 2024, China dominated the global EV battery supply chain, controlling 90% of cathode and 97% of anode material production,¹²¹ creating vulnerabilities due to reliance on a single nation. Fears of disruptions in Chinese supply as the country is handling 80% of NMC and 92% of LFP cathode minerals, are prompting policies like the EU Battery Regulation to re-localize supply chains. These regulations enforce recycling and alternative technologies development. Recycling capacity is critical but still in early stages outside China, which holds

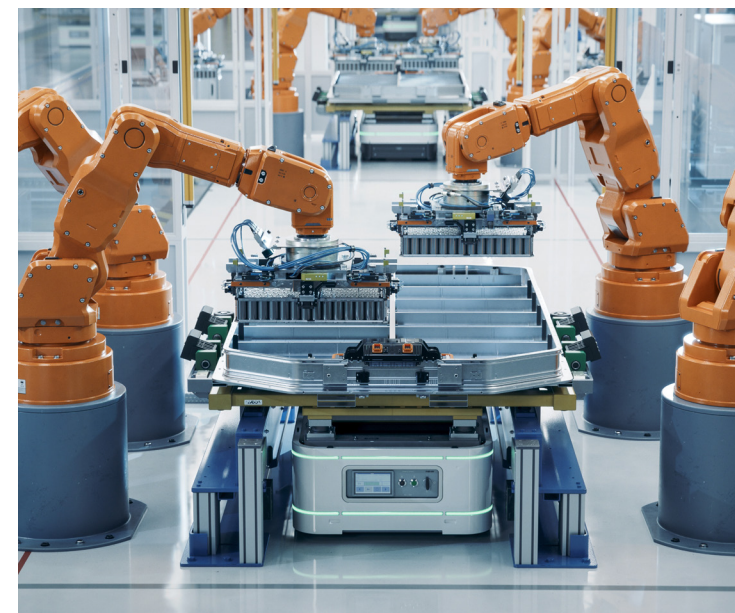
80% of 300 GWh/year. Alternative chemistries as sodium-ion batteries, reliant on abundant materials are facing delays due to low lithium prices.

- **Northvolt failure could delay European re-location efforts:** Northvolt, a Swedish EV battery manufacturer, filed for Chapter 11 bankruptcy in the U.S. in November 2024 and bankruptcy in Sweden in March 2025, marking the largest industrial bankruptcy in modern Swedish history. Once a flagship of Europe's clean-tech ambitions, Northvolt aimed to capture 25% of the European battery market by 2030. It raised over \$15 bn in financing, including a \$5 bn EU loan, with major investors like Goldman Sachs and off takers like Volkswagen.¹²²

Its failure stemmed from multiple root causes: inability to scale up production (producing only 1 GWh of its 32 GWh target by 2023), high capital costs, and supply chain disruptions. Internal issues included defective battery cells (noted as early as 2022), management's failure to address production challenges, and safety incidents, including two workers' deaths. The loss of a \$2 billion BMW contract in 2024 due to delivery delays and quality issues further eroded investor confidence. This collapse significantly impacts Europe's battery re-localization policy^{123,124} highlighting the EU's struggle to compete with China's dominance. It has sparked

pessimism, increasing investor hesitation and threatening other ventures like Verkor and ACC, with 60% of announced EU battery projects now delayed or at risk.

One strategy for European battery manufacturers would be to benefit from Chinese knowledge by entering alliances. Alternatively, attracting Chinese companies to Europe as France did successfully with Chinese owned AESC¹²⁵ allows both to re-localize the batteries production and to create local jobs. This is illustrated by the new joint venture between Stellantis and CATL, the Chinese market leader, to build an LFP cell plant in Spain.



¹¹⁹<https://about.bnef.com/insights/commodities/lithium-ion-battery-pack-prices-see-largest-drop-since-2017-falling-to-115-per-kilowatt-hour-bloombergnef/>

¹²⁰<https://www.goldmansachs.com/insights/articles/electric-vehicle-battery-prices-are-expected-to-fall-almost-50-percent-by-2025>

¹²¹<https://www.spglobal.com/automotive-insights/en/blogs/2025/05/revamping-automotive-sourcing-electric-vehicle>

¹²²<https://cepa.org/article/europes-great-battery-hope-northvolt-loses-power/>

¹²³<https://www.reuters.com/sustainability/struggling-northvolt-stokes-fear-europes-battery-future-2024-09-13/>

¹²⁴<https://carboncredits.com/northvolts-bankruptcy-how-does-it-impact-europes-battery-industry/>

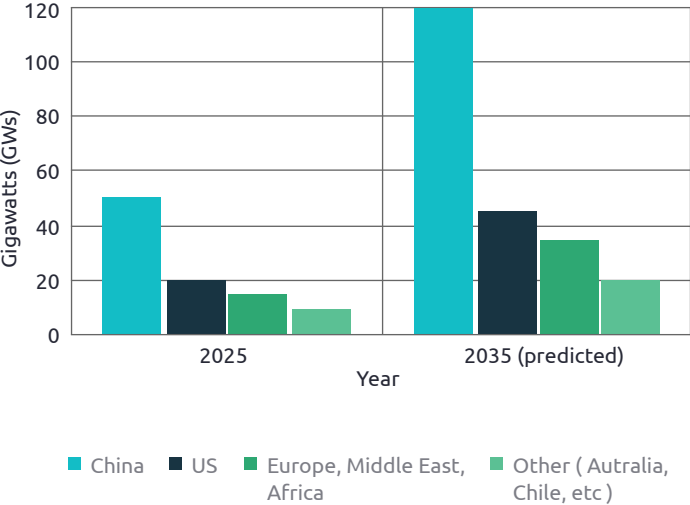
¹²⁵<https://battery-news.de/en/2025/06/11/aesc-battery-plant-in-douai-begins-mass-production/>



• **Stationary batteries enable electricity storage for grid systems**, alongside other technologies like pumped hydro, compressed air, flywheels, and thermal storage.¹²⁶

✓ *In 2024, global stationary battery installations increased by 60% from 2023 reaching 170 GWh.¹²⁸ China is leading this growth with 37GW additional installed capacity (totaling 62 GW installed) as the market shifts toward large, centralized systems with power outputs greater than 100 MW.¹²⁹ China can be expected to increase its dominance in the future.*

FIGURE 7
Global Energy Storage Additions (Gigawatts)



However, China has adopted a new policy¹³⁰ that requires that all renewable energy projects commissioned after June 1, 2025, will engage in market-based trading. The obligation to add storage capacity to renewable capacity is removed.¹³¹ This will impact negatively the Chinese stationary battery market.

By 2035, stationary applications could account for 16% of batteries deployed globally, up from 6% in 2020, propelled by falling battery costs, increased grid stability issues and reinforced grid regulations.

✓ *LFP batteries will likely remain the dominant technology* due to cost competitiveness, but sodium-ion and flow batteries are expected to capture 10–15% of the market by 2030, driven by their sustainability and suitability for long-duration storage.

✓ *Stationary battery challenges include insufficient profitability*, driven by several factors.

• High capital costs, including battery packs and installation, particularly in regions like Europe and parts of the U.S., where Levelized Cost of Storage ranges from \$200–\$350/MWh compared to \$100–\$150/MWh for gas-based alternatives¹³².

¹²⁶ <https://www.iea.org/reports/batteries-and-secure-energy-transitions>

¹²⁷ <https://www.ess-news.com/2024/12/18/bloombergnef-stationary-storage-installations-surge-to-170-gwh-in-2024/>

¹²⁸ <https://www.ess-news.com/2025/04/04/chinas-battery-storage-capacity-doubles-in-2024/>

¹²⁹ <https://www.pv-magazine.com/2025/06/12/chinas-new-pricing-policy/#:~:text=Under%20the%20new%20framework%2C%20all,pairing%20mandates%20will%20be%20removed.>

¹³⁰ Since 2022, it was mandatory to add energy storage is paired to renewables projects (usually at 10% to 30% of the renewable capacity at a one to two-hour duration)

¹³¹ <https://about.bnef.com/insights/clean-energy/global-energy-storage-growth-upheld-by-new-markets>

¹³² <https://www.lazard.com/research-insights/levelized-cost-of-energyplus-lcoeplus/>

• Regulatory hurdles, such as complex grid connection rules in the EU, and underdeveloped markets for ancillary services (e.g., frequency regulation) that limit revenue potential. In contrast, China benefits from lower costs (\$80–\$100/kWh for LFP batteries) and government incentives, enabling faster deployment¹³³

• Targeted policies and new grid regulations are essential to bridge the profitability gap and support grid-scale storage growth.

Conclusion:¹³⁴

In 2024, the growth of renewable electricity (solar and wind) was impressive, driven by Chinese solar installations. However, and except in China, the development of green hydrogen has fallen far short of political promises and forecasts.

Asia and notably China remained dominant in the battery market and the Northvolt failure outlined the difficulties in building a European battery industry.

Despite these achievements, the energy additions from low carbon sources have not been sufficient to meet the growth in the global energy demand. *Consequently, fossil fuels have continued to dominate the global energy supply, accounting for 80% of primary energy consumption¹³⁵.*

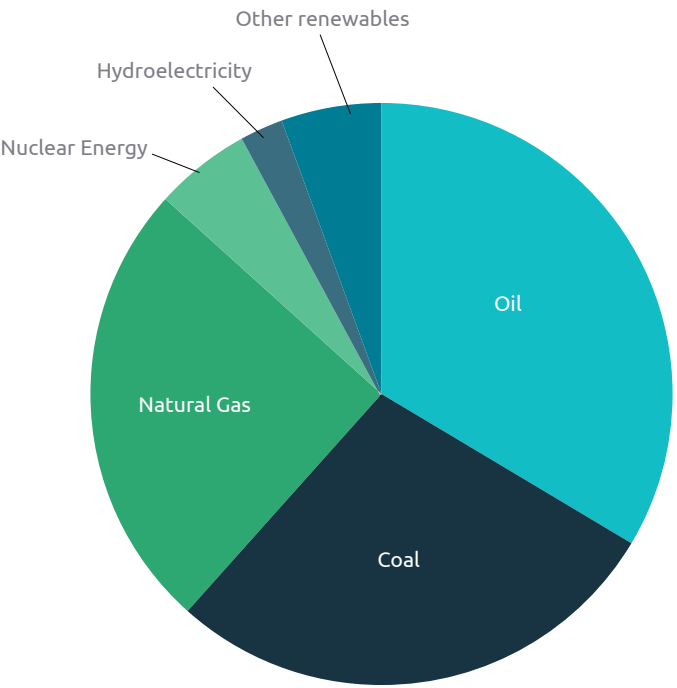
¹³³ <https://www.carbonbrief.org/qa-how-china-became-the-worlds-leading-market-for-energy-storage/>

¹³⁴ <https://about.bnef.com/insights/clean-energy/five-energy-transition-lessons-for-2025/>

¹³⁵ <https://www.iea.org/reports/world-energy-outlook-2024>



FIGURE 8
Global Energy Supply by type in 2024 (Exajoules)¹³⁶



¹³⁶Visual Capitalist: Chart: What Powered the World in 2024? <https://www.visualcapitalist.com/what-powered-the-world-in-2024>

¹³⁷<https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power>

¹³⁸<https://world-nuclear.org/information-library/country-profiles/countries-o-s/slovakia#:~:text=On%2031%20January%202023%20Mochovce,March%202025%20hot%20testing%20began.>

¹³⁹<https://www.eia.gov/todayinenergy/detail.php?id=64204>

¹⁴⁰<https://www.reuters.com/business/energy/french-nuclear-giant-edf-lifts-production-forecast-2025-beyond-2025-01-31/>

Will nuclear energy contribute enough to greenhouse gas reduction objectives?

In 2024, global nuclear energy output rose 2.6%.

This led to a total of 2,671 TWh from 2,602 TWh in 2023, , driven by new reactors in China¹³⁷, India, Slovakia¹³⁸, and the U.S.

Japanese utilities restarted two additional reactors in 2024¹³⁹ and in France, following the repairs of the stress corrosion problems, nuclear output rose by 13%.¹⁴⁰

Nuclear global electricity share held at 9%, with 440 reactors in 32 countries delivering 400 GW, 65 large reactors were under construction, and over 80 Small Modular Reactors (SMR) designs were in development¹⁴¹. Asia led with 32 reactors under construction in China, 9 in India and 3 in South Korea.

Let's recall that sanctions related to the Ukraine invasion by Russia don't apply to nuclear power. Thus Rosatom¹⁴²(fully owned by the Russian government) maintained its dominant position in the reactors' export market. In 2024, Russia was involved in over a third of the world's new reactor constructions¹⁴³, including projects in China, India, Türkiye and Egypt.

¹⁴¹<https://world-nuclear.org/our-association/publications/global-trends-reports/world-nuclear-performance-report-2024>

¹⁴²<https://www.knightsbridgesg.com/post/assessing-russia-s-nuclear-export-diplomacy-in-the-context-of-its-geopolitical-rivalries-september>

¹⁴³<https://partnershipforglobalsecurity.org/russian-international-nuclear-energy-expansion/>

¹⁴⁴<https://sfinenglish.org/historic-moment-flamanville-epr-connected-to-the-national-grid/>

In the US, Vogtle Unit 4 became operational and in France, Flamanville 3, was connected to the grid in late 2024¹⁴⁴. Both projects experienced big delays and cost overruns¹⁴⁵, highlighting Western nuclear project challenges.

The nuclear renaissance

- **In Europe¹⁴⁶** there is a renewed interest in nuclear power to have a low carbon, reliable energy source to meet climate and energy security goals. This second goal became even more important in Europe after the 2022 energy crisis linked to the Russian invasion of Ukraine. Within this trend, the EU Nuclear Alliance¹⁴⁷ was formed in 2024 with 14 member states, to mobilize the relevant economic players on these goals Let's note a positive development: the new German government has ended its country's long-standing and scientifically unjustified¹⁴⁸ opposition to nuclear power at the EU level. It finally agreed to treat nuclear energy as a low carbon technology on par with renewables.

¹⁴⁵<https://thirdact.org/georgia/2024/06/09/plant-vogtle-the-true-cost-of-nuclear-power-in-the-u-s/#:~:text=Vogtle%20Units%203%20%26%204%20took,the%20projected%20timeline%20and%20cost.>

¹⁴⁶<https://www.spglobal.com/en/research-insights/special-reports/is-europe-ready-for-a-nuclear-renaissance>

¹⁴⁷<https://www.world-nuclear-news.org/articles/european-business-nuclear-alliance-launched>

¹⁴⁸See WEMO 2024 https://www.cappgemini.com/wp-content/uploads/2024/10/World-Energy-Markets-Observatory-2024_26th-Edition.pdf and WEMO 2023 https://prod.ucwe.cappgemini.com/wp-content/uploads/2023/11/Cappgemini_WEMO_2023-report.pdf outlooks



- **In the US**, this renaissance is triggered both by Gen AI electricity needs and by the boost given to domestic nuclear power by President Donald Trump's executive orders¹⁴⁹. Following these announcements aiming to add 300 GW of new U.S. nuclear capacity by 2050, Westinghouse announced its intention to build 10 new APR1000.

Big players as Microsoft, Google, IBM and Amazon, commitments to use low carbon electricity are pushing them to sign power purchase agreements with nuclear providers as seen in Microsoft's 2024 deal to restart a unit at Three Mile Island. After securing a \$1.52 billion loan from the U.S. Department of Energy (DOE), the 800 MW Palisades nuclear power plant in Michigan, is set to restart perhaps in 2025¹⁵⁰ or the following year.

2023 COP28's participants pledged to triple nuclear capacity by 2050¹⁵¹ highlighting renewables' limitations to meet rising energy demands, particularly for baseload power needs. Let us analyse the actions needed to reach this very ambitious target:

¹⁴⁹<https://www.energy.gov/ne/articles/9-key-takeaways-president-trumps-executive-orders-nuclear-energy>

¹⁵⁰<https://planetdetroit.org/2024/10/palisades-nuclear-plant-restart/>

¹⁵¹<https://www.iaea.org/bulletin/what-the-nuclear-declaration-at-cop28-means-for-iaea-verification#:~:text=On%202%20December%202023%2C%20during,reach%20that%20target%20by%202050.>

¹⁵²<https://www.nucadvisor.com/post/stress-corrosion-cracking-on-french-npps-an-overviewrepair>

¹⁵³<https://www.world-nuclear-news.org/articles/german-nuclear-association-calls-for-restart-of-reactors#:~:text=The%20Brokdorf%2C%20Grohnde%20and%20Gundremmingen,at%20various%20stages%20of%20decommissioning.>

- **Not allowing political pressure to interfere with nuclear reactors that could continue to operate safely.** Following a government decision, in H1 2020 the French utility EDF permanently shut down the two unit of the Fessenheim nuclear power plant that could have continued to operate safely for years. This capacity was missing during the 2022-23 crisis when EDF had to stop many plants for inspections and repair of pipes impacted by stress corrosion.¹⁵² Germany, for political reasons, closed its three last reactors in 2023¹⁵³ (after the 2022 crisis) and now Germany struggles with a lack of clean dispatchable electricity to balance high renewable generation. This situation results in an increasing number of hours with negative prices. In contrast, following the 2022 energy crisis, the Belgian government wisely decided in December 2023 to extend by 10 years the lifetimes of Doel 4 and Tihange 3 (that were to be shut down by 2025)¹⁵⁴. Also, Switzerland's Federal Council is seeking to lift the country's ban on new nuclear power plants¹⁵⁵. In March 2025, companies representing the Spanish nuclear industry signed a manifesto calling for the long-term operation of the country's nuclear power plants¹⁵⁶ (under current plans, Spain's power reactors are all scheduled to shut down by 2035). The April 28, 2025, giant black-out in Spain and Portugal (see below)¹⁵⁷ strongly supports this position, as it will improve the grid management.

