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Fighting Words

This year we look at energy arguments, battles and debates: the impact of data centers on power prices, the cost of solar plus storage as baseload power, the "primary energy fallacy" that ignores waste heat, the true cost of small modular reactors, Germany's decision to shut down nuclear, China's dominance of renewable supply chains, solid oxide fuel cells as turbine alternatives, the materiality of demand response, staffing cuts at the EIA, the hype around geothermal and geologic hydrogen, the misplaced fascination with small country energy transitions, satellite vs factor-based oil & gas basin methane emissions, the mostly profitless EV industry, xAI mobile gas plant permits, negligible progress on carbon capture and renewable fuels, and the unfavorable economics of charging my Jeep Wrangler hybrid.

By **Michael Cembalest** | Chairman of Market and Investment Strategy for J.P. Morgan Asset & Wealth Management

Fighting Words: The Energy Transition in 2026

A few years ago at a conference, a client chased me onto a beach in Miami in the mid-day sun to take exception to comments I made about the pace of the energy transition and the role of natural gas. My inability to run on sand in work shoes led me to try and explain my comments but little was accomplished; by simply chronicling the pace of the transition, I was seen as endorsing it.

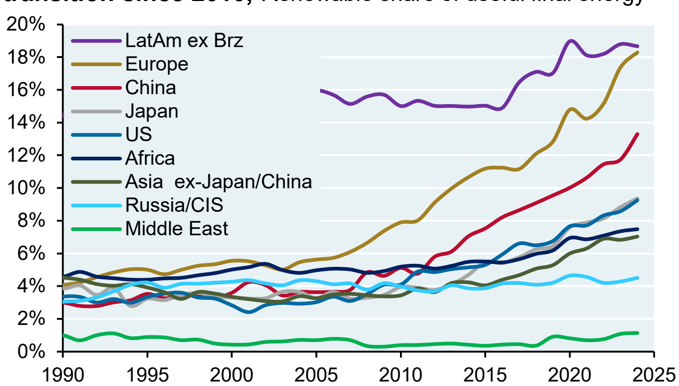
This beach debate and a dinner the same client hijacked years later were a sign of things to come. US energy policy now involves fractious debates with both sides claiming the high ground, one based on decarbonization, the other based on energy security and with both sides claiming lower cost. These battles are amplified by reduced Trump Administration subsidies for wind, solar and EVs which are likely to pin the US in the middle of the pack regarding the decarbonization of energy consumption, with the US shown on the left in dark blue.

This year we look at energy arguments, battles and debates: the impact of data centers on power prices, the cost of solar plus storage vs natural gas as baseload power, the "primary energy fallacy" that ignores waste heat, the possible cost of small modular reactors and the Trump Administration's ability to oversee development, Germany's regret over shuttering nuclear plants, China's dominance of renewable supply chains, solid oxide fuel cells as turbine alternatives, materiality of demand response programs, staffing cuts at the EIA and other science agencies, the hype around geothermal and geologic hydrogen, the misplaced fascination with small country energy transitions, satellite measures of oil & gas methane emissions, the mostly profitless EV industry, xAI mobile gas turbine permits, negligible progress on carbon capture and renewable fuels, and the unfavorable economics of charging my Jeep Wrangler hybrid. As always, we include our collection of essential energy charts, observations from Vaclav Smil and climate charts showing all-time highs in atmospheric CO_2 concentrations, temperature anomalies and ocean heat content.

A late addition: on the next page, some charts on Iran and the Strait of Hormuz.

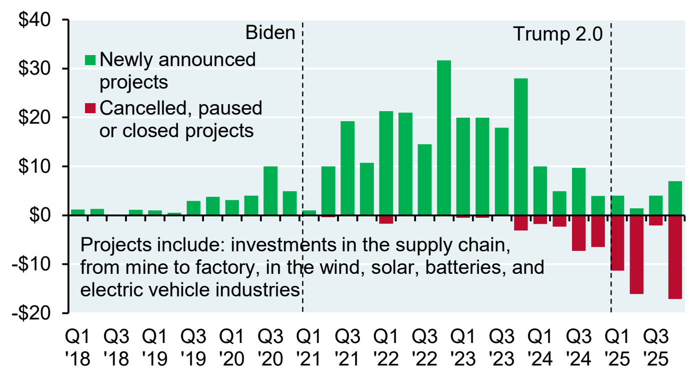
Michael Cembalest
JP Morgan Asset Management

Decarbonization has been a mostly linear industrial transition since 2010, Renewable share of useful final energy



Source: Energy Institute, IEA, JPMAM, 2025

New vs cancelled clean energy projects in the US
Capital investment, US$, billions



Source: Jay Turner (Wellesley College), Q4 2025

Note: on page 29 and in Appendix I explain "useful final energy" since it reflects customized adjustments we make to traditional energy figures to reflect the impact of heat loss in transportation, industrial applications, commercial/residential heating and power generation