¹⁵⁴<https://www.world-nuclear-news.org/articles/deal-finalised-for-belgian-reactor-restarts-in-november>

¹⁵⁵<https://www.swissinfo.ch/eng/swiss-politics/planned-end-to-ban-on-new-nuclear-power-plant-construction-sparks-new-nuclear-debate/89103321>

- **Extend the reactors' lifetimes:** In the US, 20 reactors, representing more than a fifth of the nation's fleet, are planning to operate up to 80 years¹⁵⁸. More reactors are expected to apply for an extension in the future as they get closer to the end of their operating licenses. On July 1, 2025, the French Nuclear Safety Authority authorized an extension beyond 40 years of the lifespan of EDF's 20, 1300MW capacity reactors¹⁵⁹. This authorization follows the one given in 2021 regarding the 32, 900 MW capacity reactors.

- **Reopen safe reactors:** As mentioned above two US reactors are planned to be re-opened. In Japan after the 2011 Fukushima Daiichi accident, all the country's 33 reactors were stopped. In May 2025, Japan's Nuclear Regulation Authority cleared the restart of Hokkaido Electric Power's Tomari No. 3 reactor. This approval (the first since 2021) should boost the government's effort to increase nuclear power generation and reduce dependence on fossil fuels (notably LNG). However fewer than half of Japan's operable reactors have resumed due to lengthy regulatory checks and upgrades, as well as local opposition.

¹⁵⁶<https://www.world-nuclear-news.org/articles/spanish-nuclear-industry-calls-for-rethink-of-phase-out-policy#:~:text=Companies%20representing%20the%20Spanish%20nuclear,scheduled%20to%20shut%20by%202035.>

¹⁵⁷This stability is provided by the rotating machines of nuclear plants

¹⁵⁸<https://www.energy.gov/ne/articles/whats-lifespan-nuclear-reactor-much-longer-you-might-think#:~:text=Eighty%2Deight%20of%20America's%2092,additional%2020%20years%20of%20service.>

¹⁵⁹<https://www.world-nuclear-news.org/articles/french-regulator-says-1300-mw-units-can-operate-beyond-40-years>



- **Build new large reactors:** Presently 65 large reactors are under construction, mainly in Asia, the Middle East and South America. The new US administration policy aims for construction of 300GW additional capacity by 2050 and the nuclear renaissance in Europe is favouring new constructions (see above). France, the UK, Czech Republic, Sweden, the Netherlands and Poland among others have projects to build large new nuclear plants as well as SMRs (Small Modular Reactors).

After securing its financing, the UK Energy Secretary signed on July 22, 2025, the final investment decision for Sizewell C, two EPR2 1600MW reactors¹⁶⁰. To maintain its very low-carbon electricity mix and despite a short-term electricity surplus¹⁶¹, France plans to build six new EPR2 nuclear reactors with a new design aimed at simplifying the construction. They are projected to cost €79,9 billions (in 2023€)¹⁶² with a Final Investment Decision that should be taken in 2026. The first reactors to be built at Penly (Normandy) is targeting 2038 for operational start. In June 2025, EDF and the French State finalized a more than €70 billion financing plan¹⁶³ awaiting European approval by 2026. The final EPR2 design is due to be approved by the end of 2025.

¹⁶⁰<https://www.gov.uk/government/news/sizewell-c-gets-green-light-with-final-investment-decision>

¹⁶¹<https://strategicenergy.eu/french-electricity-hits-record-lows-may/>

¹⁶²<https://www.connaissancedesenergies.org/afp/programme-depr-la-cour-des-comptes-publie-un-rapport-critique-et-recalcule-le-cout-de-flamanville-3-250114#:~:text=Selon%20un%20chiffre%20d'EDF,pr%C3%A9cise%20la%20Cour%20des%20Comptes>

¹⁶³https://energynews.pro/en/edf-and-the-french-state-agree-on-e70-billion-plan-for-epr2/#google_vignette

- **Root causes of large reactors construction overruns in western countries.** The construction of Flamanville 3, EPR French reactor, began in 2007 with an initial cost of €3.3 billion and a 2012 completion target. The commercial operation was delayed to December 2024, over a decade later. The final cost reached €23,7 billion¹⁶⁴. The construction of Vogtle Unit 3 and 4, Westinghouse AP 1000 reactors, in Georgia (US), started in 2009 with a \$14 billion budget and 2016-2017 completion goal. Costs soared to over \$30 billion, with Unit 3 operational in July 2023 and Unit 4 in April 2024.

- **In 2024, more than 80 SMR¹⁶⁵ designs were in development, however there were a limited number of SMR in operations or under construction.**

- ✓ SMRs are operational or under construction in Russia and China. Russia operates a floating nuclear power plant, called “Akademik Lomonosov,” which has two SMRs with a 35 MW capacity each. Regarding land SMRs, *Rosatom* which presently hold over 70% of the large reactor’s export market share, is working towards extending this market reach in the SMR space¹⁶⁶. It has developed the RITM-200N series SMRs reactors,

¹⁶⁴<https://www.ccomptes.fr/sites/default/files/2025-01/20250114-La-filiere-EPR%20-une-dynamique-nouvelle-des-risques-persistants.pdf>

¹⁶⁵<https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors>

¹⁶⁶<https://www.neimagazine.com/analysis/russia-bets-big-on-small-reactors-11673678/>

¹⁶⁷<https://www.neimagazine.com/analysis/russia-bets-big-on-small-reactors-11673678/?cf-view>

¹⁶⁸<https://www.world-nuclear-news.org/Articles/Chinese-HTR-PM-Demo-begins-commercial-operation>

which are adapted from the technology developed for nuclear-powered icebreakers. These reactors are already manufactured in series. A project in Yakut, featuring six RITM-200N reactors, is expected to be launched by 2027. Russia is also involved in an export project in Uzbekistan, which will also utilize RITM¹⁶⁷. China operates the world’s first modular high temperature gas-cooled reactor¹⁶⁸ as well as two other SMRs.





✓ *In the Western world SMRs are at best at the regulatory approval stages:* NuScale's 77 MW received in May 2025 its design approval from the U.S. Nuclear Regulatory Commission¹⁶⁹, TerraPower (created by Bill Gates) began Natrium¹⁶⁷ construction through a public-private partnership with the DOE.¹⁷⁰ In May 2025, the Ontario government gave the green light for the BWRX-300 SMR that should be operational in 2030 and for four units to be in operation by the middle of the next decade.¹⁷¹ Europe is behind. However, the European Commission is actively promoting the development and deployment of SMRs, through initiatives like the European Industrial Alliance on SMRs.¹⁷²

• **Advantages and disadvantages of SMRs compared to large reactors.** Small Modular Reactors offer some advantages over large nuclear reactors, including lower upfront capital costs, potential shorter construction times and flexibility to scale output by adding modules.

Their modular design and small size should favor easier industrialization. For instance a high proportion of components could be preassembled in specialized factories reducing on-site labor, costs and improving quality. Additionally, their enhanced safety features, like passive cooling, should

lower accident risks. Moreover, their smaller capacity (up to 600MW) makes them well adapted for smaller grids.

However, SMRs face disadvantages such as lack of economies of scale compared to large reactors. There is still less operational experience, and regulatory hurdles experience for new designs. With dispersed SMRs sites, it will be more difficult to strictly control nuclear material to prevent proliferation and leakages to the weapons industry. There may also be some difficulties with public acceptance due to their multiple sites.

It is difficult to calculate the SMRs LCOE (and compare it to the large reactors LCOE) as it is a nascent technology with many different designs. The inputs needed to calculate the LCOE are presently largely based on projections and are subject to change. The true cost will only become clear as enough projects move from paper to reality.

Early projects carry significant risk as was seen with the 2024 Nuscale failure in Idaho. The project was abandoned by its clients as the costs skyrocketed. Estimates are, that without the IRA subsidy, the electricity cost would have amounted to \$129/ MWh. SMR costs will depend heavily on achieving multiple deployments in one country or internationally, enabling manufacturing efficiencies and learning effects.

In addition, the supply chain is not ready as the factories necessary to manufacture SMRs components and nuclear fuel need to be financed and built.

✓ *SMRs for heat generation can be promising.* Worldwide 40% of energy is consumed for heat usages generating 50% of global emissions. Solutions exist to decarbonize heat as second-generation modern biomass and geothermal. However, their potential is limited in the case of biomass and geographically concentrated in the case of geothermal. Heat generation SMRs seem to be promising as they are simple and have passive safety features. They can de-carbonize urban heating networks by providing low-carbon thermal energy¹⁷³. Some projects are coming out. In the Western world examples can be found In France with Hexana¹⁷⁴, Calogena¹⁷⁵ and Jimmy¹⁷⁶, in North America with NuScale Power¹⁷⁷ (USA), Ultra Safe Nuclear MMR¹⁷⁸ (USA/Canada) and Westinghouse eVinci (USA).¹⁷⁹

¹⁶⁹<https://www.nuscalepower.com/press-releases>

¹⁷⁰<https://www.terrapower.com/natrium/US-Department-Of-Energy-Advanced-Reactor-Demonstration-Program-ARDP>

¹⁷¹<https://www.neimagazine.com/news/ontario-approves-darlington-bwr-x-300-smr/>

¹⁷²<https://www.world-nuclear-news.org/articles/first-smr-projects-selected-by-european-industrial-alliance>

¹⁷³<https://www.euroheat.org/news/>

[small-modular-reactors-ready-to-use-technology-tailor-made-for-district-heating-networks](https://www.euroheat.org/news/small-modular-reactors-ready-to-use-technology-tailor-made-for-district-heating-networks)

¹⁷⁴<https://www.hexana.com/>

¹⁷⁵<https://www.calogena.com/en/smr-nucleaire-calogena-a-free-carbon-heat-generator/>

¹⁷⁶<https://www.jimmy-energy.eu/en/home>

¹⁷⁷<https://www.nuscalepower.com/>

¹⁷⁸<https://nanonuclearenergy.com/nano-nuclear-energy-enters-into-agreement-to-acquire-ultra-safe-nuclear-corp-s-patented-micro-modular-reactor-mm-r-and-pylon-space-reactors-for-8-5-million-alo>

¹⁷⁹<https://westinghousenuclear.com/energy-systems/evinci-microreactor/>

Despite some progress, nuclear fusion is unlikely to reach industrial electricity generation before 2050¹⁸⁰

- **Tokamaks:** In 2024 and early 2025, the research on nuclear fusion for electricity generation achieved some milestones. The Joint European Torus (JET)¹⁸¹ in the UK set a record by producing 69 megajoules of fusion energy for six seconds, China's Experimental Advanced Superconducting Tokamak (EAST) sustained high-temperature plasma for 1,066 seconds¹⁸², and Princeton's tungsten-clad WEST tokamak¹⁸³ sustained a 50-million-degree plasma for six minutes, all steps toward durable reactor materials. Private investment surged, with companies like Commonwealth Fusion Systems promising *very optimistically* a commercial demonstrator in 2030!! But as French people say, "promises are only binding on those who believe them!"

However, the international ITER fusion project¹⁸⁴ has faced new delays and cost overruns due to several root causes. The COVID-19 pandemic disruptions, and manufacturing defects, such as cracks in vacuum vessel welds and corrosion in thermal shields, required extensive repairs. Overly optimistic planning

underestimated the complexity of assembling a first-of-its-kind tokamak. The international collaboration model, involving 35 nations, complicated coordination and component delivery. These factors have pushed costs up by €5 billion to around €25 billion and delayed full deuterium-tritium operations to 2039.¹⁸⁵

- **Inertial Confinement Fusion (ICF)** is a process that initiates nuclear fusion reactions by compressing and heating targets filled with deuterium and tritium. The confinement is triggered by powerful laser.

In December 2022, the National Ignition Facility (NIF) (Lawrence Livermore Laboratory in California) achieved a fusion ignition generating more energy from the fusion reaction than the laser energy used to trigger it. Specifically, the experiment delivered 2.05 megajoules (MJ) of laser energy to the target, resulting in a fusion output of 3.15 MJ, achieving a net energy gain. However, this gain only accounts for the energy delivered to the target, not the total energy consumed by the laser system, which is significantly higher (around 300 MJ). *So, contrarily to some statements, this experiment was not net energy positive.* Since then, the NIF has achieved fusion ignition multiple times with improved energy gains but far from being net energy positive.

¹⁸⁰<https://interestingengineering.com/energy/top-7-nuclear-fusion-stories-of-2024>

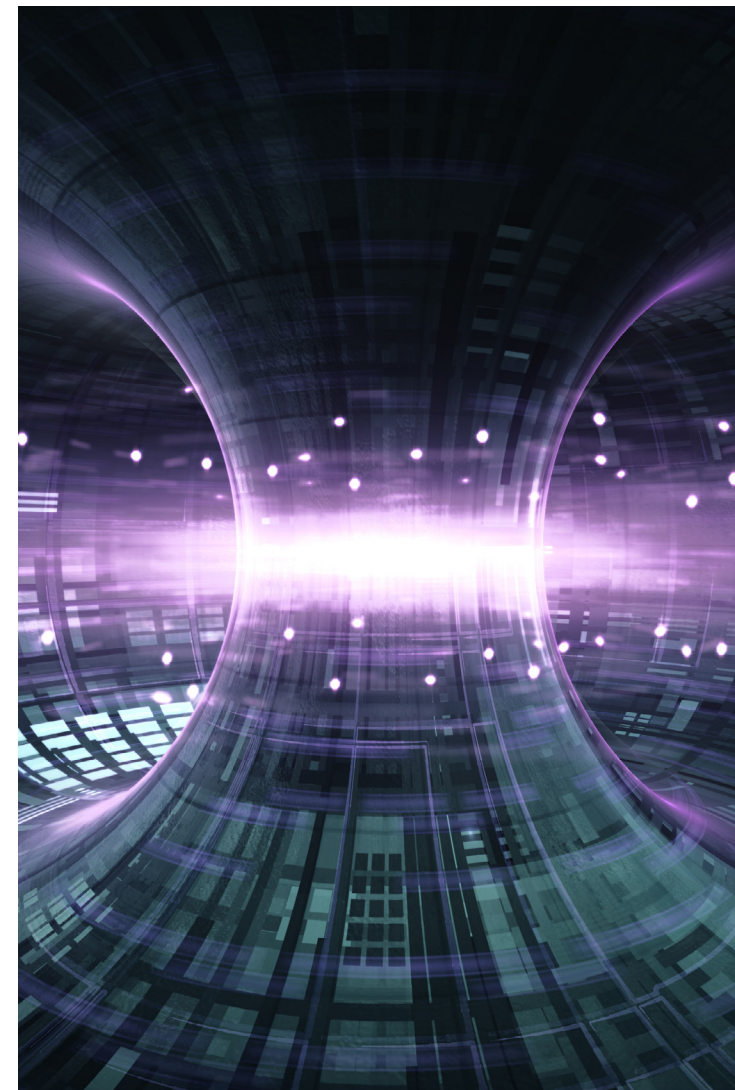
¹⁸¹<https://www.fz-juelich.de/en/news/archive/announcements/2024/jet-fusion-reactor-achieves-new-world-record-in-final-experiments#:~:text=JET%20Fusion%20Reactor%20Achieves%20New%20Record%20in%20Final%20Experiments,-8%20February%202024&text=The%20Joint%20European%20Torus%20JET,set%20a%20new%20world%20record>

¹⁸²[https://english.news.cn/20250120/1d4e392ccae4f8f29e8e9cdd0f9360c5/c.html#:~:text=20%2C%202025.,The%20Experimental%20Advanced%20Superconducting%20Tokamak%20\(EAST\)%2C%20dubbed%20China's%2022_quest%20for%20fusion%20power%20generation.](https://english.news.cn/20250120/1d4e392ccae4f8f29e8e9cdd0f9360c5/c.html#:~:text=20%2C%202025.,The%20Experimental%20Advanced%20Superconducting%20Tokamak%20(EAST)%2C%20dubbed%20China's%2022_quest%20for%20fusion%20power%20generation.)

¹⁸³<https://www.pppl.gov/news/2024/fusion-record-set-tungsten-tokamak-west>

¹⁸⁴ https://www.theregister.com/2024/07/04/iter_new_baseline_project_delays/

1859 years more than the original schedule





Even if an ICF experiment achieves a net positive energy gain, significant challenges must be solved before a first plant prototype could be built. Among the challenges let's cite:

- ✓ Repetition Rate: ICF requires rapid, repetitive fusion shots (10–100 per second) to generate continuous power. Current systems like NIF operate at a few shots per day
- ✓ Fusion targets Target Production and Cost reductions from ~\$100,000 per target to cents,
- ✓ Materials and Reactor Design: The intense neutron flux from fusion reactions damages reactor walls, requiring advanced materials that can withstand years of exposure.
- ✓ Tritium Supply and Breeding: Tritium, a key fusion fuel, is scarce and expensive. Commercial plants must breed tritium

in-situ using lithium blankets, but efficient, safe, and scalable tritium breeding systems are still in early development.

- ✓ Economic Viability: The high capital cost of building an ICF plant, estimated at billions of dollars, combined with unproven operational reliability, makes it difficult to compete with established energy sources.

Despite some progress, fusion has not yet been proven for energy usages. The fusion reaction necessitates extreme temperature conditions raising fundamental questions on material durability, and scalability.

Barring an unexpected breakthrough, fusion energy generation is very unlikely to impact climate goals before 2050.

Conclusion: To accelerate nuclear electricity development, it is essential to maintain rigorous safety standards in plant operations to prevent accidents that could, on top of the damage produced, slow down nuclear plant deployment. Achieving the ambitious COP28 goal of tripling nuclear capacity by 2050, requires avoiding politically motivated reactor closures, reopening viable dormant reactors, extending the life of safe reactors and building numerous new nuclear facilities. New capacity will combine large-scale reactors (1,000 MW or more) and small modular reactors (SMRs). China and Russia are emerging as dominant players in global nuclear development, while Western countries face challenges with construction delays and high costs¹⁸⁶ that must be overcome.

Finally, unless a major scientific breakthrough occurs, nuclear fusion is unlikely to have a significant impact on electricity generation by 2050.



¹⁸⁶Construction costs account for 80% of nuclear electricity's final cost



Will the electrical grids be able to adapt to the energy transition challenges?

Grids are the backbone of the energy transition because they connect diverse electricity sources like power plants and renewable generation to consumers, ensuring reliable power transmission, distribution and supply.

However, grid balancing, which is the process of matching electricity supply with demand in real time, is becoming increasingly difficult to achieve.

Indeed, many phenomena must be considered, particularly:

- ✓ Due to the dimension of grids as compared to the wavelength at 50 or 60 Hz, propagation laws apply and the system is no longer stationary,
- ✓ When supply is larger than demand there is an increase in voltage,
- ✓ On the other hand, when demand becomes larger than production, there is a decrease of voltage,

¹⁸⁷ Electricity demand is projected to rise 4% annually through 2030: <https://www.iea.org/reports/electricity-2024>

¹⁸⁸ Congestions occurs when existing lines cannot manage peak loads or renewable energy flows, leading to curtailment or high costs, such as the \$20.8 billion in U.S. congestion costs in 2022

¹⁸⁹ A single hyperscale facility can need a capacity of 1 GW

¹⁹⁰ <https://datacentremagazine.com/critical-environments/power-hungry-data-centres-put-pressure-on-irelands-grid>

- ✓ All the energy which is introduced in the grid at different positions must have the correct phase to avoid oscillations due to interferences.

Moreover, demand is also variable, driven by daily and seasonal usage patterns, which adds further balancing complexity.

Below we will elaborate on challenges related to grid extensions and grid balancing, notably with high renewables penetration. We will then suggest technical (including AI), regulatory, political and social solutions.



Grid building and strengthening challenges

- **By 2040, the equivalent of the existing global grid needs to be built or refurbished.** This will address multiple needs: rising electricity demand¹⁸⁷, grid congestion¹⁸⁸, integration of renewable energy farms, and the rapid growth of data centers.^{189,190}

Fully reaching national energy transition plans on time means adding or refurbishing a total of over 80 million kilometres of grids by 2040, the equivalent of the entire existing global grid.¹⁹¹ Substantial investments are needed in developing Asian countries where the electricity losses on the grids are much higher than for advanced economies due to overloaded lines and undersized transformers, which in turn result from inadequate planning, unplanned expansion, and poor maintenance practices.¹⁹²

By 2030, investment needs should reach more than \$500bn per year compared to less than \$400bn in 2024¹⁹³, with emphasis on digitalizing¹⁹⁴ and modernizing distribution grids.¹⁹⁵

¹⁹¹ <https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions/executive-summary>

¹⁹² <https://www.adb.org/sites/default/files/publication/1050701/energy-transition-readiness-developing-asia-pacific.pdf>

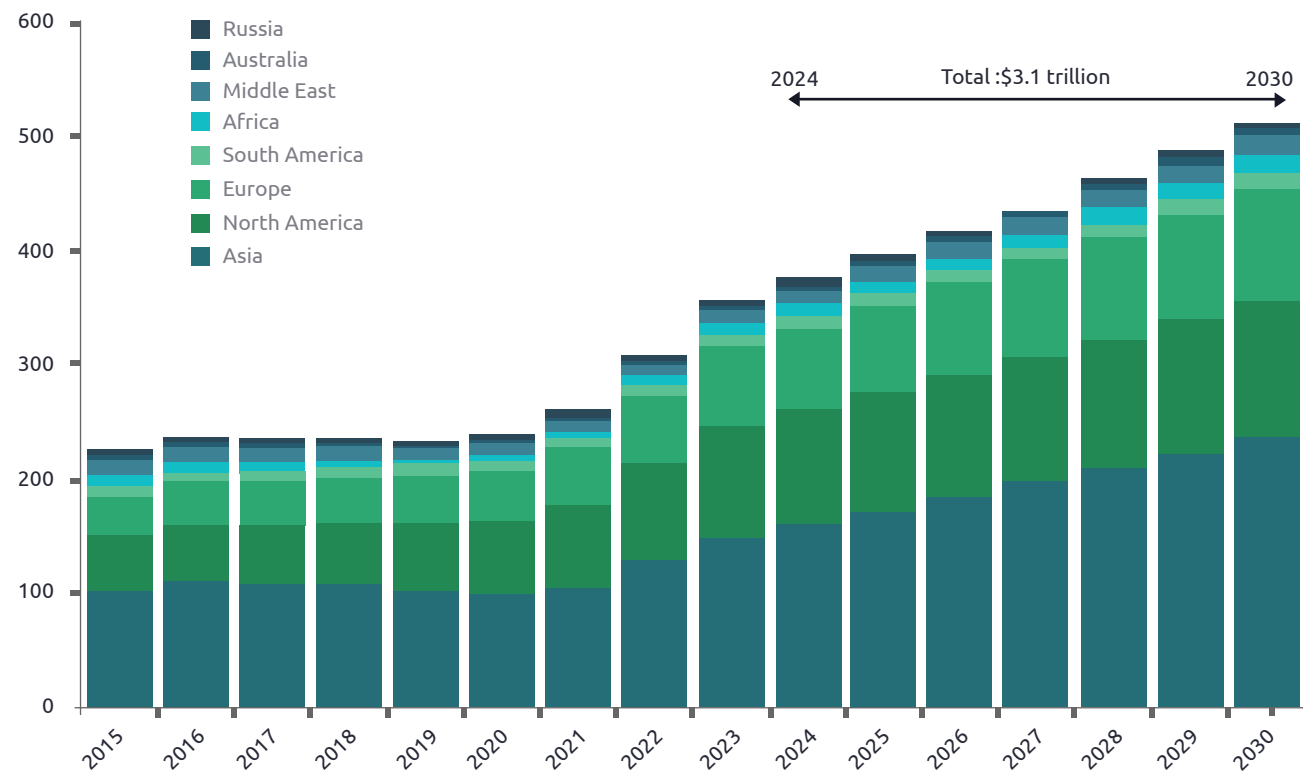
¹⁹³ <https://about.bnef.com/insights/clean-energy/significant-investment-needed-to-ready-the-global-power-grid-for-net-zero-bloombergnef-report/>

¹⁹⁴ Investing in digital technologies increased from about 12% of total grid investment in 2016 to about 20% in 2022.

¹⁹⁵ <https://iea.blob.core.windows.net/assets/ea2ff609-8180-4312-8de9-494bcf21696d/ElectricityGridsandSecureEnergyTransitions.pdf>



FIGURE 9
Power grid investments by region* Billion USD, nominal¹⁹⁶



¹⁹⁶Rystad Energy, Enable or inhibit: Power grids, key to the energy transition, require \$3.1 trillion in investments by 2030, <https://www.rystadenergy.com/news/power-grids-investments-energy-transition-permitting-policies>
¹⁹⁷<https://www.cnbc.com/2023/02/21/why-its-so-hard-to-build-new-electrical-transmission-lines-in-the-us.html>

However, building new transmission lines brings technical, economic, and regulatory hurdles.¹⁹⁷ These barriers vary from one region to the other. Access to finance and high capital costs hinder progress in many emerging and developing economies. In Europe, the U.S. and Japan, public opposition to new projects poses the greatest obstacle¹⁹⁸.

For instance, the Cardinal-Hickory Creek 345 kV line in the US¹⁹⁹, planned to reduce congestion in the Midwest, faced over five years delays due to lawsuits from landowners and environmental groups worried about farmland and wildlife impacts.

- The Südlink transmission project, designed to transport wind power from Northern to Southern Germany, was started in 2014 but required revisions to use underground cables instead of overhead lines to secure public approval. This change tripled costs and delayed completion from 2022 to 2028, significantly impacting the project timeline²⁰⁰ and cost.

These factors can extend timelines to 7–15 years, as seen in Spain’s stalled Galicia-Aragon interconnector,²⁰¹ opposed by rural communities. This has pushed the completion of the project from 2030 to 2035.

¹⁹⁸<https://about.bnef.com/insights/clean-energy/significant-investment-needed-to-ready-the-global-power-grid-for-net-zero-bloombergnef-report/>
¹⁹⁹<https://www.cardinal-hickorycreek.com/joint-news-release-cardinal-hickory-creek-transmission-line-energized/>
²⁰⁰<https://www.enerdata.net/publications/daily-energy-news/germany-starts-construction-700-km-suedlink-transmission-line.html>
²⁰¹<https://montelnews.com/news/17057854-463d-492c-9b88-50b02292f133/commissioning-of-spain-france-interconnectors-put-back-to-2035>



- **Integrating decentralized renewable energy sources into the grids is challenging.** Connecting renewable capacities necessitates complex studies to assess grid impact, which can take years due to backlogs and understaffing at grid operators.²⁰² Regulatory and permitting delays, including environmental reviews and local opposition, further complicate connections. Additionally, the high cost of grid upgrades, sometimes borne by developers, can render projects uneconomical.

In July 2024, total wind, solar PV and hydropower capacity in various development stages waiting for grid connections amounted to 3000 MW²⁰³ equivalent to around five times the amount of solar PV and wind capacity added in 2024.

The United States has a very large queue of clean energy projects with the wait average time up from 2.1 years in 2000 to 3.7 years in 2021²⁰⁴. In Europe 1,700 GW of renewables are stuck in grid connection queues across 16 countries.²⁰⁵ Other countries with significant backlogs include China²⁰⁶, where rapid solar and wind deployment faces grid bottlenecks, and India, aiming for 500 GW of renewable capacity by 2030²⁰⁷ but hampered by grid infrastructure and financing challenges.

These delays result in significant project withdrawals, with most queued projects in the US dropping out due to costs or timelines. These grids connection inefficiencies are depriving the impacted regions of new renewable capacity they would need to meet their 2030 energy and climate targets.

Globally, countries are addressing connection queue bottlenecks through grid reforms, introducing new measures to speed up connection timelines.

Streamlining connection processes through automation and standardized protocols can reduce study times. FERC's²⁰⁸ Order 2023 in the US mandates faster queue processing and penalties for delays, aiming to cut wait times²⁰⁹. In Europe^{210,211} the November 2024 EU Action Plan for grids is aimed at fixing structural issues but urgent short-term actions are needed on the very long grid connection queues. In Germany, the timelines for permitting have been significantly reduced through reforms aligned with the EU RED III Directive. Standard renewable energy projects are now capped at 12 months, and in designated acceleration zones, at 6 months. Grid connection processes are also being digitized and supported by expert pools to speed up approvals.²¹²

- **Grid operators face significant challenges in managing distributed generation (DG) and microgrid.** This is due to their decentralized nature, bidirectional power flows, and impact on grid stability²¹³. Distributed Generation (DG), such as rooftop solar and small-scale wind, introduces variability and unpredictability, complicating voltage and frequency control. Also when DG sources generate more electricity than local loads consume, power flows back up the distribution network towards the transmission grid. This "reverse power flow" can overload distribution lines and transformers, creating interferences potentially leading to equipment failures.

Traditional grid protection systems are designed for one-way power flow. DG can complicate these systems, making it harder to detect and isolate faults, potentially leading to wider-spread outages. Finally, microgrids, which operate independently, challenge operators with coordination issues. For example, their islanding capabilities can disrupt load balancing if not properly synchronized.

- **Grid operators will also face challenges with Gen AI increase (see above)**

²⁰²<https://emp.lbl.gov/queues>

²⁰³<https://www.iea.org/reports/renewables-2024/electricity>, <https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions/executive-summary>

²⁰⁴<https://decarbonization.visualcapitalist.com/gridlock-visualizing-the-u-s-clean-energy-backlog/>

²⁰⁵<https://beyondfossilfuels.org/2025/05/13/>

²⁰⁶<https://www.japantimes.co.jp/environment/2025/08/05/energy/china-renewables-power-grid/>

²⁰⁷<https://www.bef.org/research/case-study/india-s-renewable-energy-boom-the-power-of-solar-and-beyond#:~:text=This%20includes%20a%20pledge%20to,zero%20carbon%20emissions%20by%202070.>

²⁰⁸FERC: Federal Energy Regulatory Commission (US).

²⁰⁹<https://www.ferc.gov/explainer-interconnection-final-rule>

²¹⁰<https://www.ecofinconcept.de/eu-grid-action-plan-will-help-renewables-but-urgent-action-needed-on-excessive-connection-queues/>

²¹¹[https://www.europarl.europa.eu/RegData/etudes/BRIE/2025/772854/EPRS_BRI\(2025\)772854_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2025/772854/EPRS_BRI(2025)772854_EN.pdf)

²¹²<https://www.cleanenergywire.org/news/germany-grants-fast-track-areas-shorter-approval-times-renewables-and-electrolysers>

²¹³<https://energy.sustainability-directory.com/question/how-does-distributed-generation-affect-grid-stability/>



- **Climate change exacerbates these risks**, as extreme weather can disrupt renewable output, with hurricanes reducing solar generation and destroying the grid networks. Rising temperatures reduce transmission line efficiency. In the United States, for example, the effects of global warming are expected to reduce overhead lines capacity by an average of 1.9% to 5.8% between 2040 and 2050, compared to the 1990–2010 period²¹⁴. Extreme cold weather can damage grids, threatening the security of electricity supply as seen for instance in Texas²¹⁵ in February 2021 when an ice storm, followed by two additional winter storms, caused below-freezing temperatures. Demand for electricity surged while nearly half the grid's generating capacity failed as wind turbines froze, natural gas pipelines and storage facilities were crippled, and power plants faltered. The Electric Reliability Council of Texas (ERCOT) initiated rolling blackouts that left over 4.8 million customers without power for extended periods. The event highlighted the challenges of electricity management in the face of climate-related risks.

To mitigate climate change impacts, grid operators are adopting resilience strategies, including advanced weather forecasting²¹⁶, and infrastructure hardening investments, such as elevating substations to protect them against floods, or using fire-resistant materials against wildfires. The EU Commission highlighted that, without adaptation,

grid damage could multiply sixfold by the middle of the century.²¹⁷

- **Modernizing grids to integrate distributed, greener energies and increasing the connected IoTs increases cyber-attack risks.**^{218,219} This is in part because it introduces more players that all must comply with security rules to keep the grid safe. Grids that are strategic assets, are also vulnerable to *state sponsored cyberattacks* as illustrated by the repeated Russian linked attacks on the Ukrainian grid.²²⁰ In 2022, Chinese-linked hackers infiltrated seven Indian State Load Dispatch Centers, threatening grid stability, though no outages occurred. In 2023, 61% of all recorded cyberattacks worldwide originated from Russia, many of which targeted critical infrastructure, with attacks ranging from ransomware incidents to attempts at grid disruption.²²¹

As electricity's role grows in a decarbonized future, power systems become prime targets for cyberattacks. Avoidance strategies include defense-in-depth with robust firewalls implementation, encryption, multi-factor authentication, and continuous monitoring to detect threats. Regular cybersecurity training reduces vulnerabilities. Grid-enhancing

²¹⁴<https://www.sciencedirect.com/science/article/abs/pii/S2352467725000773>

²¹⁵<https://www.ebsco.com/research-starters/power-and-energy/2021-texas-power-crisis>

²¹⁶Europe's ENTSO-E is using AI enabled predictive models to manage storm-related disruptions.

²¹⁷https://www.eca.europa.eu/ECAPublications/RV-2025-01/RV-2025-01_EN.pdf

²¹⁸<https://www.wired.com/story/youre-not-ready-for-a-grid-attack/>

²¹⁹<https://www.govtech.com/security/>

²²⁰[critical-infrastructure-how-to-protect-water-power-and-space-from-cyber-attacks](https://www.ironnet.com/blog/cyber-attacks-on-the-power-grid)

²²¹<https://www.ironnet.com/blog/cyber-attacks-on-the-power-grid>

²²²<https://www.eurelectric.org/in-detail/cybersecurity-in-the-power-sector/>

²²³<https://www.darktrace.com/products/endpoint>



technologies (see below) and AI-driven threat detection, like Darktrace's platform²²², enhance resilience.

- **Grid balancing challenges with high shares of variable renewable energy.** Intermittent wind and solar generation complicates supply predictability. For instance, solar power peaks during daylight but drops at night, creating steep ramping requirements, as seen in California's "duck curve,"²²³ where rapid dispatch of non-renewable resources is needed to meet evening demand. As solar capacity grows, duck curves are getting steeper and thus more difficult to manage. High renewable penetration levels can lead to overproduction during peak generation, causing negative pricing and curtailment, or shortages during low weather-related generation, increasing outage risk. For example, U.S. outages are already costing \$150 billion annually²²⁴.

Storing large-scale electricity remains expensive and complex, with current technologies falling short. Lithium-ion batteries, costing ~\$115/kWh, typically store only a few hours of grid supply. Pumped hydro storage, which can provide up to 80% of global large-scale storage, is limited in Western countries due to scarce suitable sites, with most already developed. Emerging solutions like flow

batteries or gravity storage are not yet cost-competitive. Additionally, the lack of inertia from inverter-based renewables, unlike traditional rotating turbines, can destabilize grid frequency and voltage integration. This trend is expected to continue in the coming years with increased renewables penetration and the closure of fossil-fuel plants.

The maximum share of intermittent renewables – such as wind and solar – that can be accommodated by grids has to be analyzed case by case. Indeed, it depends on grid infrastructure, energy storage capacity, dispatchable generation sources like hydroelectric or nuclear power, demand response capabilities and advanced grid management technologies.

When the share of intermittent renewables exceeds the grid's capacity, operational issues arise.

- **Negative prices and curtailment** occur when supply exceeds demand, and producers, must then pay utilities or consumers to take excess electricity to avoid curtailment or grid instability. If negative prices persist or grid stability is at risk, operators may curtail renewable output. Episodes of negative electricity prices are becoming increasingly common, particularly during periods of high renewable generation and low demand. In 2024, in Germany,

negative prices occurred for 457 hours in 2024, up from 301 hours in 2023 with prices dropping as low as -€135/MWh during peak wind and solar output, driven by the country's 60% renewable energy share and constrained transmission to the Southern industrial region (see above). Solar curtailment increased by 97% driven by rapid growth in PV deployment and unusually high solar radiation in the summer²²⁵ amounting to 3.5% of total renewable electricity generation.