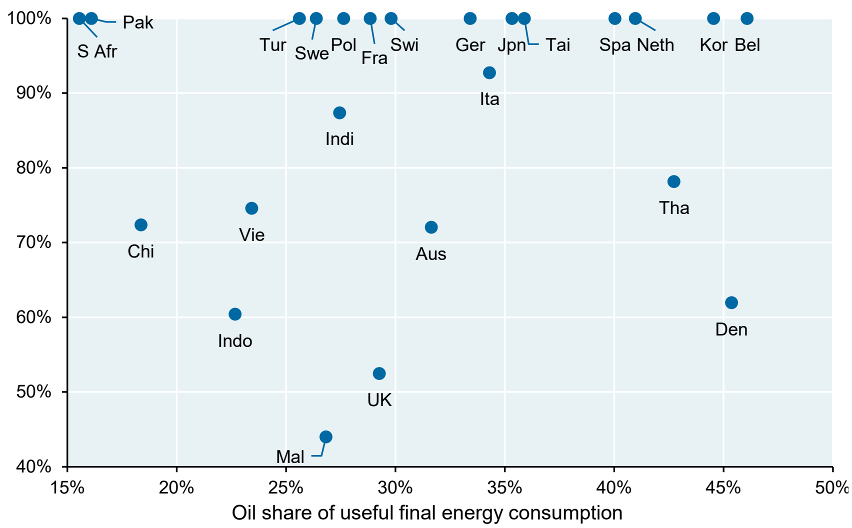
The cover art is inspired by the three-way shootout at the end of the 1966 western "*The Good, The Bad and the Ugly*". Instead of Lee Van Cleef, Clint Eastwood and Eli Wallach, the cover battle is between advocates of wind & solar, oil & gas and nuclear. You can decide for yourself which is good, which is bad and which is ugly

On Iran and the Strait of Hormuz, the US invasion and the worst prediction of all time

How disruptive could the closure of the Strait of Hormuz be? Around 20% of global oil consumption goes through the Strait, a much higher share than the Strait's 3% share of global natural gas consumption[1]. Natural gas is still primarily consumed where produced or sold cross-border via pipelines; for all the focus on LNG, it's still just 14% of global gas consumption. However, for certain countries imported LNG makes up 90%-100% of their natural gas consumption (Japan, Korea, Taiwan, France, Portugal, Benelux, etc). As energy markets reopen, Brent oil and European gas prices have spiked but are way below levels seen during the 2022 inflation surge.

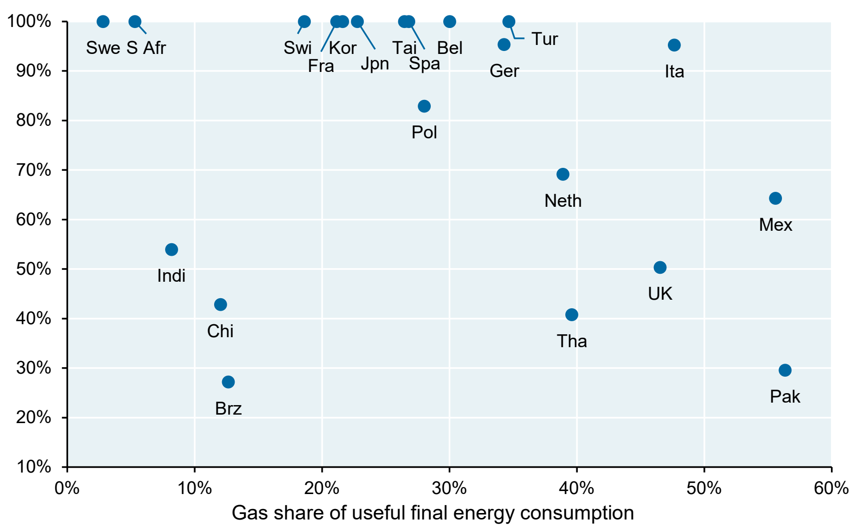
The charts look at the intersection of two important things: energy sensitivity on the X axis (the oil and gas share of useful final energy consumption) and import sensitivity on the Y axis (the import share of oil and gas consumption). In other words, the worst place to be is the upper right: high energy exposure and also high import sensitivity. Exporters are not shown since their import sensitivity is less than zero.

Sensitivity to OIL price spikes
Import share of oil consumption



Source: Energy Institute, IEA, JPMAM

Sensitivity to GAS price spikes
Import share of gas consumption



Source: Energy Institute, IEA, JPMAM

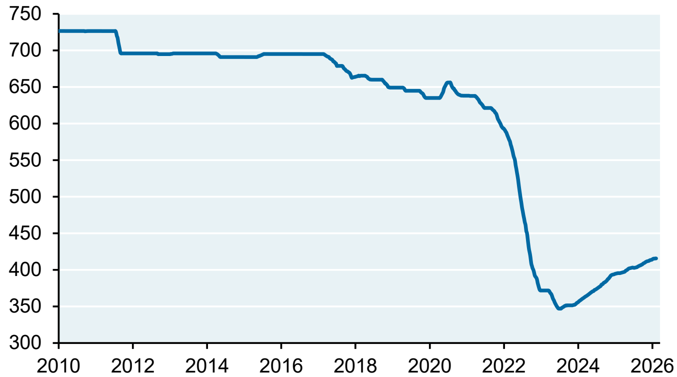
Key points

- China is more insulated on both charts than you might have suspected, primarily since domestically produced coal is such a large share of its energy consumption and since it does have some of its own gas production
- Taiwan and Korea are highly exposed, as are Italy, Germany and the Netherlands
- Spain is a great example of why there's too much focus on electricity and not enough on final energy. While Spain's grid is only 20% reliant on fossil fuels due to its high renewable share of power, its overall energy consumption is 70% reliant on fossil fuels, 100% of which is imported
- Sweden is a better example of where these sensitivities are lower. While Sweden imports 100% of its oil & gas needs, fossil fuels only make up 35% of energy consumption due to wind+hydro+nuclear and a very high degree of electrification of final energy
- While Mexico shows up with material gas exposure, most is imported from the US rather than the Persian Gulf

[1] Around 75% of global oil trade is maritime compared with just 14% for natural gas. Within these amounts, 27% of maritime oil goes through the Strait of Hormuz and 22% of maritime LNG goes through the Strait.