Similarly, California's CAISO market saw 1,180 hours of negative electricity prices in 2024²²⁶ a significant increase from 530 hours in 2023. These negative prices, driven by solar oversupply (30% solar penetration) and grid constraints led to around 2.2 million MWh of curtailed energy.

The weekend of May 10-11, 2025, saw some of the lowest hourly prices ever recorded in Europe, with the Belgian EPEX clearing at a record low of minus €462.33/MWh on May 11. The same day, as much as 12 GW of solar power was curtailed in Spain and 3.5 GW in France.²²⁷

These cases illustrate how grids with limited ability to absorb excess renewable energy – due to insufficient storage, outdated transmission, or slow demand response – face economic inefficiencies as these curtailment episodes reduce electricity generators revenue.

²²³<https://www.eia.gov/todayinenergy/detail.php?id=56880>

²²⁴<https://greenridgesolar.com/price-perils-power-outages-battery-backup/#:~:text=Power%20outages%20cost%20the%20U.S.,can%20be%20just%20as%20serious.>

²²⁵<https://www.pv-magazine.com/2025/04/03/pv-curtailment-jumps-97-in-germany-in-2024/>

²²⁶<https://www.renewableenergyworld.com/solar/negative-prices-in-caiso-what-ppa-buyers-and-renewable-developers-need-to-know/#:~:text=There%20were%20~1%2C180%20hours%20in,6%25%20of%20total%20hours.>

²²⁷<https://www.spglobal.com/commodity-insights/en/news-research/latest-news/electric-power/051325-solar-power-curtailments-spread-across-europe-in-early-may>



- **Blackouts:** When these challenges are mismanaged, the power system fails, triggering widespread blackouts. Though rare, these events are immensely costly²²⁸, disrupting economies and people's lives.

✓ *Blackout costs:* the 2021 Texas blackout cost an estimated \$195 bn in damages.²²⁹ In 2019-2020, California had several outages and blackouts. A single blackout, on October 7, 2019, likely costed small commercial and industrial businesses \$2.4 bn.²³⁰

The damage costs related to Iberia's huge April 2025 blackout calculations are still not finalized²³¹. Spain's main business lobby CEOE²³² estimated the outage would shave 1.6 billion euros or 0.1%, off gross domestic product. It took oil refineries a week or more to resume their operations fully, some industrial equipment's had been damaged and food had to be thrown away because of the lack of refrigeration.

Exact costs vary due to deferred economic impacts and recovery efforts. These are direct costs excluding health related issues. Let's examine some significant black-outs and their root causes.

✓ *Blackout root causes and recommendations.* Over the past decade, several significant electrical blackouts have disrupted regions worldwide, often exposing vulnerabilities in aging infrastructure, lack of vegetation management or inadequate power grids operations.

- **On April 28, 2025, the Iberian Peninsula, encompassing Spain and Portugal, suffered one of Europe's most severe blackouts**^{233,234,235} impacting 55 million people for up to 18 hours, halting transportation and causing eight deaths. Three reports from Spanish Ministry (MITECO), the Spanish TSO REE and the Spanish association of energy companies AELEC analyzed the event, with other reports pending²³⁶. The blackout began with frequency oscillations (0.2–0.6 Hz) from 12:03, culminating in a cascading failure triggered by a transformer trip in Granada at 12:32:57. This was followed by disconnections in Badajoz and Seville, losing 15 GW of generation, mostly solar.

Causes include insufficient voltage control due to poor planning by REE, with too few conventional plants scheduled to compensate for a possible grid unbalance. Indeed, in the South, there was a high share of solar (73%) energy and a low grid inertia. Also, some

plants failed to follow voltage regulation protocols in this disturbed grid situation. Moreover, inadequate interconnection capacity with France and cascading disconnections from a transformer failure explain the blackout. Grid restoration, completed by April 29, relied on hydropower, gas turbines, and imports from Morocco (900 MW) and France (2 GW).

- **On July 4, 2025, a major blackout struck the Czech Republic**²³⁷, affecting Prague and six regions, disrupting public transport, trapping people in elevators, and halting industrial operations. The root cause was a fallen high-voltage phase conductor triggering a cascading failure across eight substations. The incident exposed vulnerabilities in aging grid infrastructures, with heat-related stress and equipment fatigue as possible factors. A detailed investigation into the precise cause is ongoing.
- These incidents underscore recurring themes: grids strained by high intermittent renewables, insufficient cross-border interconnections, and fragility of grids with low inertia due to increasing renewable energy integration and closure of conventional plants. Thus, grid operators can struggle to maintain frequency and voltage stability during sudden losses of equipment or generation.

²²⁸<https://pinkerton.com/our-insights/blog/the-impact-of-power-outages>

²²⁹<https://www.austintexas.gov/sites/default/files/files/HSEM/2021-Winter-Storm-Uri-AAR-Findings-Report.pdf>

²³⁰<https://www.bloomenergy.com/bloom-energy-outage-map/>

²³¹<https://www.insurancejournal.com/news/international/2025/04/30/821937.htm>

²³²Confederación Española de Organizaciones Empresariales

²³³<https://www.theguardian.com/environment/2025/apr/29/what-caused-the-blackout-in-spain-and-portugal-and-did-renewable-energy-play-a-part>

²³⁴<https://theconversation.com/spain-portugal-blackouts-what-actually-happened-and-what-can-iberia-and-europe-learn-from-it-255666#:~:text=REE%20sources%20indicate%20that%20the,for%20balancing%20supply%20and%20demand>

²³⁵<https://www.theguardian.com/business/2025/may/02/blackouts-energy-outage-risks-europe-worldwide-spain-portugal-france>

²³⁶<https://hayaenergy.com/blog-iberian-peninsulas-blackout-on-28-april-new-information/>

²³⁷<https://www.osw.waw.pl/en/publikacje/analyses/2025-07-09/czech-republic-without-power-lessons-blackout>

Integrating high shares of intermittent renewables: technical, regulatory, and political solutions

• Technical solutions

✓ Additional infrastructure

- **Growth of stationary battery systems falls short of energy transition needs** Large-scale energy storage systems can store excess energy generated during periods of high renewable output and release it when production is low. This enables grid balancing. The stationary batteries market that grew in 2024, is projected to grow from \$5 billion to \$150 billion by 2030²³⁸. In 2024, the US utilities added 10.4 GW of new battery storage capacity and additions should double in 2025²³⁹. Battery storage capacity now exceeds pumped hydro capacity, totaling more than 26 gigawatts. Despite this growth, battery capacity was only 2% of the 1,230 GW of utility-scale electricity generating capacity. In Europe a 15% annual growth to 22 GWh of newly deployed Battery Energy Storage Systems (BESS) in 2024 expanded the battery fleet to 61 GWh

²³⁸<https://pvcase.com/blog/renewable-energy-and-grid-stability-modern-infrastructure-challenges-and-solutions/>

²³⁹<https://www.eia.gov/todayinenergy/detail.php?id=64705>

²⁴⁰https://api.solarpowereurope.org/uploads/SPE_European_Battery_Outlook_2025_62b89db476.pdf

²⁴¹<https://justenergy.com/blog/vehicle-to-grid/>

²⁴²<https://www.sciencedirect.com/science/article/pii/S2590174524003428>

²⁴³<https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-cars>

with Germany, Italy, and the UK accounting for 2/3 of these additions. Significant BESS expansion in Europe is forecasted²⁴⁰ to reach a total capacity to 400 GWh by 2030, which remains far below the 780 GWh levels required to meet the flexibility needs in a renewable-driven energy system. Measures to boost BESS growth include *enhancing their economic viability*, removing regulatory barriers, and prioritizing storage in national energy strategies.

- **Vehicle to grid**^{241,242} Globally, in 2024 there were around 40 million electric vehicles (EVs) on the road²⁴⁰ and that number is expected to grow. Vehicle-to-grid (V2G) technology enhances grid stability by enabling EVs to act as mobile energy storage units, supplying stored power back to the grid during peak demand or renewable energy fluctuations, thus balancing supply and demand²⁴³. They can also provide ancillary services as frequency regulation. In Denmark, a V2G pilot with Nissan Leaf vehicles demonstrated that each EV performed 100 hours frequency services and generated 1,860€ per year by participating in energy markets. Renault launched a V2G offer in France at the end of 2024²⁴⁴, and in July 2025 in the UK, Octopus Energy partnered with BYD to introduce the country's first all-

²⁴⁴<https://www.batterypowertips.com/how-does-vehicle-to-grid-technology-work-to-improve-sustainability/>

²⁴⁵<https://www.renault.fr/renault-mag/thematique-innovations/avec-mobilize-v2g--la-future-renault-5-electrique-devient-une-so.html>

²⁴⁶<https://www.electrive.com/2025/06/24/octopus-energy-and-byd-launch-uks-first-v2g-bundle/>

in-one V2G bundle²⁴⁶: a compatible EV, bi-directional charger, and smart tariff, together enabling free home charging and turning EVs into grid-supporting assets. However, V2G is still in early stages, as many EVs are not vehicle-to-grid ready. Furthermore, EV drivers often have worries such as lack of reliable bidirectional EV charging infrastructure and their vehicle not being available if they urgently need it.





• **Increasing grid sensors:**

- *Smart meters*^{247,248,249}: By 2023, 1.06 billion smart meters for electricity, water, and gas were installed worldwide. Smart meter implementation varies globally, with different progress across regions. The EU's 2019 Clean Energy Package mandated 80% smart meter²⁵⁰ coverage by 2020. At the end of 2023, only 60% percent of the electricity customers in EU27+3 had a smart meter with Italy, France, UK, Spain, and Scandinavia leading, while Germany and Eastern Europe lag due to costs and privacy concerns. The penetration of smart electricity meters in North America reached 82 % in 2024²⁵¹ led by Canada, California and Texas. With a compound annual growth rate projected at 3.8% over the period to 2029, the penetration of smart meters in the US should increase to 94% and in Canada to 96% in 2029.

In 2023, the Asia-Pacific region achieved a smart meter penetration rate of 49%²⁵², largely driven by successful nationwide rollouts in China²⁵³ and Japan. With planned nationwide deployments

in Australia, South Korea, India, Indonesia, and Singapore, the region's smart meter penetration is expected to reach 67% by the end of this decade. Smart electrical meters improve grid balancing by delivering to the operators, real-time electricity usage, enabling them to align supply with demand. They support dynamic load management and demand response programs²⁵⁴, encouraging reduced consumption during peak times. Smart meters also instantly detect outages and power quality issues and enable quick electricity repair.

New-generation smart meters offer significant improvements over earlier models, including enhanced connectivity, real-time monitoring, renewable energy integration, improved security, and consumer empowerment through accurate billing and flexible tariffs.²⁵⁵

- *Other IoTs devices enhance real-time control*. These include Phasor Measurement Units.²⁵⁶ (PMUs),

Smart Transformers²⁵⁷, and Distributed Energy Resource Management Systems (DERMS)²⁵⁸. PMUs measure the amplitude and phase of the voltage or the current. They are used to improve operators' visibility into what is happening throughout the grid network. Smart Transformers enable the bidirectional flow of electricity between the consumers and the grid in an efficient manner, thus improving renewable electricity grid integration. DERMS is a software platform that is used to organize the operation of the aggregated Distributed Energy Resources. within a power grid. It has similarities with a Virtual Power Plant.

IoT sensors monitor equipment health and environmental conditions, enabling predictive maintenance and rapid fault detection, reducing probability of outages.

²⁵¹<https://www.thefastmoe.com/technology-solutions/43134-smart-meter-penetration-in-north-america-hits-82-as-utilities-shift-to-second-gen-technology#:~:text=WATCH%20NOW-,Smart%20Meter%20Penetration%20in%20North%20America%20Hits%2082%25%20as,Shift%20to%20Second%20Gen%20Technology&text=A%20new%20research%20report%20from,over%2082%20percent%20in%202024.>

²⁵²<https://www.iot-analytics.com/smart-meter-adoption/>

²⁵³Smart meter penetration rate has reached 100% in China. <https://www.ytl-e.com/news/quarterly-publication/questions-smart-meter.html>

²⁵⁴In Ontario, Canada, thanks to smart meters, Hydro One's program shifted 5% of peak load to off-peak hours

²⁴⁷<https://iot-analytics.com/wp-content/uploads/2024/02/Global-Smart-Electricity-Meter-Adoption-2024-vweb.png>

²⁴⁸<https://www.precedenceresearch.com/smart-meters-market>

²⁴⁹<https://www.esc-partners.com/blog/smart-meter-adoption-in-the-us-tops-65>

²⁵⁰<https://www.berginsight.comsmart-electricity-meter-penetration-rate-in-europe-reached-60-percent-at-the-end-of-2023>

²⁵⁵<https://energyguide.org.uk/snets2-smart-meters/>

²⁵⁶https://www.enerdynamics.com/Energy-Currents_Blog/What-Is-a-Phasor-Measurement-Unit-and-How-Does-it-Make-the-Grid-More-Reliable.aspx

²⁵⁷https://transformers-magazine.com/files/Smart-Transformers-Revolutionizing-the-renewable-energy-landscape_final.pdf

²⁵⁸<https://www.next-kraftwerke.com/knowledge/derms>



- **Inertia increase:** Supplying inertia on a grid with a high share of intermittent renewables is critical to maintain stability, as these sources lack the physical inertia provided by traditional synchronous generators. Grid inertia can be emulated using advanced technologies such as grid-forming inverters²⁵⁹, and battery energy storage systems (BESS) equipped with virtual synchronous machine (VSM)²⁶⁰ controls.
- **Managing congestion:** Electricity congestion arises from limited transmission capacity when demand exceeds the available infrastructure. In the United States transmission grid congestion costs peaked at almost \$21 bn²⁶¹ in 2022 and fell to an estimated \$11.5 bn in 2023 thanks to less extreme weather events and lower gas prices. The cost of managing congested EU power grids reached €4.26bn in 2023²⁶², down 21% on the year before, mainly due to lower power prices.

There are different ways to manage congestion:

- Constructing new electrical transmission lines is a key strategy to alleviate grid congestion. New lines increase grid capacity, enabling better integration of renewable energy sources and facilitating power transfer between regions. For example, in Spain, the Red Eléctrica's 400 kV line from Galicia to Asturias²⁶³, completed in 2024, reduced congestion by 20%, allowing excess wind power to reach demand centers. These projects that often span on more than 10 years, require careful planning to address technical, regulatory, local public oppositions and economic challenges²⁶⁴.
- Implementing Demand Response (DR) programs incentivizes consumers to reduce electricity use during peak times. (see below)
- Increasing energy storage systems (see above) that store excess renewable energy and dispatch it during high demand, reducing congestion.

These solutions complement new lines, offering faster, cost-effective ways to manage congestion.

- Interconnections between countries enable cross-border electricity trade and resource sharing. For instance, the North Sea Link between Norway and the UK, operational since 2021, facilitates bidirectional trade, allowing Norway to export surplus hydropower and the UK to supply wind power, reducing electricity supply costs and cutting emissions.²⁶⁵ In March 2022, Ukraine's electricity grid was synchronized with the ENTSO-E Continental European grid, ensuring ongoing stability despite Russian attacks. The connection supports 935 million kWh of imports and export revenues.

Stronger interconnections between Spain and France or Morocco might have mitigated the April 2025 blackout by enabling faster power imports to balance the grid after the 15 GW generation loss.²⁶⁶

In Europe, the ENTSO-E synchronous grid connects 667 GW of generation, enabling efficient renewable integration but requiring robust management rules implementation and cybersecurity to prevent cascade failures.

²⁵⁹[Grid-forming inverters are power electronics that actively control voltage and frequency to stabilize grids, mimicking synchronous generators.](#)

²⁶⁰Virtual Synchronous Machine (VSM) controls are advanced algorithms in inverters that emulate the inertial characteristics of traditional synchronous generators

²⁶¹https://gridstrategiesllc.com/wp-content/uploads/Grid-Strategies_2023-Transmission-Congestion-Report.pdf

²⁶²[https://montelnews.com/news/0c669a04-99cc-440a-80b5-4ea70ebdde05/eu-power-grid-congestion-cost-eur-4bn-in-2023-acer#:~:text=\(Montel\)%20The%20cost%20of%20managing,regulatory%20agency%20Acer%20on%20Wednesday](https://montelnews.com/news/0c669a04-99cc-440a-80b5-4ea70ebdde05/eu-power-grid-congestion-cost-eur-4bn-in-2023-acer#:~:text=(Montel)%20The%20cost%20of%20managing,regulatory%20agency%20Acer%20on%20Wednesday)

²⁶³<https://www.ree.es/en/press-office/news/press-releases/2019/02/red-electrica-invests-more-9-million-euros-improve-asturias-galicia-axis>

²⁶⁴<https://powerline.net.in/2025/05/01/cea-notifies-draft-cea-technical-standards-for-construction-of-electrical-plants-and-electric-lines-regulations-2025/>

²⁶⁵<https://www.nationalgrid.com/national-grids-north-sea-link-strengthens-electricity-supply-and-repays-its-carbon-cost-just-six>

²⁶⁶<https://smcint.com/electrical-testing/analysis-of-spains-april-2025-blackout-causes-low-inertia-grid-risks-and-protection-solutions/>



✓ *Data and software-based solutions*

- **Grid Enhancing Technologies (GETs):**^{267,268} They are hardware and software solutions designed to optimize the capacity, efficiency, and reliability of existing power transmission and distribution. The US Department of Energy is presently investing nearly \$84 million in these advanced technologies. Examples of GETs include Dynamic Line Rating (DLR), Advanced Power Flow Control (APFC), and Transmission Topology Optimization.
- DLR uses real-time weather data and sensors to assess the true capacity of transmission lines. Its efficiency gains are substantial in congested regions. A comprehensive review²⁶⁹ found that traditional static transmission lines capacity ratings are significantly more conservative than necessary. DLR ratings exceed static limits by 15-30% about half the time, with some studies showing capacity increases up to a remarkable 45%, particularly valuable during peak congestion periods.
- APFC, part of Flexible AC Transmission Systems (FACTS), employs devices like phase-shifting transformers or Smart Wires technology to reroute power and balance overloaded lines.