One thought I had regarding the US when the invasion occurred: the US Strategic Petroleum Reserve is much lower than usual due to a Biden Administration decision to heavily draw upon it. The goal at the time was to combat the inflationary consequences of Biden's fiscal and monetary policies, rather than any geopolitical issues that the Reserve is primarily designed to address.

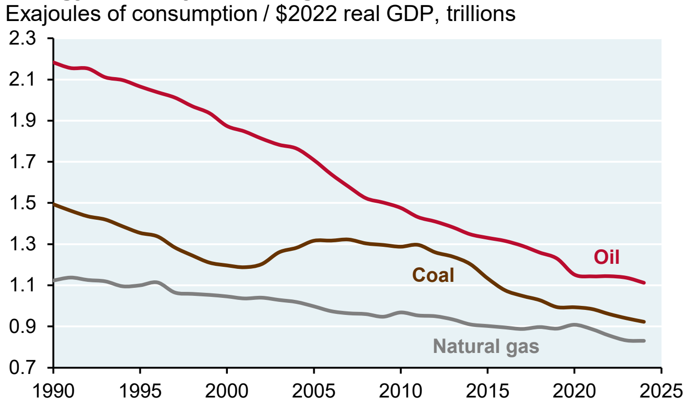
US Strategic Petroleum Reserve total inventory
Barrels, millions



Source: DOE, Bloomberg, JPMAM, February 20, 2026

My next thought: this is a glass half full approach but in many countries, the oil intensity of GDP has fallen in half since the 1990 Gulf War. Gas and coal intensities of GDP fell as well, although by a lesser extent. In other words, the world needs less fossil fuels to grow than it used to. This is a by-product of more energy efficient machines and vehicles, and displacement of coal by more efficient natural gas turbines and furnaces for electricity and thermal heat in most places except China. As a result, I would not be surprised to see only modest GDP contractions due to temporary oil and gas price spikes.

Energy intensity of GDP, global
Exajoules of consumption / $2022 real GDP, trillions



Source: Energy Institute, IEA, JPMAM, 2025

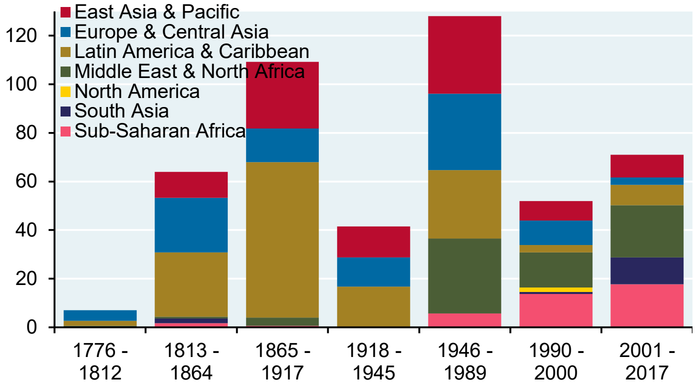
Energy efficiency measures	1990	Latest
Aviation MJ per passenger-km	2.9	1.1
Light duty vehicle miles per gallon	21.2	28.0
Oil and gas furnace fuel efficiency	65%-70%	80%-95%
Combined cycle gas turbine max efficiency	0.5	0.6
Refrigerator energy, kWh per year	960.0	400.0
Air conditioner Seasonal Energy Efficiency	8.0	15.0
Window air leakage, cu feet per minute per sf	0.3 - 0.5	0.1 - 0.3
Standard lighting, lumens per watt	8 - 10	80 - 100
Limited progress: Class 8 trucks and containerships		

Global energy mix shifts, ex-China	1990	Latest
Coal share of fossil fuel final energy	28%	21%
Nat gas share of fossil fuel final energy	33%	44%

Source: JPMAM, 2025

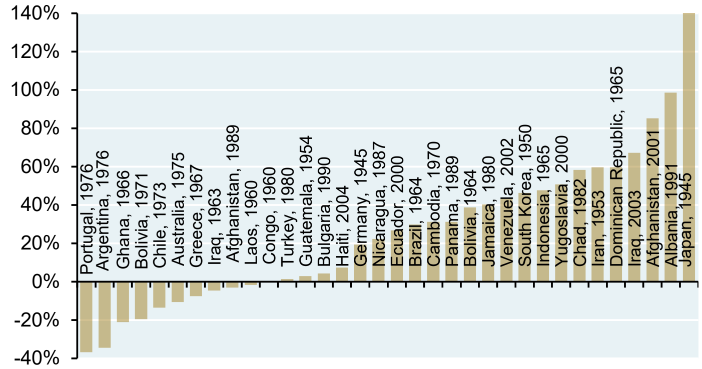
A history of US interventions. The first chart shows the number of US interventions by era and region. The important questions revolve around what happens next. US interventions tend to result in increased economic growth on an ex-post basis, though often without much additional democracy. As illustrated in the fourth chart, most autocratic regimes toppled via coercion are replaced by dictatorship. While the President highlighted the goal of regime change in Iran, what may be just as acceptable to the Administration is an autocratic Iran whose policies in the region are less antagonistic to US interests. Recall the US-aligned autocratic regime of the Shah which followed the 1953 ouster of Iran's democratically elected President Mossadegh. By most accounts, Mossadegh was ousted by the CIA and the British in Operation Boot/Ajax after he nationalized Iran's oil industry.