- Transmission Topology Optimization uses software to reconfigure power flows, reducing congestions. These technologies, still underutilized, have shown significant promises, with potential to save billions in congestion costs.

- **How can artificial intelligence help?** Artificial intelligence (AI) enhances the integration of distributed energy resources (DERs) by coordinating microgrids, improving heating and cooling efficiency particularly for data centers and buildings, reduces computation for cryptocurrency mining, and optimizes charging for electric vehicles, and home batteries. Adding AI to Virtual Power Plants (VPP) management²⁷⁰

allows precise energy forecasting and demand response optimization. The Department of Energy estimates that tripling the scale of VPPs by 2030 could help meet electricity demand growth and save annual grid costs on the order of \$10 billion.²⁷¹ By analyzing weather, consumption, and production data, AI improves renewable output predictions, reducing curtailment. As an example, Google combined weather data with power data from 700 megawatts of wind energy sourced in the Central United States. It then used machine learning, to better predict wind production and electricity supply and demand. This has resulted in a 20% increase in revenue for wind farms.²⁷²

Additionally, AI can simulate cyberattack scenarios, as seen in the US's CRISP program, strengthening grid defences by generating robust security protocols.²⁷³

²⁶⁷<https://www.sciencedirect.com/science/article/abs/pii/S0378779624001925>

²⁶⁸<https://afore.org/resources/assessment-and-evaluation-of-grid-enhancing-technologies-gets/>

²⁶⁹<https://www.forbes.com/sites/annabroughel/2025/03/27/dynamic-line-rating-grid-technology-to-reduce-your-electric-bills/>

²⁷⁰A Virtual Power Plant (VPP) is a network of decentralized, medium-scale power generating units as well as flexible power consumers and storage systems

²⁷¹<https://www.smart-energy.com/industry-sectors/smart-grid/solving-the-grids-ai-power-struggle-with-virtual-power-plants/>

²⁷²<https://www.forbes.com/sites/jeffmahon/2020/05/31/thanks-to-renewables-and-machine-learning-google-now-forecasts-the-wind/#49c7e94e1865>

²⁷³https://www.energy.gov/sites/default/files/2021-12/CRISP%20Fact%20Sheet_508.pdf



Regulatory and political measures impact on grid balancings:

Grid balancing is significantly influenced by regulatory frameworks governing curtailment, merit order, permitting, and grid tariffs. These regulations shape how Transmission System Operators (TSOs) and utilities manage the integration of renewable energy sources. Below, we explore the impacts of these regulatory aspects on grid balancing.

✓ The merit order²⁷⁴, is a regulatory mechanism to dispatch generation sources to meet the demand based on their marginal costs. In Europe, EU regulations favour renewables with near-zero marginal costs, pushing fossil fuel plants to a backup role. However, this can lead to instability when renewable output drops suddenly, requiring rapid ramp-up of gas or coal plants, as observed in the UK's 2019 blackout, where insufficient reserve capacity contributed to outages.²⁷⁵ As already pointed out in previous WEMO Outlooks, the current merit order mechanism, prioritizing renewables, needs re-evaluation to ensure grid stability.

✓ *Permitting* regulations significantly impact grid balancing by delaying the construction of new transmission lines needed to alleviate congestion and integrate variable generation (see above).

✓ *Funding*: As seen above, by 2030, investment needs to reach a 50% increase compared to 2024 investments²⁷⁶. Securing this funding is critical for maintaining a reliable power system.

These investments can be funded through:

- a. *Subsidies*: For example, in 2023, U.S. Department of Energy announced nearly \$3.5 billion in awards under its Grid Resilience and Innovation Partnerships program, known as GRIP.²⁷⁷
- b. *Private funding*: For example, Eleclink²⁷⁸ interconnector between France and the UK has been financed entirely through private funds, unlike other interconnector projects, which are underwritten by electricity consumers.
- c. *Grid Tariffs* are the main TSOs funding source in Western countries. These regulated charges, set by bodies like the Federal Energy Regulatory Commission

(FERC) in the US or the National Energy Regulators in Europe (as CRE in France), are levied on electricity users based on usage (e.g., \$/kWh and/or \$/kW).

The asset base for calculating TSO tariffs, known as the Regulated Asset Base (RAB), includes the capital costs of transmission infrastructure adjusted for depreciation and approved investments. The allowed return rate on the (RAB) varies by region and regulatory framework. It is often calculated using the Weighted Average Cost of Capital (WACC)²⁷⁹, balancing returns on equity and debt.

Tariff increases are capped by regulators to balance investment needs with consumer affordability. For example, in July 2025, as part of its efforts to reduce electricity costs, the European Commission directed National Regulatory Authorities to evaluate the potential for incentive-based regulation and adjust relevant performance indicators and benchmarks accordingly²⁸⁰. However, tariff structures prioritize hardware solutions like new transmission lines, such as MISO's²⁸¹ \$22 billion Midwest projects²⁸², over cheaper GETs. Reforms like FERC's Order 1920²⁸³ aim to promote GETs but face slow implementation.

²⁷⁴<https://www.squeaky.energy/blog/understanding-power-markets-merit-order-and-marginal-pricing>

²⁷⁵https://www.ofgem.gov.uk/sites/default/files/docs/9_august_2019_power_outage_report.pdf

²⁷⁶<https://about.bnef.com/insights/clean-energy/significant-investment-needed-to-ready-the-global-power-grid-for-net-zero-bloombergnef-report/>

²⁷⁷<https://www.utilitydive.com/news/doe-largest-ever-grid-investment-GRIP-xcel-miso-spp/697141/>

²⁷⁸<https://www.eleclink.co.uk/about-us/who-we-are>

²⁷⁹Recent WACs varied from 4.65% in UK, 5.62% in Australia and 6-7% in the US.

²⁸⁰https://energy.ec.europa.eu/news/commission-continues-action-lower-energy-bills-new-guidance-renewables-grids-infrastructure-and-2025-07-02_en

²⁸¹MISO: Midcontinent Independent System Operator

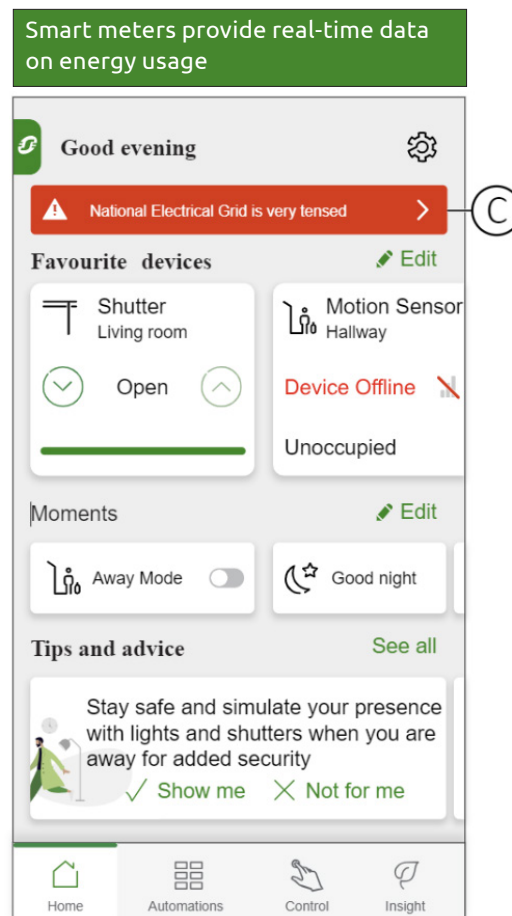
²⁸²<https://www.utilitydive.com/news/miso-regional-transmission-expansion-plan-2024-mtep/735483/>

²⁸³<https://www.ferc.gov/explainer-transmission-planning-and-cost-allocation-final-rule>

✓ *Demand response (DR²⁸⁴)* refers to programs that incentivize consumers to reduce or shift electricity usage during peak demand or grid stress. Tools for implementation include:

- Time-Of-Use (TOU) tariffs (which charge higher rates during peak hours to encourage off-peak consumption),
- Direct load control allowing utilities to remotely adjust appliances like air conditioners,
- Smart meters providing real-time usage data, and
- Automated Demand Response (ADR) systems that integrate IoT and automation for rapid response. For example:

- Southern California Edison's TOU pilot program demonstrated significant grid benefits by encouraging consumers to shift energy use to off-peak hours saving utilities costs on peaking plants and reducing grid strain. This also cut carbon emissions by aligning consumption with renewable availability²⁸⁵.
- In France, during the 2022-2023 energy crisis (that was combined with a lower nuclear generation output), the government launched an "Energy Sobriety Plan" using the RTE's (Reseau de Transport d'Electricité) Ecowatt tool (see the figure). This campaign triggered a 6% reduction in electricity consumption compared to the 2014–2019 average.²⁸⁶



Conclusion: Electrical grid operators face numerous challenges, including integrating a growing share of intermittent renewable energy, managing the closure of thermal power plants that provide grid stability, adapting to climate change and extreme weather, mitigating cyberattacks risks, addressing underfunding, navigating complex regulations, and overcoming public resistance to new overhead lines.

Simplifying regulations, especially for approving new power lines, revising pricing to fund necessary investments, using new AI enabled tools, and aligning renewable energy production growth with grid capacity are critical to addressing these challenges.

²⁸⁴<https://www.iea.org/energy-system/energy-efficiency-and-demand/demand-response>
²⁸⁵<https://www.ecohedge.com/blog/how-time-of-use-rates-support-grid-decarbonisation/>
²⁸⁶<https://analyseetdonnees.rte-france.com/en/electricity-review-keyfindings>



What technologies will support the energy transition?

The first part of this chapter covers specific energy related technologies, while the second part will cover AI related improvements.

Energy-specific technology progress^{287,285,289}

The following table summarizes the main technologies progress and shows their Technology Readiness Level (TRL)²⁹⁰. TRL varies from stage 1 "Exploratory research transitioning basic science into laboratory" to stage 9 "Wide-scale commercial deployment."

²⁸⁷<https://www.iea.org/reports/clean-energy-innovation/innovation-needs-in-the-sustainable-development-scenario>
²⁸⁸<https://www.weforum.org/stories/2025/01/4-key-trends-to-watch-in-clean-energy-technology-in-2025/>
²⁸⁹<https://www.iea.org/data-and-statistics/charts/global-investment-in-clean-energy-and-fossil-fuels-2015-2024>
²⁹⁰<https://nap.nationalacademies.org/read/21712/chapter/14#290>
²⁹¹<https://www.nature.com/articles/s41377-024-01461-x>
²⁹²<https://www.technologyreview.com/2024/01/15/1086482/the-race-to-get-next-generation-solar-technology-on-the-market/>
²⁹³<https://www.mdpi.com/2313-0105/11/3/90#:~:text=Recent%20advancements%20focus%20on%20addressing,conductivity%20and%20better%20interfacial%20stability.>
²⁹⁴<https://www.sciencedirect.com/science/article/abs/pii/S1385894724088855>
²⁹⁵<https://www.grepow.com/blog/what-is-a-silicon-anode-lithium-ion-battery.html#:~:text=Silicon%20anode%20lithium%20Dion%20batteries%20are%20a%20type%20of%20rechargeable,over%20traditional%20lithium%20Dion%20batteries.>
²⁹⁶<https://www.hydrogennewsletter.com/powering-the-future-latest-breakthroughs-in-pem-electrolyzers-for-green-hydrogen-in-2025/#:~:text=Market%20Growth%20and%20Capacity%20Expansion,USD%209.12%20billion%20by%202034.>

FIGURE 10

Technology	TRL	Key Details
Perovskite Solar Cells, ^{291, 292}	4	Efficiency >26%, tandem cells ~34%. Challenges: stability, scalability, heavy metal toxicity. Pilot production by Oxford PV and Saule Technologies.
Lithium-Ion Solid state batteries, ^{293,294}	4-6	High energy densities (up to 400 Wh/kg) and improved safety. Challenges: dendrite formation, scalability, and high manufacturing costs.
Lithium-Ion batteries with silicon anode, ²⁹⁵	7	High energy density abundant material, fast charging but stability, safety and manufacturing issues. It requires standardized testing for TRL 9.
PEM Electrolyzers, ²⁹⁶	7	Commercial small-scale use, efficient with renewables but high cost and limited durability. Scaling to GW-level needed for TRL 8-9.
Solid Oxide Electrolyzers (SOE), ²⁹⁷	5	High efficiency at high T° but material durability and cost issues.
Alkaline Water Electrolyzers	9	AWEs are a proven, cost-effective technology. Challenges like gas crossover, slow response to intermittent power, and carbonate formation in electrolytes require ongoing R&D
Hydrogen Storage (Solid Form), ^{298,299,300}	3	Metal hydrides and chemical carriers at lab/prototype stage. Challenges: scalability, high desorption temperatures, slow kinetics.
Carbon Capture	4-9	Carbon Capture, varies in TRL. Post-combustion capture using amine-based solvents, is at TRL 9, with operational facilities. Pre-combustion and oxy-fuel combustion capture systems are at TRL 7–8. Direct Air Capture is at TRL 4–6, with pilot projects not yet commercially viable
High Temperature super-conductors, ³⁰¹	6-7	HTS cables have zero electrical resistance at liquid nitrogen temperatures (77 K) and can carry 10 times more power for the same footprint reducing transmission losses. Pilot projects by Nexans and AMSC, ²⁹⁹
Small Modular Reactors	6-8	See dedicated chapter
Advanced Modular Reactors	4-6	AMRs, designs include molten salt reactors (MSRs), high-temperature gas-cooled reactors (HTGRs), and sodium-cooled fast reactors (SFRs). Their promises are like SMRs. None has achieved commercial operation targeting deployment by the early 2030s
Nuclear Fusion	2-3	See dedicated chapter



AI impact on technological progress: Multiple technologies are driving progress, but one stands apart. AI and particularly generative AI should significantly impact technological advancements in the energy sector – including digital twins, modelling, equipment design and maintenance, operations, grid management (see above), and material innovation³⁰³. Below is a detailed breakdown of its potential contributions, based on current trends and capabilities:

- **Digital Twins:** AI and particularly generative AI can enhance digital twins – virtual replicas of physical energy systems – allowing more accurate, dynamic, and predictive models. It can simulate complex scenarios and optimize system behavior in real time.

- ✓ *Scenario Simulation:* using digital twins it will be possible to generate thousands of operational scenarios to stress-test power plants, wind or solar farms. This will help improve resilience and efficiency.
- ✓ *Real-Time Optimization:* AI will make it possible to update digital twins with real-time sensor data, enabling predictive maintenance and performance improvements.

²⁹⁷<https://www.sciencedirect.com/topics/engineering/solid-oxide-water-electrolysis>

²⁹⁸<https://onlinelibrary.wiley.com/doi/abs/10.1002/est2.546>

²⁹⁹<https://academic.oup.com/ce/article/7/1/190/7126621>

³⁰⁰<https://www.catf.us/resource/techno-economic-realities-long-distance-hydrogen-transport/>

³⁰¹<https://www.verifiedmarketreports.com/blog/top-7-trends-in-high-temperature-cables/>

³⁰²<https://www.nexans.fr/en/business/power-transmission-distribution/superconductivity/high-temperature-superconductors.html>

³⁰³<https://pages.awscloud.com/rs/112-TZM-766/images/GEN-energy-transformative-gen-ai.pdf>

- **Modelling and simulation:** Gen AI can create highly detailed and adaptive models for energy systems, improving forecasting and decision-making. Applications include:

- ✓ *Improved renewable generation forecasting* by creating precise models for wind or solar output based on improved weather prediction, historical data, and geographic factors.
- ✓ *Decision support and advance operation* by using optimization and AI to better operate the grid for current and next operations.

- **Capital project delivery:** Gen AI can help optimize schedules and clarify optimization and delivery trade-offs leading to gains in efficiency (time and money).

- **Improved Equipment Design:** Gen AI can accelerate the design of energy equipment (e.g., turbines, solar panels, batteries) by generating optimized designs based on performance criteria, material constraints, and environmental factors. Applications include:

- ✓ *Rapid Prototyping:* Create and test virtual prototypes, reducing the time and cost of physical iterations.
- ✓ *Customization:* Design region-specific equipment tailored to local climate or grid requirements. For example, Gen AI could help design next-generation solar panels with improved heat dissipation, increasing efficiency in high-temperature regions.

- **Maintenance (Predictive and Preventive):** Gen AI can predict equipment failures and optimize maintenance schedules, minimizing downtime and extending asset lifespans. Applications include:

- ✓ *Anomaly Detection:* Analyze sensor data to identify subtle signs of wear in transformers, turbines, or grid infrastructure.
- ✓ *Maintenance Scheduling:* Generate optimized maintenance plans based on usage patterns and historical failure data.
- ✓ *Repair Guidance:* Provide technicians with AI-generated repair instructions. For example, Gen AI could predict a gas turbine's failure risk by analyzing vibration patterns and scheduling maintenance before a costly breakdown.
- ✓ *Critical mode operations:* Design operation rules to keep equipment running until the next maintenance scheduled.

- **Improved Equipment Operations:** AI can optimize the real-time operation of energy equipment, by improving efficiency and reducing waste. Application includes:

- ✓ *Dynamic Tuning:* Adjust operating parameters in real time to maximize output under stressful operations.
- ✓ *Energy Efficiency:* Optimize fuel consumption in fossil fuel plants or battery discharge rates in storage systems.

- **Improved Electrical Grid Operations (as discussed earlier)**



- **New Materials:** Gen AI can accelerate the discovery and design of advanced materials for energy applications, such as batteries, solar cells, and superconductors.
- **Energy Savings:** Gen AI can identify opportunities for energy conservation Applications include:
 - ✓ *Industrial Processes redesign:* Simulate and redesign energy-intensive processes, like cement or steel production, to enable lower consumption. Example: Gen AI has been used to analyze a factory's energy usage patterns and generate a retrofit plan to cut consumption by 20%.
- **Despite promising Gen AI driven improvements, challenges must be overcome including:**
 - ✓ *Data Availability and Quality:* Generative AI relies on high-quality well-organized datasets which is still a challenge for many companies.
 - ✓ *AI models understanding:* AI and generative AI relies on large and complex models that are not fully understood yet, leading to a huge number of untested cases with no direct guarantee of their relevance.

- ✓ *Self-fulfilling loops:* with successful usage of AI models to predict failures, usual failures should be avoided and will progressively disappear from the training of the next AI models. Thus the AI trained agent can misunderstand critical situations.
- ✓ *Computational Costs:* Training and running generative models can be energy-intensive, requiring careful management to avoid negating energy savings.
- ✓ *Organizational changes and people:* New agile organizations and procedures must be implemented. Moreover, there is a need for employee training and job definition shift, in particular for junior tasks. Also, recruiting scarce AI talent may prove to be difficult.
- ✓ *Electricity consumption:* In 2024, generative AI significantly increased electricity consumption in Western countries, primarily due to the energy-intensive nature of training and deploying large-scale AI models in data centers³⁰⁴ (see above).

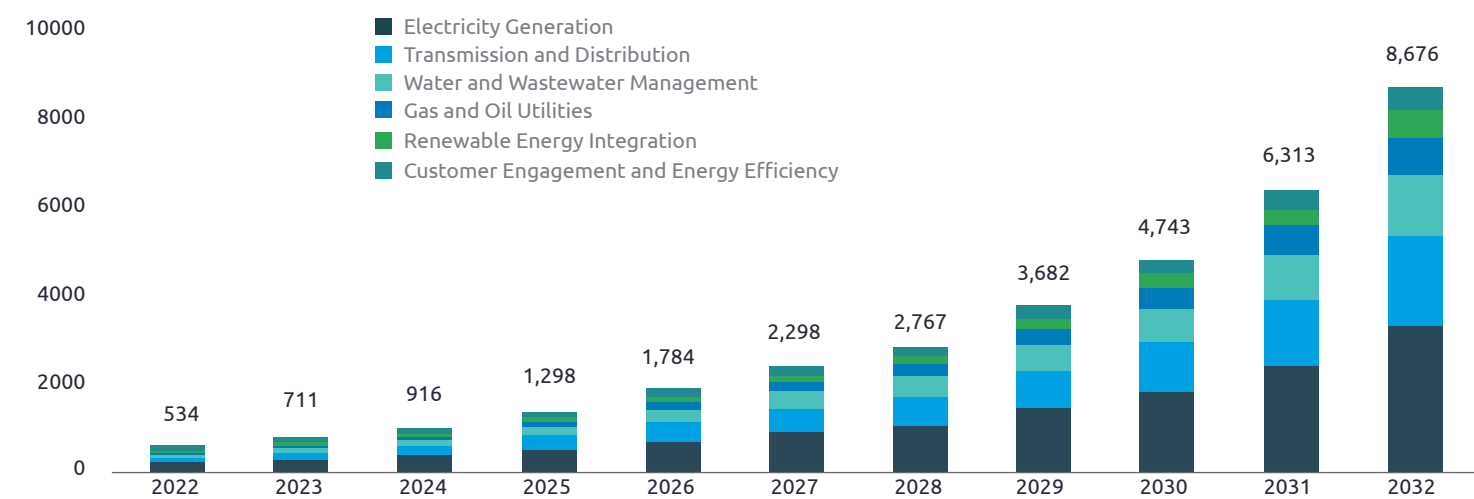
Direct-to-chip liquid cooling and oil immersion cooling are key advancements, enabling higher chip density. Furthermore, AI-powered systems optimize cooling performance based on real-time data analysis.³⁰⁵

³⁰⁴<https://www.iea.org/news/ai-is-set-to-drive-surging-electricity-demand-from-data-centres-while-offering-the-potential-to-transform-how-the-energy-sector-works>

³⁰⁵<https://encoradvisors.com/data-center-cooling-companies/#:~:text=What%20are%20the%20latest%20innovations,for%20flexible%20data%20center%20designs>



FIGURE 11
Generative AI in utilities market³⁰⁸
(USD Million)



³⁰⁶<https://masterofcode.com/blog/generative-ai-in-energy-and-utilities>
³⁰⁷<https://www.birlasoft.com/articles/generative-ai-frontier-energy-utilities-oil-gas-innovation>
³⁰⁸<https://marketresearch.biz/report/generative-ai-in-utilities-market/>
³⁰⁹<https://newsroom.ibm.com/2024-02-26-New-IBM-Study-Data-Reveals-74-of-Energy-Utility-Companies-Surveyed-Embracing-AI-https://marketresearch.biz/report/generative-ai-in-utilities-market/>

³¹⁰<https://www.alpha-sense.com/blog/trends/generative-ai-in-energy/>
³¹¹<https://menlovc.com/2024-the-state-of-generative-ai-in-the-enterprise/>
³¹²<https://www.ibm.com/downloads/documents/us-en/12f5a711174dc2ac>
³¹³<https://www.mckinsey.com/industries/metals-and-mining/our-insights/beyond-the-hype-new-opportunities-for-gen-ai-in-energy-and-materials>

• **Time and cost of Gen AI adoption:**^{306,307} Gen AI adoption is already happening, as confirmed by a recent survey³⁰⁹ showing that 74% of Energy & Utility companies surveyed have implemented or are exploring using AI in their operations. The market for generative AI in Utilities is expected to be worth around \$9 bn by 2032 from \$534 million in 2022, growing at a CAGR of 33.1% during the forecast period³¹⁰. The cost of adoption by the sector will be significant.³¹¹

However, so far, the results are disappointing as only 25% of AI initiatives have delivered the expected Return On Investment (ROI), over the past three years, according to a report from IBM, which surveyed 2,000 CEOs around the world during the first quarter of 2025.³¹² But even with less than impressive returns so far, CEOs are still confident that AI is the future; 85% of these leaders expect a positive ROI for scaled AI investments by 2027.

The straightforward use cases³¹³ generally do not require a lot of technical expertise or specialization to deploy and will likely be rapidly commoditized, but, even for those, change management continues to be a main challenge. Examples include standard back-office functions, such as assistants and agents that automate administrative functions or customer-facing chatbots. A strong impact has already been observed for software developers and data scientists.



By contrast, the ambitious, groundbreaking use cases are more innovative and consequently require more customization – sometimes even a trained-from-scratch LLM³¹⁴. And although they may have the potential to deliver significantly more value, they also require substantial upfront investment in capabilities and infrastructure.

For example, utilities – organizations with thousands of miles of transmission lines, pipelines, and other remote infrastructure – often spend millions of dollars on asset integrity. Corrosion and predictive-maintenance models can be retrained with the integration of many sources of data, including traditional records, such as past damage, visual inspections, and data from sensors on the asset itself. Other sources of data, such as drone and satellite-based images can also be integrated. Thus, AI and Gen AI can significantly improve the effectiveness of this core function.

- **Gen AI and emissions³¹⁵:** According to certain studies, CO₂ emissions could potentially be reduced by 5-10% by 2030.³¹⁶ However, the electricity consumption growth driven by LLM development, raises concerns about reliance on fossil fuels in regions with insufficient low emission electricity capacity. For example, Microsoft's emissions are up 30% since 2020 due to data center expansion³¹⁷. These dynamics underscore the need for energy-efficient AI algorithms, efficient data center cooling and low emission electricity availability for data centers.
- **Quantum computing:** Present prototype quantum computers consume large amounts of electricity, although they are in limited numbers so far. However, in the foreseeable future, the first machine capable of using a significant number of qubits (quantum bit, a basic unit of quantum information) will be ready. They will be able to crack almost all the current cybersecurity systems, posing a huge threat to all critical defense and financial systems. Today the only known non-quantum options use much more energy-intensive algorithms and communications. This may pose an additional stress on the electricity system.

³¹⁴LLM Large Language Model

³¹⁵<https://www.weforum.org/stories/2024/07/generative-ai-energy-emissions/>

³¹⁶<https://www.bcg.com/publications/2023/how-ai-can-speedup-climate-action#:~:text=1,.related%20adaptation%20and%20resilience%20initiatives.>

³¹⁷<https://www.cnbc.com/2024/05/15/microsofts-carbon-emissions-have-risen-30percent-since-2020-due-to-data-center-expansion.html>





The geopolitical impacts on the energy sector

✓ Throughout 2024 and the first half of 2025, geopolitical tensions escalated, driven by the Russia-Ukraine war and Middle East conflicts. *Control over energy resources and critical raw materials has fuelled these conflicts, which, in turn, have disrupted their supply chains.* One motive for Russia's invasion of Ukraine may have been to secure rare earth deposits, gas transit pipelines, and oil fields in Crimea. The strategic agreement signed between the United States and Ukraine in 2025 supports this analysis. The ongoing Russia-Ukraine conflict prompted new EU sanctions on Russian gas. This war threat, combined with reduced U.S. NATO funding, is pushing European countries to increase their defense budgets.

✓ *The 12-day war between Israel and Iran*, aimed at preventing Iran's nuclear weapon development, occurred in a region rich in oil and gas production. Thanks to shale oil and shale gas, the United States became the first oil producer globally³¹⁸ and the top LNG exporter³¹⁹. It was thus able to support Israel's 2025 military actions without concerns about Middle East oil supply disruption. While its importance has decreased, the Strait of Hormuz

remains a critical chokepoint for global energy trade, with approximately 20% of the world's oil and 20% of global (LNG) passing through it. Due to a combination of economic self-interest, pressure from its client China, fear of U.S. retaliation and weakened military capacity, Iran did not close the Strait of Hormuz during the 12-day war. During this conflict oil prices rose moderately with Brent crude rising from ~\$69 /bl to ~\$81/bl, far below potential spikes that could have resulted from a disruption of the Strait of Hormuz.

The US position as top oil and gas supplier, a weak global oil demand growth in 2025 (~0.7% annually)³²⁰, high global oil stocks (~7.7 mb)³²¹, and Saudi Arabia and the UAE signaling their readiness to increase their oil output if needed, are the main causes of this moderate growth. After the end of the 12-day war, Brent crude price dropped and stabilized at \$67/bl below the pre-war level.

The moderate effect on oil prices during the war highlights the Middle East's declining influence on oil prices.

Houthi attacks on Red Sea shipping disrupted ~12% of global seaborne oil trade³²², forcing reroutes around Africa and adding an extra 10 to 14 days to the traditional 30 to 40-day trip from Asia to Europe.³²³ This raised shipping rates by 200-400%³²⁴. Despite those attacks, for

the reasons analyzed above, oil prices remained stable. On the gas trade side, since early 2024, LNG tankers have avoided the Red Sea route, rerouting around Africa. The avoidance of the Red Sea route by LNG tankers has allowed Qatar to keep its LNG deliveries in the Pacific, while U.S. LNG stays in the Atlantic. In the first half of 2025, the U.S. exported roughly 80% of its LNG to Europe. Qatar exported 80% to Asia. Qatar is benefiting from this fragmentation of global LNG trade as it spares Doha from competing with U.S. volumes head-on³²⁵.

As analyzed above, in 2024 and early 2025, China solidified its global leadership in all green technologies including renewable energies, nuclear energy, electric batteries and green hydrogen. In reaction, the European Union is trying to implement a sovereignty policy.

✓ President Trump's 2025 election led to a significant overhaul of U.S. energy policy, favoring fossil fuel expansion and imposing high tariffs on clean technologies. This new policy reflects both a sovereignty approach and climate change skepticism. It has already had an important impact both in the US and globally.

Let's look more precisely at the impact of these geopolitical tensions on energy.

³¹⁸<https://www.eia.gov/todayinenergy/detail.php?id=61545>

³¹⁹<https://www.eia.gov/todayinenergy/detail.php?id=64844>

³²⁰<https://www.iea.org/reports/oil-market-report-june-2025>

³²¹<https://www.arbatcapital.com/post/oil-market-report-june-2025>

³²²<https://www.cfr.org/in-brief/how-houthi-attacks-red-sea-threaten-global-shipping>

³²³<https://procurementmag.com/supply-chain-management/red-sea-disruption-trade>

³²⁴<https://www.ezyimport.com/red-sea-shipping-crisis-recent-houthi-attacks-and-global-implications/#:~:text=200%2D400%25%20rate%20increases%20on,East%20Coast%20rates%20increased%20120%25>

³²⁵<https://www.barrons.com/articles/houthis-china-iran-shipping-ca577a16?st=7mWnNy>



China is the global leader in green technologies ³²⁶

- **Green equipment manufacturing capacity:** In 2024, China had ~80% of solar panel global production capacity, ~65% of global wind turbines production capacity. It held more than 80% of the battery cells global production capacity. It solidified its dominance in green hydrogen³²⁸, holding 60% of the world electrolyzer manufacturing capacity.
- China’s nuclear installed capacity was 61 GW in 2024, with 29 reactors (33 GW capacity) under construction. This represents nearly half of the global new projects in the world.
- It dominates the processing of critical material needed for the energy transition such as Cobalt (76% market share), graphite (90% market share) and Rare Earth Elements (REE) (90% market share). China gained its dominant position by investing heavily in refining capacity of these minerals.
- **Carbon Capture and Storage (CCS):** China captured 2.05 million tons of CO₂ in 2024, primarily in the power and the chemical sectors, with projects like Yanchang CCS targeting 400,000 tons/year.

³²⁶<https://www.washingtonpost.com/climate-solutions/2025/03/03/china-renewable-energy-green-world-leader/>

³²⁷ IEA: Energy Technology Perspective 2024: <https://www.iea.org/reports/energy-technology-perspectives-2024>

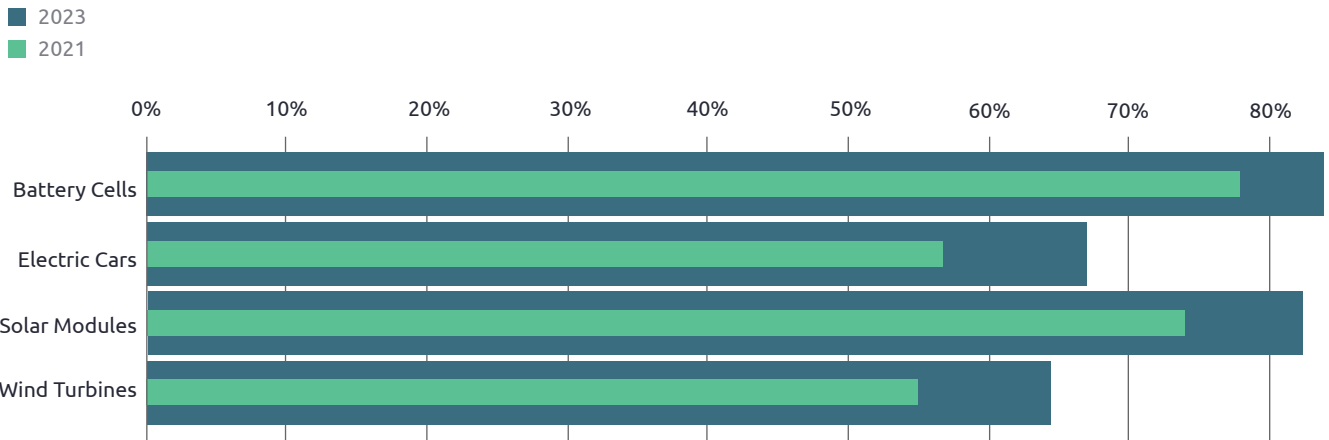
³²⁹ S&P Global: Revamping automotive sourcing for the EV market, <https://www.spglobal.com/automotive-insights/en/blogs/2025/05/revamping-automotive-sourcing-electric-vehicle-market?>

³³⁰ <https://www.carbonbrief.org/>

[analysis-clean-energy-contributed-a-record-10-of-chinas-gdp-in-2024/](https://www.carbonbrief.org/analysis-clean-energy-contributed-a-record-10-of-chinas-gdp-in-2024/)

³³¹ <https://www.iea.org/reports/world-energy-investment-2024/overview-and-key-findings>

FIGURE 12
Chinese share of global installed production capacity ³²⁷



In summary, in 2024, China solidified its global leadership in *green energy investments*^{330,331}, allocating 6.8 trillion yuan (\$940 billion) to the clean energy sector, including solar, wind, batteries, EVs, and green hydrogen. This is to be compared to the \$685 billion invested by the U.S. (\$315 billion) and by Europe (\$370 billion).

China’s dominance stems from vast manufacturing capacity, low production costs (e.g., solar panels at around \$0.15/

watt vs. \$0.30-0.50 /watt in Europe and US³³²), and state-backed policies. In addition, Chinese manufacturers have overcapacities regarding the domestic market which pushes them to export at low prices.