US interventions by era and region, 1776 - 2017
Number of interventions



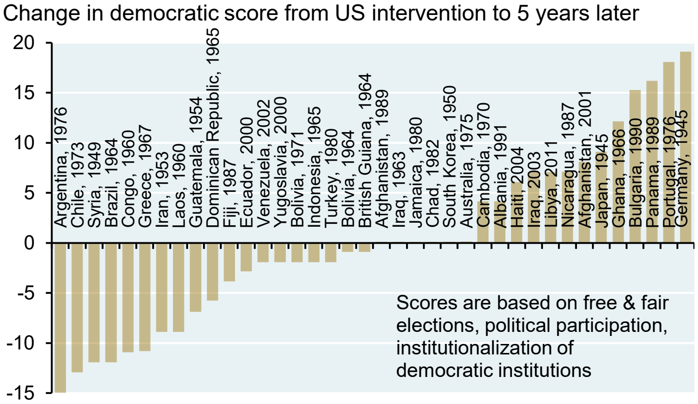
Source: Tufts University, Geopolitical Economy, September 13, 2022

GDP growth rate change: 10 years following US intervention vs 10 years prior, Percent



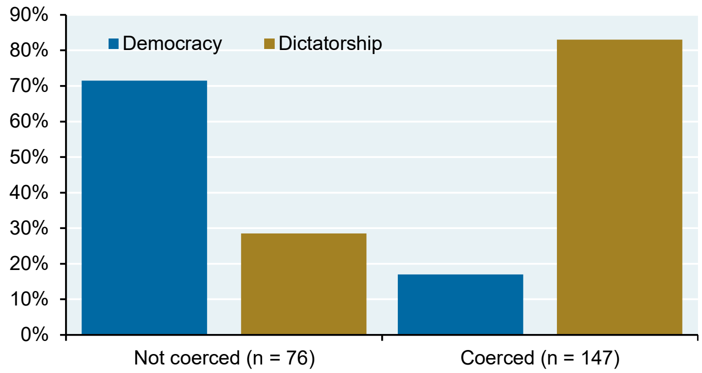
Source: "Thrifty Authoritarians", Savickas (American University), 2016

Democratic change post regime change
Change in democratic score from US intervention to 5 years later



Source: "Thrifty Authoritarians", Savickas (American University), 2016

Mode of autocratic collapse and subsequent regime
Percent



Source: Geddes et al, American Political Science Association, June 2014

Some analysts believe that thwarting Chinese ambitions is a better explanation for the US invasion of Iran than regime change[2]. The rationale: China buys 80% of Iranian oil at steep discounts, it committed $400 bn of investment in Iran as part of a 25-year strategic partnership, it built most of Iran's surveillance network, it recently planned to replenish Iran's ballistic missile stockpile and sell Iran supersonic anti-ship cruise missiles. China's objective: tie the US up in the Middle East and reduce its capacity for any response regarding Taiwan.

They don't call it an "Ivory Tower" for nothing. One of the most hilariously wrong assessments ever made comes from Princeton's Richard Falk and his Op-Ed in the New York Times (of course) in 1979 after meeting with Ayatollah Khomeini: "The depiction of Khomeini as fanatical, reactionary and the bearer of crude prejudices seems certainly and happily false. What is also encouraging is that his entourage of close advisers is uniformly composed of moderate, progressive individuals…..Having created a new model of popular revolution based, for the most part, on nonviolent tactics, Iran may yet provide us with a desperately needed model of humane governance for a third-world country."[3]

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[2] "*The Iran Strike is all about China*", Zineb Riboua, Free Press/Hudson Institute, March 2, 2026

[3] "*Trusting Khomeini*", New York Times, Professor Richard Falk (Princeton), February 16, 1979

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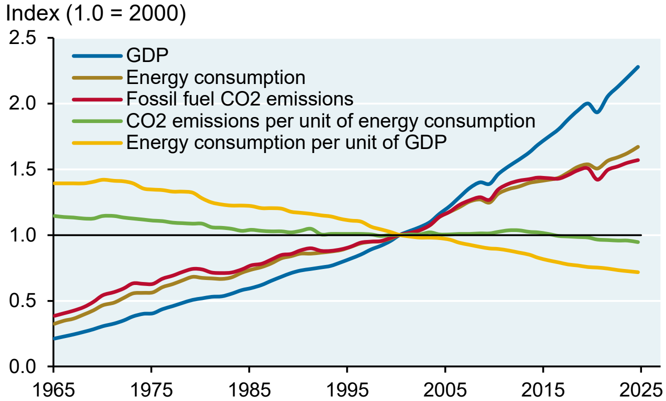
There are a lot of different topics here; this is meant to be consumed a la carte rather than in one sitting.

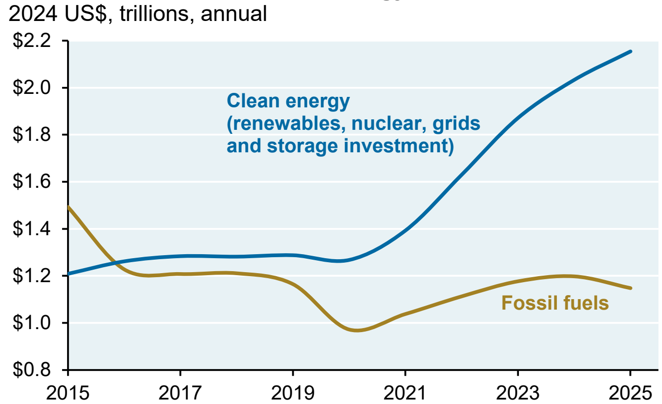
The big picture: global GDP is now growing much faster than global CO_2 emissions. However, the falling energy intensity of GDP (yellow series) has played a bigger role than decarbonization of the energy supply (green series), at least so far. In principle, the pace of decarbonization should increase given the pace of global clean energy investment relative to fossil fuel investment shown in the second chart.

Global growth, energy, emissions and energy intensity
Index (1.0 = 2000)



Source: Global Carbon Project, November 13, 2025

Global investment in clean energy and fossil fuels
2024 US$, trillions, annual



Source: IEA, JPMAM, 2025

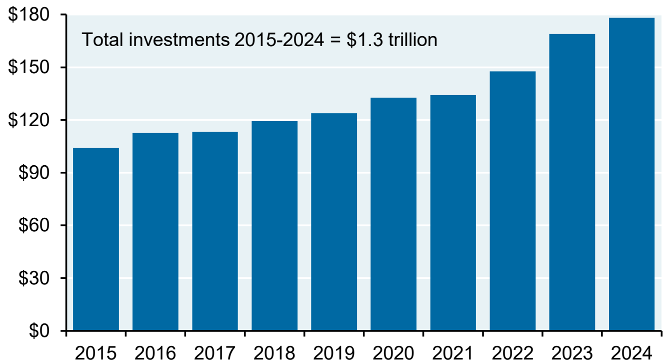
Data centers: the pitchforks are gathering regarding their impact on US power prices

First of all, US power prices have only risen by 2 cents per kWh in real terms (using GDP/PCE deflators) on a national level since 2022, from 13 cents to 15 cents, so some commentary on data center impacts is a bit disconnected from the actual data. Electricity prices are also just 1.4% of average household expenditures.

Defenders of the data center faith also argue that rising US power prices are linked more to grid investment than to buildout of new generation. They've got some facts to back them up: EEI cites investor-owned utilities investing more than $1.3 trillion into the grid over the last 10 years[4], deploying $178 billion in 2024 which was the 13th year in a row of record capital spending. Large amounts of grid investment were not related to new data center demand but to grid resilience: nearly 34% of transmission and 37% of distribution investment in 2022 was tied to system hardening against wildfires, floods, hurricanes and other risks[5]. Other factors affecting power prices that are unrelated to data centers: natural gas pipeline constraints in the Northeast.

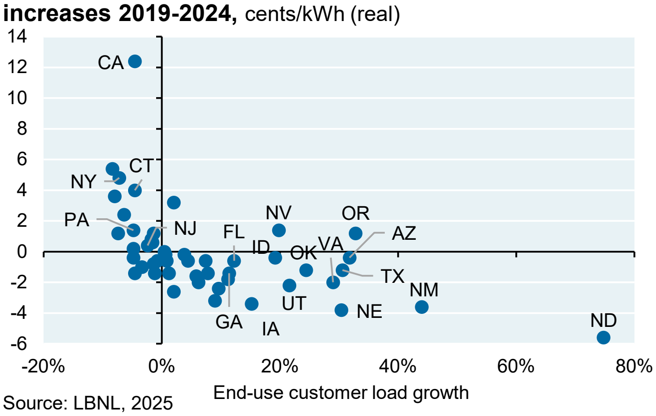
In a similar vein, LBNL's analysis[6] of retail electricity prices from 2019-2024 found that load growth was *inversely* correlated with electricity prices, a finding many see as exonerating data centers. Like the EEI study, LBNL also found that transmission and distribution costs have been rising while generation costs have been falling.

US investor owned utility grid investments
US$, billions



Source: EEI 2024 Financial Review, July 2025

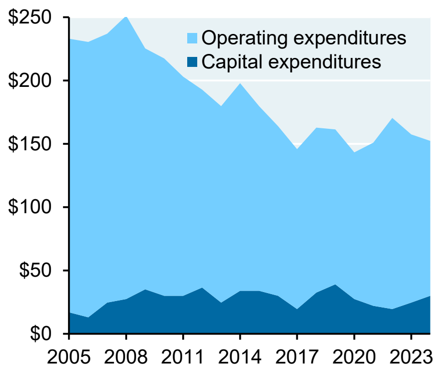
Correlation between load growth and retail electricity price increases 2019-2024, cents/kWh (real)



Source: LBNL, 2025

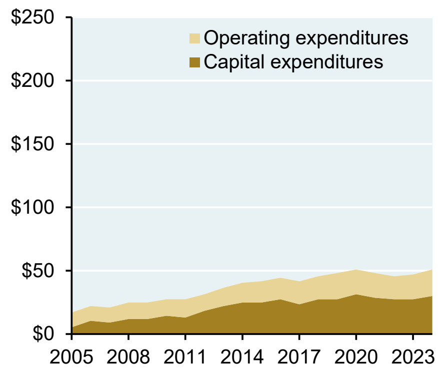
Annual US electric investor-owned utility expenditures:

Generation
2024 US$, billions



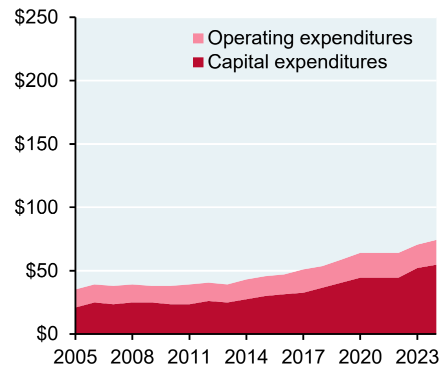
Source: LBNL, Brattle, FERC, October 2025

Transmission
2024 US$, billions



Source: LBNL, Brattle, FERC, October 2025

Distribution
2024 US$, billions



Source: LBNL, Brattle, FERC, October 2025

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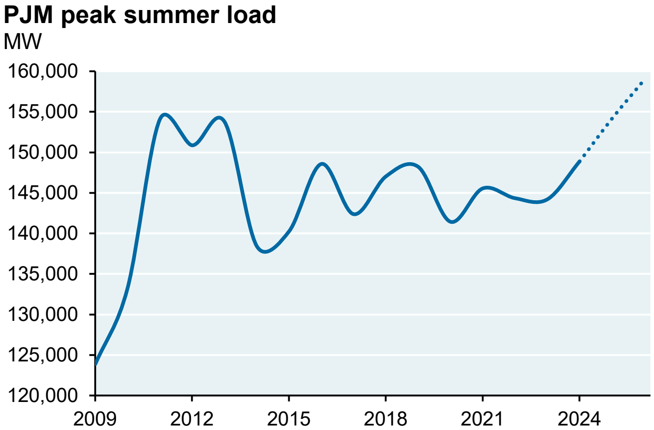
[4] Edison Electric Institute Financial Review, 2024; and "*Retail Rate Trends in the US*", Charles River Associates (prepared for EEI), February 2, 2026