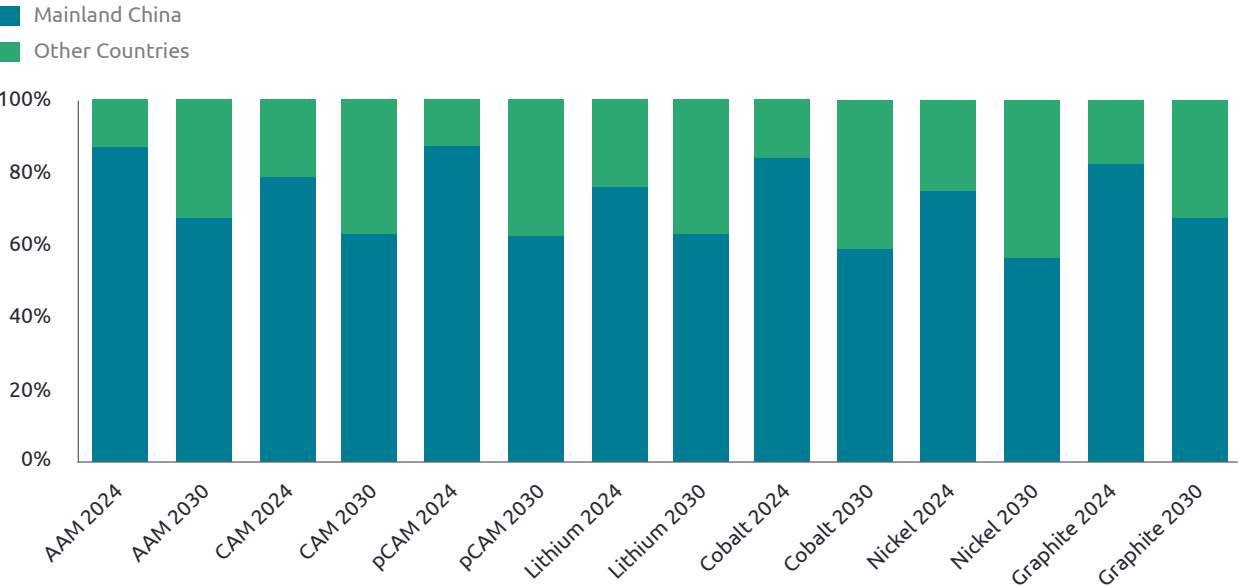
- Taking advantage of this dominance, in July 2025, China put export restrictions on critical EV batteries technologies and on lithium supply by adding them to the government’s export control list³³³. Inclusion on this list means that transferring the technologies concerned overseas will require a government-issued license, These new controls are like the restrictions on certain rare earth elements introduced earlier in 2025.

³³² [https://gycxsolar.com/solar-system-price-in-china/#:~:text=Global%20solar%20panel%20pricing%20varies, cost%20\\$0.30%2D\\$0.50/watt](https://gycxsolar.com/solar-system-price-in-china/#:~:text=Global%20solar%20panel%20pricing%20varies, cost%20$0.30%2D$0.50/watt)

³³³ <https://edition.cnn.com/2025/07/17/business/china-new-export-controls-ev-battery-intl-hnk>



FIGURE 13
Share of mainland China in battery material market³²⁹



Europe is reacting to the geopolitical situation while keeping its focus on GHG reduction

• **The EU is trying to establish an energy sovereignty policy:** Reacting to the massive importation of cheap solar panels (98%) and wind turbines (59%), the European Commission introduced in early 2025 a regulation outlining non-tariff criteria for renewable energy auctions³³⁴. The target was to bolster the EU's clean technology supply chain. From 30

December 2025, member states will be required to include pre-qualification criteria such as responsible business conduct, cybersecurity and contribution to sustainability and resilience.

• **Despite the U.S. withdrawal from the Paris Agreement, the EU remains committed to its GHG reduction targets.** The EU is aiming for a substantial reduction in greenhouse gas emissions, targeting a 55% cut by 2030 and achieving net-zero emissions by 2050. This commitment

is legally enshrined in the European Climate Law. The “Fit For 55” policy packages³³⁵ includes incentives, subsidies and taxes to achieve the 2030 emission reduction target.

In July 2025, the European commission submitted to the European members a road map for its climate achievements by 2040³³⁶ (an intermediary milestone between 2030 and 2050). The objective is to reduce its emissions by 90% (compared to 1990) at that horizon. To obtain an agreement from its member states, the EC has introduced some flexibility. It finally recognizes “technology neutrality” implying that nuclear contributes as renewables to emissions reduction³³⁷. It accepts the usage of international credits obtained by financing emission reductions outside Europe and the integration in the Emission Trading System (ETS) of emission reductions obtained thanks to Carbon Capture and Storage systems. This proposal should be accepted or amended by September 2025 on time for Europe’s Nationally Determined Contribution (NDC)³³⁸ submission before COP 30 meeting in November 2025. Although exemplary for Emission Reduction, this policy

³³⁴<https://www.lesechos.fr/industrie-services/energie-environnement/bruxelles-impose-des-criteres-pour-des-energies-renouvelables-made-in-europe-2167409>
³³⁵https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal/fit-55-delivering-proposals_en#:~:text=Under%20the%20European%20Climate%20Law,fit%20to%20meet%20this%20target.
³³⁶https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en#:~:text=In%20July%202025%2C%20the%20Commission.Political%20Guidelines%20for%202024%2D2029%20.
³³⁷This scientific approach is a victory for France that has a large nuclear share in its electricity generation
³³⁸<https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs>



will decrease European manufacturers' competitiveness by imposing complex regulations and carbon costs (especially for energy intensive industries like steel and chemicals).

In 2024, the EU-27 accounted only for 6.4% of global emissions³³⁹, a small share compared to China's 33% share. If not followed by other regions, the Europe efforts will not have a significant impact on global GHG emissions.

New US Energy policy is a combination of sovereignty and climate skepticism

• Policy description:

- ✓ A sovereignty policy: The Trump administration's energy policy^{340,341}, centered on achieving "American energy dominance," prioritizes domestic production of fossil fuels, including oil, natural gas, coal, and critical minerals. It intends to reduce regulatory barriers to their development by accelerating permitting for energy projects, lifting restrictions on federal land and offshore drilling and promoting liquefied natural gas (LNG) exports. *Nuclear energy*³⁴² being a domestic energy resource, the Trump administration has expressed strong support for an accelerated development of both large plants and SMRs as reliable, low-carbon electricity source.

- ✓ A climate skeptical approach while combatting Chinese green technologies' dominance. A significant aspect of the policy involves rolling back climate and renewable energy initiatives from the previous administration³⁴³. President Trump has withdrawn the U.S. from the Paris Climate Agreement, halted federal offshore wind leasing, and paused funding from the "Inflation Reduction Act" (IRA) and "Infrastructure Investment and Jobs Act" (IIJA) for renewable energy projects. The One Big Beautiful Bill Act (OBBBA), signed into law by President Trump on July 4, 2025, significantly modifies clean energy tax incentives enacted under the IRA. Specifically, the bill scales back some of these incentives by tightening domestic content requirements and foreign entity restrictions and imposing new qualification deadlines, while phasing out others.³⁴⁴

The Trump administration is actively pursuing the repeal of key CO₂ emissions regulations³⁴⁵, including the 2009 Endangerment Finding³⁴⁶, power plant emissions limits, and vehicle standards, with actions announced as recently as July 29, 2025. The 2026 budget proposal, unveiled on May 2, 2025³⁴⁷,

slashes over \$15 bn in funding for renewable energy and carbon capture projects and \$6 bn for EV charging infrastructure. It also intends to eliminate EV tax credit, aiming to save \$2.5 billion over a decade.

- ✓ The administration aims to lower energy costs for consumers by increasing domestic supply and reducing reliance on foreign energy sources. These new policies also address state-level regulations perceived as overreaching, particularly those imposing restrictive climate or environmental justice measures³⁴⁸. The Trump administration has also taken a firm stance against offshore wind development³⁴⁹. An executive order issued on January 20, 2025, indefinitely paused new offshore wind lease sales and halted federal permits for both onshore and offshore wind projects, citing environmental and economic concerns and high costs. This policy coupled with the repeal of Inflation Reduction Act tax credits could stall around 32 GW of planned offshore wind capacity.

However, the tariffs imposed on energy products importation (mainly from China) will push the cost for consumers up. They are also making investment in several new energy projects uneconomical.

³³⁹ <https://www.iea.org/reports/global-energy-review-2025/CO2-emissions>

³⁴⁰ <https://www.whitehouse.gov/presidential-actions/2025/01/unleashing-american-energy/>

³⁴¹ <https://natlawreview.com/article/executive-orders-president-trump-reshapes-federal-environmental-and-energy-policy>

³⁴² <https://www.whitehouse.gov/articles/2025/05/president-trump-signs-executive-orders-to-usher-in-a-nuclear-renaissance-restore-gold-standard-science/>

³⁴³ <https://rhg.com/research/trump-2-0-whats-in-store-for-us-energy-and-climate/>

³⁴⁴ <https://www.energypolicy.columbia.edu/assessing-the-energy-impacts-of-the-one-big-beautiful-bill-act/>

³⁴⁵ <https://edition.cnn.com/2025/07/29/climate/trump-epa-endangerment-finding>

³⁴⁶ A 2009 scientific finding that human-caused climate change endangers human health and safety

³⁴⁷ <https://www.eenews.net/articles/trump-budget-would-decimate-climate-renewables-funding/>

³⁴⁸ <https://www.whitehouse.gov/presidential-actions/2025/04/protecting-american-energy-from-state-overreach/>

³⁴⁹ <https://www.offshorewind.biz/2025/01/21/us-president-trump-issues-executive-order-suspending-offshore-wind-leasing/>



• Global impact of US energy policy:

- ✓ *Increasing US LNG exports could create a surplus on the international gas market.* The US is presently the largest worldwide LNG exporter with around 20% of the global LNG exports.³⁵⁰ The Trump administration's lifting of the Biden-era pauses on LNG export permits, enacted on January 20, 2025, is projected to significantly increase U.S. LNG exports^{351,352}. The Department of Energy approved the Commonwealth LNG project in Louisiana, adding 9.5 million metric tons per annum (MTPA) to export capacity as early as 2026. Estimates are at nearly 100 MTPA in additional capacity by 2031 from advanced projects, nearly doubling current exports of approximately 88.4 MTPA³⁵³ in 2024. Selling this new amount of LNG could prove difficult as countries like Qatar are also increasing their LNG capacities³⁵⁴. This is probably one of the underlying reasons of the inclusion of a clause, in the US-EU tariff agreement, mandating increased EU purchases of American energy (see below).

³⁵⁰<https://www.eia.gov/todayinenergy/detail.php?id=64844#:~:text=The%20United%20States%20remained%20the%20world's%20largest%20liquefied%20natural%20gas%20exporter%20in%202024,-Data%20source%3A%20U.S.&text=The%20United%20States%20exported%2011.9,the%20world's%20largest%20LNG%20exporter.>

³⁵¹<https://www.reuters.com/business/energy/lng-companies-hail-trump-decision-lift-freeze-export-permits-2025-01-22/>

³⁵²<https://www.reuters.com/business/energy/trump-doe-approves-venture-global-lng-exports-louisiana-project-2025-03-19/>
LNG of MTPA is approximately 122.82 bcm per annum.

³⁵³89 MTPA of LNG is approximately 122.82 bcm per annum.
³⁵⁴<https://www.jpmorgan.com/insights/global-research/commodities/liquefied-natural-gas#:~:text=Overall%2C%20J.P.Morgan%20Research%20forecasts,oversupplied%20market%2C%E2%80%9D%20Chaturvedi%20said.>

- ✓ *The US policy on wind offshore is negatively impacting European Companies* This policy shift, targeting projects like Atlantic Shores and Beacon Wind, has financial repercussions on European offshore developers such as Ørsted and some major European energy companies including EDF, Engie, and RWE. EDF recorded a \$940 million write-off on its Atlantic Shores project off New Jersey after partner Shell withdrew, citing the new administration's hostility to offshore wind. It is seeking to divest from its renewable assets in the US and Brazil after big losses in 2024.^{355,356} Another French utility, Engie, through its joint venture with the Portuguese EDP Renewables, has delayed the Southcoast Wind project in Massachusetts and Rhode Island³⁵⁷, pushing construction from 2024 to 2029 due to regulatory uncertainties. In its 2024 accounts, it has depreciated its US offshore assets by more than €100 Million³⁵⁸.

³⁵⁵<https://www.power-technology.com/news/edf-stake-sale-north-american-brazilian-business/2cf-view>

³⁵⁶In 2024, EDF Renewables reported a net loss of €1.45 billion on a turnover of €2.4 billion https://tecsol.blogs.com/mon_weblog/2025/07/edf-veut-all%C3%A9ger-sa-pr%C3%A9sence-dans-les-renouvelables-en-am%C3%A9rique-selon-les-%C3%A9chos.html

³⁵⁷Engie, through its joint venture with EDPR, has delayed the Southcoast Wind project in Massachusetts and Rhode Island

³⁵⁸<https://www.engie.com/sites/default/files/assets/documents/2025-03/ENGIE%20FY%202024%20-%20Transcript.pdf>

³⁵⁹<https://www.investing.com/news/stock-market-news/rwe-has-stopped-offshore-wind-activities-in-united-states-4003885>

³⁶⁰<https://www.offshorewind.biz/2025/05/13/equinor-situation-for-empire-wind-unsustainable-we-need-to-find-way-forward-for-project-quickly/#:~:text=offshoreWIND.biz,Equinor:%20'Situation%20for%20Empire%20Wind%20Unsustainable%2C%20We%20Need%20to.Way%20Forward%20for%20Project%20Quickly'&text=Following%20reports%20saying%20Equinor%20may,the%20project%20moving%20again%20quickly.&text=%E2%80%9CThe%20situation%20for%20the%20Empire,work%20order%20was%20not%20lifted.>

RWE, Germany's largest power producer, that holds three offshore wind leases in U.S. waters off the coasts of New York, Louisiana and California, halted all U.S. offshore wind activities, with very large negative financial impacts.³⁵⁹ Also, Norwegian utility, Equinor said it would halt offshore construction of its Empire Wind I project off the coast of New York because it received a stop-work order.³⁶⁰

- ✓ *U.S. tariffs on Chinese clean tech firms* are pushing them to expand internationally. To circumvent U.S. tariffs on clean tech products, Chinese companies are redirecting sales to Europe, despite stricter EU regulations, and to developing nations at potentially reduced prices. After lengthy negotiations, as of June 2025, US tariffs are ranging from 25 to 100% across clean tech goods e.g.: electric vehicles at 100%, solar cells at 50%, Lithium-ion electrical vehicle batteries at 25%, thus increasing the costs for US citizens. To dodge those tariffs Chinese companies have established plants in Southeast Asia. Goods from those countries now dominate solar panel supplies in the U.S. as Chinese-made products have nearly vanished. Following a yearlong investigation, in April 2025 the US commerce department has announced the new tariffs up to 3,521%,³⁶¹ targeting companies in those countries.

³⁶¹<https://www.energyconnects.com/news/renewables/2025/april/us-imposes-tariffs-up-to-3-521-on-asian-solar->



- ✓ *U.S. tariffs deal on European goods include a requirement to purchase American energy:* In July 2025, the EU and US struck a deal that will see tariffs of 15% on most of the bloc's exports to the US.³⁶² In the other direction, US exports tariffs to the EU, currently at 10%, will be free. In addition, the EU will "double down" on its purchases of American energy, buying \$750bn worth of energy during the next three years. Averaging out to \$250 bn each year, this represents a substantial increase over current purchases of US energy, which range from \$92 to \$100 bn. However, it's important to remember that the European Commission is not buying any of these commodities and neither is the US government selling them.
- ✓ *Securing critical minerals resources is prompting the US to enter international deals* The US administration's policy prioritizes securing critical minerals and Rare Earth Elements to counter China's dominance. On March 20, 2025, it used emergency powers to fast-track U.S. mining³⁶³. In addition, it seeks to secure resources outside the US. The U.S.-Ukraine minerals deal, signed April 30, 2025³⁶⁴, provides access to Ukraine's lithium, graphite (20% of global reserves), and uranium in exchange for reconstruction funding, The US push for

Greenland's 1.5 million tonnes of rare earth element reserves, via the proposed "Make Greenland Great Again Act," is awaiting approval by the U.S. Congress. The next step would be agreement with Denmark. If finalized, this policy³⁶⁵ should be beneficial to US security of supply in the long term. In the short term, due to slow mining development, these agreements will not change China's critical minerals supply dominance (80% of U.S. REEs) However, on June 27, 2025³⁶⁶, a U.S.-China agreement alleviated concerns over potential Chinese rare earth embargoes, with China committing to supply rare earth elements to the U.S. in exchange for the removal of U.S. trade countermeasures.

- ✓ *Impact on global emissions:* The Trump administration's policy could result in significantly increasing US emissions compared to Biden's climate plans. However, this increase is complex to evaluate as many factors are in play. On the one hand, the decrease of clean energy investments and the increase of fossil fuel usage will increase emissions. But on the other hand, cheap gas could replace coal in power plants, and the economic impact of tariffs could slow down the US economy, which would have the effect of reducing emissions.³⁶⁷

³⁶²<https://www.euronews.com/my-europe/2025/07/29/eu-and-us-spin-conflicting-versions-of-trade-deal>

³⁶³<https://www.newsweek.com/explained-donald-trump-rare-earth-minerals-quest-2037622>

³⁶⁴<https://www.csis.org/analysis/what-know-about-signed-us-ukraine-minerals-deal>

³⁶⁵<https://foreignpolicy.com/2025/02/26/trump-rare-earth-critical-mineral-resource-ukraine-greenland-canada/>

³⁶⁶<https://www.china-briefing.com/news/us-china-tariff-rates-2025/>

³⁶⁷<https://www.carbonbrief.org/analysis-trump-election-win-could-add-4bn-tonnes-to-us-emissions-by-2030/>



Are we at a tipping point of the energy transition?

There are signs of a growing disengagement from climate action by companies and banks. Public support for renewable energy is decreasing due to concerns over unaffordable costs and the "Not in my backyard" syndrome. Moreover, European increased defense budget financing is putting pressure on EU and national budgets and could result in reduced funding for climate change actions.

Financial institutions are scaling back their commitments on emission reductions.

The Trump administration's energy policies, including executive orders promoting coal production³⁶⁸, have prompted several major U.S. financial institutions to retreat from their zero-coal commitments. Six prominent banks, including JPMorgan Chase and Citigroup³⁶⁹, managing over \$14.29 trillion in assets (20% of the Net-Zero Banking Alliance's total), have withdrawn from the alliance, citing increased regulatory uncertainty and the new US administration policy. This withdrawal could impede the global energy transition by prolonging financing of coal.