[5] EEI/PPL "*America's Electric Companies*", April 27, 2023

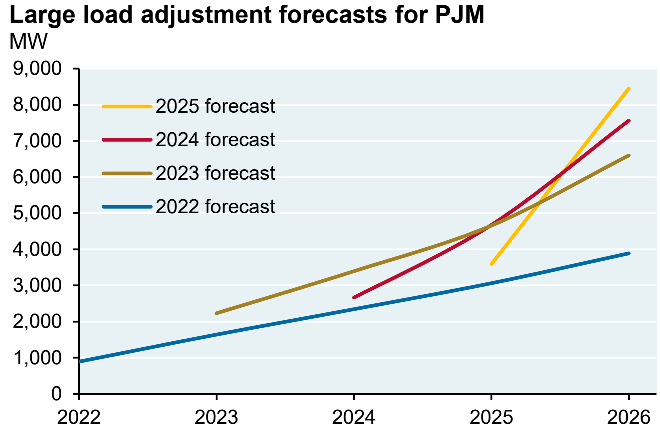
[6] "*Factors influencing recent trends in retail electricity prices in the US*", LBNL, Electricity Journal, 2025. LBNL found that (a) declining generation costs mostly reflect falling *operating* costs rather than declining *capital* costs, and (b) operating cost declines are mostly due to falling natural gas prices. In other words, generation costs are not declining due to falling wind/solar costs even though some analysts misconstrue LBNL's report in that way

But…for part of LBNL's analysis period, data centers were less of a factor than they are now. There's also empirical evidence that data centers *are* partly responsible for increases in US electricity prices in select locations, even though they only make up 4%-6% of US power demand. Let's take a look.

Monitoring Analytics, the independent market watchdog for the mid-Atlantic PJM region, concluded in June 2025 that 75% of the region's increased capacity payments for 2025/2026 and increase in large load forecasts were the direct result of data center demand[7]. See chart on the right for PJM's evolving projection of its peak loads, and page 9 for a deep dive on rising PJM capacity payments and the White House response.

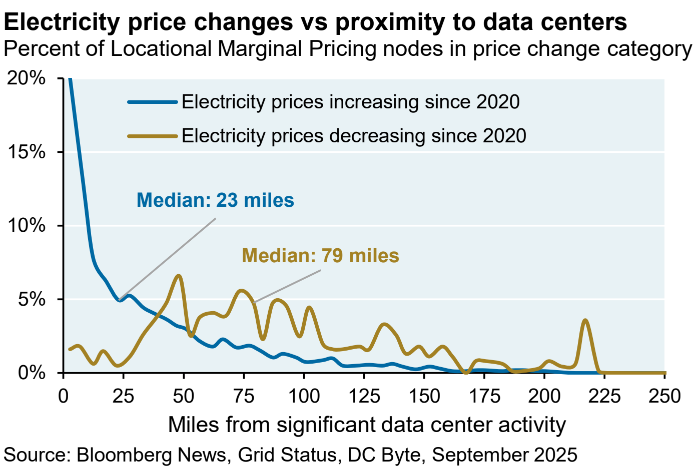


Source: Monitoring Analytics, JPMAM, June 2025



Source: Monitoring Analytics, JPMAM, June 2025

More circumstantial evidence: an analysis of power prices, local electricity nodes and their proximity to data centers[8]. The analysis incorporates data from 25,000 Locational Marginal Pricing nodes across seven different Regional Transmission Organizations where wholesale electricity prices were measured from 2020-2025. In the chart, the blue series shows nodes with power price increases and the gold series shows nodes with power price decreases. **The concentration of nodes with rising power prices was located much closer to data centers than nodes with falling power prices**.



Source: Bloomberg News, Grid Status, DC Byte, September 2025

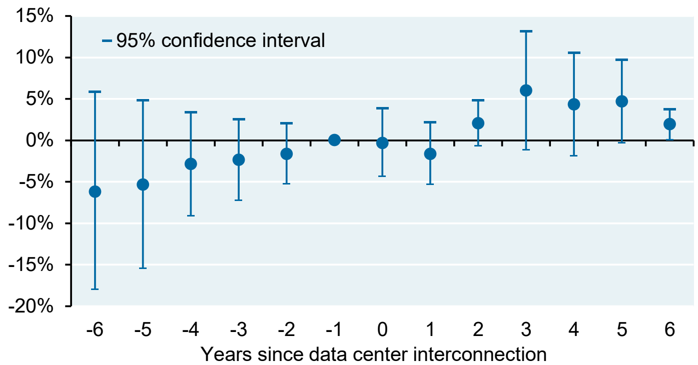
Location Marginal Prices reflect real-time location-specific electricity price signals in wholesale markets that are designed to incentivize congestion relief. LMPs incorporate generation costs, transmission congestion costs and energy losses. There are over 60,000 LMPs in the US, each of which was established by an ISO or RTO under FERC supervision

[7] In the 2025-2026 Monitoring Analytics report, the increase in base residual auction (BRA) payments ascribed to data center loads was $9.3 billion, while total BRA payments were $14.7 billion. In the 2024-2025 report, total BRA payments were $2.2 billion. Therefore: $9.3 / ($14.7 - $2.2) is ~75%

[8] *"AI Data Centers Are Sending Power Bills Soaring"*, Saul et al (Bloomberg), September 2025

A recent study takes a closer look at data centers and power prices in the state of Virginia. The authors analyzed the impact of new data center connections on Locational Marginal Prices in Virginia given its data center concentration. The results show that data center entry into a local market increases marginal electricity prices by $2.58 per MWh, a 7.3% increase driven mostly by higher congestion prices[9]. Furthermore, the authors found that these congestion price increases were much higher in census tracts with greater shares of renewable capacity than in tracts with greater shares of fossil fuel capacity. The implication: data centers require power to be transmitted from more distant generation sources when associated tracts have a high renewable share.

Data center impact on locational marginal electricity prices
Percent change from one year prior to interconnection

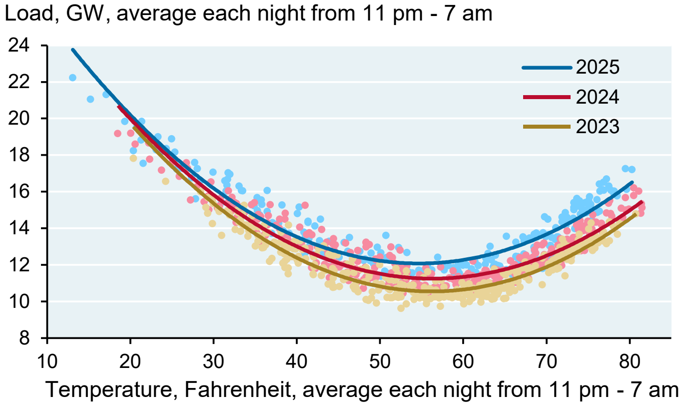


Source: USAEE Working Paper, Mamkhezri et al, November 2025

Note: renewables are often credited at the system level (not delivery to the specific node). Many sustainability constructs don't require physical matching between a site's consumption and renewable generation

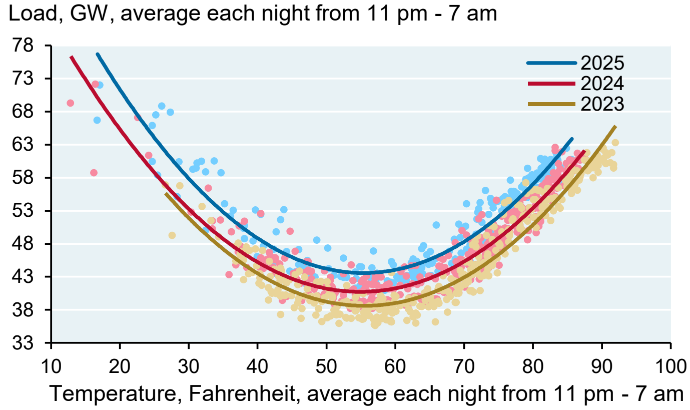
Lastly, consider the increase in nighttime loads in Virginia and ERCOT since 2023. The increase in nighttime loads in data center heavy areas such as the Northern Virginia Dominion Zone and ERCOT are shown below. Nighttime loads are less influenced by industrial production or population. As shown in the charts, there was a consistent nighttime load increase from 2023 to 2025 at ambient temperatures of 50°-60° F (i.e., temperatures that generally do not prompt a lot of air conditioning or electric heating demand). What's still active then? Data centers and battery price arbitrage; EV charging isn't large enough to move the needle yet. Nighttime load can be viewed as positive as it represents consistent load that allows utilities to monetize capital deployed assets and does not put additional strain during peak hours; but it's another sign of rising data center demand.

Dominion Zone night time temperature vs load by year
Load, GW, average each night from 11 pm - 7 am



Source: JP Morgan US Power Trading, August 8, 2025

ERCOT night time temperature vs load by year
Load, GW, average each night from 11 pm - 7 am



Source: JP Morgan US Power Trading, August 20, 2025

These examples are part of the circumstantial evidence pointing to a data center impact on power prices in some locations, but my opinion doesn't matter. **What matters more is that a data center backlash is underway, as we outline next after a deep dive on PJM.**

[9] "*The hidden cost of the cloud: data centers and electricity market inefficiency*", Jamal Mamkhezri (Georgia Tech and New Mexico State University), Xiaochen Sun (New Mexico State University), Yuting Yang (University of New Mexico), USAEE Working Paper No. 25-660, November 2025; partial funding received from the DoE

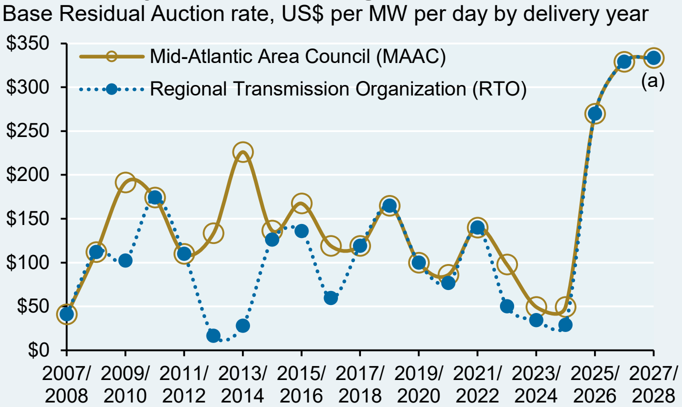
What's going on with PJM? A push to allocate more incremental costs to data centers

The PJM region (data center alley: VA, PA, MD, OH) has 67 GW of existing and planned data center capacity, the largest cluster in the US (ERCOT-TX 20 GW, CAISO-CA/NV 8 GW). PJM has attracted attention due to spikes in its capacity payments, which are **"**insurance premiums" paid to generators to commit future supply or commit to demand response reductions during peak demand. While capacity payments take place in wholesale markets, they're partially flowing through to retail power prices in MD and NJ. Factors driving the spike in PJM capacity payments include retirement of thermal assets, data centers and declines in capacity accreditation for solar and storage (see bottom table).