³⁶⁸<https://apnews.com/article/trump-coal-ai-data-centers-energy-dominance-693e2604785c07ff790d9afd2e06d543>

³⁶⁹<https://www.theguardian.com/business/2025/jan/08/us-banks-quit-net-zero-alliance-before-trump-inauguration>

³⁷⁰ESG: Environment Social Governance

³⁷¹<https://www.financierworldwide.com/trump-and-esg-the-outlook-for-2025>

³⁷²<https://perkinscoie.com/insights/blog/glass-lewis-voting-policy-changes-2025-8-things-know>

³⁷³https://insights.bdo.com/rs/116-EDP-270/images/IND-2024-Agnostic-CFO-Survey_Report_email.pdf?version=0&mkt_tok=MTE2LUVEUC0yNzAAAAGbx8L8KDDEbMGk7zjyKMiYCPD8ohiUrrGkRILo-PTXFJ_3hamNodxBOPyc9b6GM-CvvcYvrgdli0mHSxtNEv7bwIzeBczsHGVVfA7ZJB-nEA4R_-o

³⁷⁴<https://www.ainvest.com/news/poland-crossroads-2025-election-redraw-europe-energy-map-2505/>

³⁷⁵<https://www.euractiv.com/section/eet/news/german-gas-drive-fuels-fears-of-climate-backsliding/>

³⁷⁶<https://www.euractiv.com/section/eet/news/hungary-and-gazprom-in-talks-for-extra-russian-gas-for-budapest-in-2025/>

Political changes in the US are negatively impact ESG³⁷⁰ outlooks.³⁷¹

The new US Administration claims that ESG practices are detrimental to business and that unnecessary regulations impede economic growth. After the US withdrawal from the Paris Agreement, the US and US companies are no longer formally committed to limiting global warming and face fewer regulations related to emissions and environmental standards. International firms that work with the US administration have shifted away from their former ESG commitments, and proxy advisory firms such as Glass Lewis³⁷² (that advise shareholders on their voting at the general assemblies) have also scrapped their ESG requirements.

Some companies may struggle to meet their own ESG goals in a less supportive regulatory environment such as the US and could fear losing opportunities in the US. However, there is still support for ESG policies in many C-suites. According to the 2024 BDO survey³⁷³, 53% of CFOs surveyed said they have embedded ESG principles into their core business strategy or are actively working on it, compared to 33% a year before. This commitment to ESG objectives is more pronounced in European companies than in American.



Political changes in European countries are signalling a slowing down on energy transition efforts:

- **In Poland**, the newly elected President Karol Nawrocki has a vision of "energy sovereignty" prioritizing Poland's traditional ties to coal, U.S. LNG, and bilateral alliances over EU climate mandates³⁷⁴. This could slow down the country's efforts on clean technologies implementation.
- In August 2025, the new **German** conservative lead new government declared that it wants to build 20 GW capacity of gas-fired power plants by 2030, to guarantee energy supplies for their struggling industry.³⁷⁵ Let's recall that Germany closed (for political reasons) all its nuclear plants and that it has decided to phase-out its coal plants by 2038.
- **Hungary's** energy policy in 2025 continues to rely heavily on natural gas, particularly from Russia, which supplies ~75% of annual consumption. In October 2024 it entered into negotiations with Gazprom to increase gas imports³⁷⁶



via the Turk Stream pipeline, despite EU efforts to reduce Russian fossil fuel dependence. Critics highlight Hungary's slow progress on reducing gas consumption and urge stronger energy efficiency and renewable measures to meet climate goals.

Big oil & gas companies are reducing their commitments on climate actions.

In recent years, some large oil and gas companies like BP and Shell have significantly scaled back their commitments to low-carbon energy and emissions reduction³⁷⁷, shifting focus to more profitable oil and gas production. BP, once a leader in climate action, abandoned its 2030 target to cut oil and gas production by 40% and revised its emissions reduction goal from 35-40% to 20-30% by 2030.³⁷⁸

In July 2025, it announced that it agreed to sell its US onshore wind business to LS Power. The business includes interests in 10 operating onshore wind assets across seven US states with a total generating capacity of 1.3GW net.

The root causes of this pivot include a focus on higher financial return on oil and gas projects compared to less profitable renewable energy projects due to their increasing costs, regulation complexity and political uncertainties.

Contrary to BP's rollback of climate commitments, TotalEnergies maintained its climate actions³⁷⁹, continuing to invest in low-carbon energies. In 2024, it allocated €5 billion (27% of its capital expenditure) to renewables, low-carbon fuels, and electricity, commissioning 1.5 GW of solar and wind capacity and targeting 100 GW of renewable capacity by 2030, alongside a 30% reduction in Scope 1 and 2 emissions³⁸⁰ by 2030 from 2015 levels³⁸¹. These commitments are driven by EU regulatory pressures and shareholder support for its net-zero 2050 goal. However, at the end 2024, TotalEnergies paused the development of its offshore wind project in New York, citing political uncertainties³⁸².

The retreat of oil majors from low-carbon commitments is bad news for global emissions reduction goals as the top 5 investor-owned companies (ExxonMobil, Chevron, Shell, TotalEnergies, and BP), accounted for a combined 2.2 GtCO₂ (equivalent to 5.1% of global fossil CO₂ emissions).³⁸³

Will the EU's increased defense spending lead to a reduction in its climate change initiatives?

The Trump administration's reduction in U.S. funding for NATO, coupled with ongoing Russian aggression in Ukraine,

has compelled European nations to significantly increase their defence budgets³⁸⁴. They now aim at increasing their defence spendings to 3.5% of their GDP³⁸⁵ with countries like Poland aiming to 5%.

With EU debt-to-GDP at 81%³⁸⁶ and deficits at 3.2% in 2024, new funding space is limited. EU could be tempted to reallocate part of the €580 billion set aside in the 2021-2027 multiannual budget to achieve climate neutrality by 2050³⁸⁷. Balancing climate actions and military priorities will require innovative financing to avoid compromising climate goals. Fears are growing that the development budgets reductions will also threaten the COP29 agreement to provide \$300 bn in annual climate finance to developing nations³⁸⁸. That is after the U.S. announced it was abandoning the "loss and damage fund"³⁸⁹, established after the COP28, in Dubai.

Will the energy transition's extra costs reduce public support for sustainable energy?

Efforts to move electricity generation to cleaner resources require heavy capital investment – between \$3.5 trillion and \$4.5 trillion per year globally – to achieve a zero-carbon economy by 2050. This cost is being borne across various industries, public and private funds, and individuals.³⁹⁰

³⁷⁷<https://grist.org/economics/bp-exxon-shell-backing-off-climate-promises/>

³⁷⁸<https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-agrees-to-sell-us-onshore-wind-business-to-ls-power.html>

³⁷⁹<https://zerocarbon-analytics.org/archives/energy/unpacking-the-energy-transition-strategies-of-oil-and-gas-majors>

³⁸⁰<https://globalclimateinitiatives.com/en/e-brochures-knowledge/direct-and-indirect-emissions/#~:text=Scope%201%3A%20Direct%20GHG%20emissions,imported%20for%20the%20organization's%20activities>

³⁸¹<https://totalenergies.com/sustainability/climate-and-sustainability-energy/reducing-our-scope-1-and-2-emissions>

³⁸²<https://ffshorewind.biz/2024/11/27/totalenergies-halts-us-offshore-wind-project-amid-political-uncertainty/#~:text=TotalEnergies%20Halts%20US%20Offshore%20Wind,York's%20latest%20offshore%20wind%20solicitation>

³⁸³<https://carbonmajors.org/briefing/The-Carbon-Majors-Database-2023-Update-31397>

³⁸⁴<https://www.bruegel.org/analysis/defending-europe-without-us-first-estimates-what-needed>

³⁸⁵<https://www.heritage.org/defense/report/natos-underspending-problem-americas-allies-must-embrace-fair-burden-sharing>

³⁸⁶<https://ec.europa.eu/eurostat/web/products-euro-indicators/w/2-22042025-ap#:~:text=In%20the%20euro%20area%20the,from%2080.8%25%20to%2081.0%25>

³⁸⁷<https://www.heritage.org/global-politics/commentary/eu-should-prioritize-defense-not-climate-change-funding>

³⁸⁸<https://unfccc.int/news/cop29-un-climate-conference-agrees-to-triple-finance-to-developing-countries-protecting-lives-and>

³⁸⁹<https://fiftrustee.worldbank.org/en/about/unit/dfi/fiftrustee/fund-detail/frld#:~:text=In%20a%20historic%20decision%20at,and%20the%20eradication%20of%20poverty.&text=An%20unexpected%20error%20occurred,contact%20your%20Tableau%20Server%20Administrator>

³⁹⁰<https://www.publicpower.org/periodical/article/what-will-energy-transition-cost>

³⁹¹For example: to isolate their house or to change car after 2035 to buy an EV

³⁹²<https://www.city-journal.org/article/the-political-cost-of-the-energy-transition>

The financial burden of energy transition policies on citizens in Western nations differs significantly based on regional factors, available natural resources, and national energy strategies. This burden manifests through elevated electricity and fuel costs, higher taxes, and increased personal expenditures.^{391,392}

Germany's Energiewende, which focuses on shifting to renewable energy, has estimated a cost of €387 billion in investments, with an additional €310 billion in subsidies, totaling €696 billion³⁹³. It has driven electricity costs among the highest in the OECD. Due to subsidies for renewables and grid upgrades costing³⁹⁴, German households are paying \$0.40 per kWh in 2025, roughly more than the double of the U.S. average of \$0.18/kWh.

These extra energy transition costs weigh on citizens with tight budgets, particularly low-income households. Public concerns over the rapid expansion of renewable energy were evident in debates at the French Parliament in June 2025³⁹⁵. For years, the French government has delayed adopting the new Multiannual Energy Program due to significant controversies. In June 2025, a bill proposing a moratorium on renewable energy passed its first reading in Parliament but was ultimately rejected, reflecting the views of a notable portion of the population.

³⁹³<https://www.foronuclear.org/en/updates/news/nuclear-energy-could-have-saved-germany-e332-billion-according-to-research/#:~:text=According%20to%20the%20study%2C%20Germany's,subsidies%2C%20totaling%20%E2%82%AC696%20billion.>

³⁹⁴<https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/>

³⁹⁵ <https://www.rj-homr-solar.fr>, <https://www.taiyangqnews.info>

³⁹⁶<https://www.iea.org/reports/world-energy-outlook-2024>

Summary and Conclusion:

In this Outlook of the 27th edition of WEMO, after reviewing the key trends of 2024 regarding energy and climate change, we tried to answer three questions:

- Will nuclear energy contribute enough to the Energy Transition?
- Will the electrical grids be able to adapt to the Energy Transition challenges?
- What technologies will support the Energy Transition?

We then reviewed the impact of present geopolitics on the energy sector and ultimately arrived at a critical question: are we at a tipping point in the energy transition?

The 2024 energy outlook highlighted a complex transition landscape. This landscape was marked by strong renewable energy growth driven by Chinese solar installations, continued challenges in scaling green hydrogen production and consumption, and difficulties in building a European battery industry.

Solar and wind capacity additions surged, with global clean energy investments reaching \$2000bn, driven by China investments and helped by policies like the U.S. Inflation Reduction Act and EU's Green Deal.

Green hydrogen development lagged due to technical difficulties in scaling up electrolyzers manufacturing, high costs, regulatory uncertainties, and a mismatch between demand and production.

Stationary battery installations, led by China, grew 60% from 2023 with prices dropping by 20%. By 2035, stationary applications could account for 16% of batteries deployed globally, propelled by falling battery costs and increased grid stability issues linked to growing intermittent renewables penetration.

Despite these impressive steps, the energy additions from low carbon sources have not been sufficient to meet the growth in total global energy demand, meaning the use of fossil fuels has continued to increase. Consequently, *fossil fuels have continued to dominate the global energy supply, accounting for 80% of primary energy consumption*³⁹⁶.



***Achieving the ambitious COP28 goal of tripling nuclear capacity by 2050.***

This goal requires avoiding politically motivated reactor closures, reopening viable dormant reactors, extending the life of safe reactors (the most cost-effective option), and building numerous new nuclear facilities. New nuclear capacity will combine large-scale reactors (1,000 MW or more) and small modular reactors (SMRs). China and Russia are emerging as dominant players in global nuclear development, while Western countries face challenges in the form of construction delays and high costs³⁹⁷. To address this, Western nations must simplify reactor designs and regulations, reinvigorate the supply chain and promote nuclear as a low carbon source of energy to attract good people at all levels from students to researchers, to designers and skilled workforces.

For SMRs to contribute significantly, serial production across countries and harmonized safety standards are essential. They still must prove their cost effectiveness. This “nuclear renaissance” in the West requires sustained political support, financing and public approval. Finally, unless a major scientific breakthrough occurs, nuclear fusion is unlikely to have a significant impact on electricity generation before 2050.

³⁹⁷Construction costs account for 80% of nuclear electricity's final cost

³⁹⁸Power outages cost the U.S. economy \$150 billion annually <https://greenridgesolar.com/price-perils-power-outages-battery-backup/>

³⁹⁹<https://www.americanexperiment.org/the-levelized-cost-of-blackouts/>

⁴⁰⁰Comparable to the solar generation cost

Grid infrastructure is the backbone of a successful energy transition.

Yet decision-makers, often unfamiliar with the complex mechanisms of grid balancing, tend to overlook their importance. Grid operators face numerous challenges, including integrating a growing share of intermittent renewable energy, managing the closure of thermal power plants that provide grid stability, adapting to climate change and extreme weather, mitigating cyberattack risks, addressing underfunding, navigating complex regulations, and overcoming public resistance to new overhead lines, which take several years to build. Digital technologies will help in addressing grid challenges, but they alone are not sufficient.

Simplifying regulations, especially for approving new power lines, revising pricing to fund necessary investments (equipment and digital), and aligning renewable energy production growth with grid capacity are critical. Grids will likely continue to face difficulties in their efforts to balance supply and demand, leading to negative prices, curtailment, power outages³⁹⁸ and even blackouts. According to the “Center of the American Experiment”³⁹⁹ the average levelized cost of blackouts in the US is likely to grow from an average of \$4.90/ MWh during the 2024-2028 period to an average of nearly \$50/MWh⁴⁰⁰ during the 2039-2043 period as more blackouts occur. The root causes of these increased blackouts are uncontrolled growth of renewables and lack of grid adaptation.

There are no technical silver bullets to meet 2030 goals.

Despite promising advancements in energy technologies, no single innovation, except potentially nuclear fusion – which is expected to remain pre-industrial until 2050 – is sufficient to reach Paris Agreement targets. Thus, large scale deployment of mature technologies is essential. Those technologies comprise: enhanced solar panel efficiency, advanced electrolyzers, high-density batteries with reduced environmental and mining impacts, and generation III nuclear reactors.

Governments and institutions should enhance the legal and financial frameworks to facilitate the large-scale deployment of these proven technologies. The private sector should boost its investments, provided they yield profitable returns. Maintaining R&D efforts is important for longer-term improved solutions.

AI and Gen AI will transform the energy sector.

This is especially true in the cases of electricity generation and grid capacity. Over the next ten to fifteen years, we can expect to see utilities increasingly adopting Gen AI, which will also necessitate significant workforce reskilling. Data quality, privacy, and ethical concerns are critical, alongside the need to curb electricity demand from GenAI-driven data centers.



Throughout 2024 and the first half of 2025, geopolitical tensions escalated.

These tensions were driven by both the Russia-Ukraine war and Middle East conflicts. *Control over energy resources and critical raw materials has fuelled these conflicts, which, in turn, have impacted their supply chains. China's remarkable dominance in green energy technologies is driving Western nations to adopt more sovereign approaches to securing energy and critical mineral supplies.*

The U.S.'s shift towards a fossil fuel-focused energy policy reflects both a sovereign approach and a climate skeptical approach. It is already having a significant impact inside and outside the US. High American tariffs on Chinese clean energy related goods are pushing Chinese companies to expand their international footprint to avoid these tariffs. The challenges faced by offshore wind projects are affecting European utilities and oil and gas companies, as they are pulling back from their US ventures with financial losses.

These sovereignty policies, which are difficult to implement effectively, will likely increase the cost of the energy transition for citizens. They are also increasing market fragmentation and unpredictability thus slowing down capital investment in energy projects.

Despite Europe's commitment to ambitious climate goals and some progress in countries like China and India, *there are signs of a growing disengagement from climate action by companies and banks.* Public support for renewable energy is decreasing due to concerns over energy transition costs.

⁴⁰¹<https://www.dailykos.com/stories/2025/7/9/2332521/-Climate-Brief-Scientists-issue-New-Dire-Warning-The-Earth-is-careening-toward-Catastrophe>

Moreover, the "Not In My Backyard" syndrome fuels local resistance to renewable energy projects. Increased defense spending related to the Russia-Ukraine war, and the US reduced commitment to NATO funding, will strain EU and national budgets, risking reduced funding for climate change actions.

Meanwhile, global greenhouse gas emissions continued to rise in 2024, accompanied by an increase in extreme weather events. In this context, ***the path to a successful energy transition appears more uncertain than ever*** as confirmed by a recent report from more than 60 climatologists. Their warning was dire: "Things are all moving in the wrong direction!"⁴⁰¹

Climate change could increase the number and the severity of natural disasters. Some of these disasters such as major fires would further increase carbon emissions. On the other hand, they could have the effect of alerting politicians and pushing them to act more decisively to combat climate change.

There is an urgent need to accelerate adaptation measures to address the impact of climate change, while also improving access to electricity – a vital resource – for a greater number of people on Earth.

Colette Lewiner

Paris, September 2, 2025

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About Capgemini

Capgemini is a global business and technology transformation partner, helping organizations to accelerate their dual transition to a digital and sustainable world, while creating tangible impact for enterprises and society. It is a responsible and diverse group of 350,000 team members in more than 50 countries. With its strong over 55-year heritage, Capgemini is trusted by its clients to unlock the value of technology to address the entire breadth of their business needs. It delivers end-to-end services and solutions leveraging strengths from strategy and design to engineering, all fueled by its market leading capabilities in AI, generative AI, cloud and data, combined with its deep industry expertise and partner ecosystem. The Group reported 2024 global revenues of €22.1 billion.

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