In January, the White House and 13 PJM governors signed a statement of principles urging PJM to host **a one-time emergency auction whose costs would be solely borne by large loads such as data centers**, unless they have behind the meter capacity or agree to be curtailable. The statement also supported an extension of the two-year price cap that affects regular PJM auctions (without the cap, the recent PJM auction would have cleared at $530 per MW per day). The Executive Branch and governors cannot compel PJM to hold such an auction. PJM responded by announcing a "Critical Issue Fast Path" that creates avenues for large loads to build their own generation or enter into a "Connect and Manage" framework that entails curtailment, something called "Accelerated Interconnection Tracks" and some kind of backstop generation procurement process to address short-term reliability needs.

PJM capacity prices are soaring

Base Residual Auction rate, US$ per MW per day by delivery year



Source: NRG Energy, July 23, 2025. (a) uncapped would have been $530/MW

Maryland: impact of 2025/26 PJM capacity auction on customer bills

Utility	Bill increase, %
Baltimore Gas & Electric	14%
Allegheny Power Systems	24%
Delmarva Power & Light	2%
Potomac Electric Power	10%

New Jersey: impact of 2025/26 PJM capacity auction on residential & small commercial bills

Utility	Bill increase, %
Atlantic City Electric	36%
Jersey Central Power & Light	34%
Public Service Electric & Gas	33%
Rockland Electric Company	36%

Source: State of Maryland Office of People's Counsel, New Jersey Basic Generation Service Auction, 2025

My sense is that if emergency backstop auctions were held in PJM, data centers would probably participate in them. Power can be just 10% - 15% of data center lifetime costs; so the opportunity cost of operating delays can be much higher than having to pay more to secure the availability of power. As a result, data center migration out of PJM solely due to rising capacity costs is unlikely. There are attributes of some PJM states that make them attractive for data centers (tax incentives, low latency, liquid power market trading hubs, water and reliable grid infrastructure). The new rules favor the giants since companies that fall under the large load definition that lack hyperscaler balance sheets may find it harder to finance the new costs. Last point: some utilities within PJM are questioning whether re-regulation would be the better option (Exelon, First Energy, PPL and PSEG); I agree with them.

Declines in PJM effective load carrying capability for solar and storage contributed to rising capacity payments

Delivery year	Nuclear	Coal	Gas combined cycle	Gas combustion turbine	Tracking solar	Onshore wind	Demand resource	4hr storage	8hr storage
2023/24	-	-	-	-	54%	15%	-	83%	100%
2024/25	-	-	-	-	50%	21%	-	92%	100%
2025/26	95%	84%	79%	62%	14%	35%	76%	59%	68%
2026/27	95%	83%	74%	60%	11%	41%	69%	50%	62%
2027/28	95%	83%	74%	61%	8%	41%	92%	58%	70%

Source: PJM, JPMAM, 2025

The data center backlash

Some states now aim to apply higher rates to data centers to account for impacts on generation, transmission and distribution costs, and require mandatory participation in curtailment[10] programs under certain conditions:

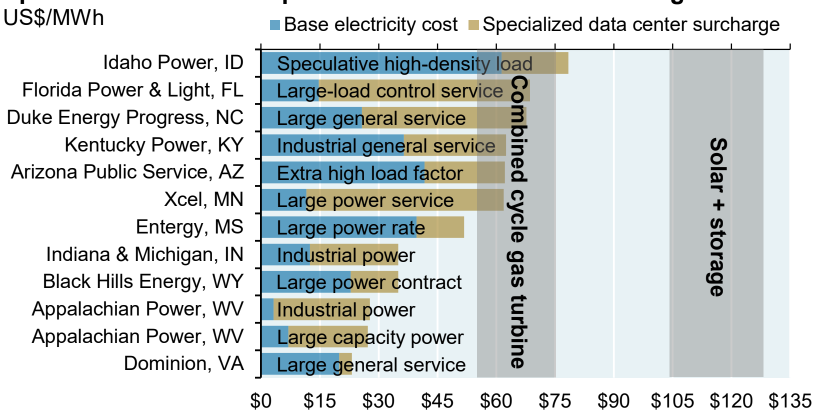
- *Texas*. Texas passed a bill in June 2025 that (a) requires large energy users interconnected after 2025 to pay retail rates based on peak demand, and (b) allows ERCOT to issue mandatory curtailment to large loads (>75 MW) interconnected on or after December 31, 2025. The bill also directed the Public Utility Commission of Texas to establish a review process for large load customers attempting to draw from the grid
- *Oregon*. The legislature is seeking to develop new higher power rates for data center customers after electric bills rose by 50% over the last four years
- *California*. A new bill proposes a special rate structure for data centers to ensure that grid investments are fully recovered while protecting residential ratepayers from increased costs
- *Georgia*. The Public Service Commission is weighing a new rule to require large-load customers over 100 MW to pay transmission and distribution costs associated with their projects
- *Ohio*. In 2024, AEP Ohio proposed new utility rates requiring data centers and crypto mining firms with loads over 25 MW to pay minimum charges
- *Indiana*. The Utility Regulatory Commission approved an increase in industrial tariffs for power provided by Indiana Michigan Power
- *Utah*. In 2025, the legislature passed a law to ensure that large load customers are responsible for all incremental costs associated with new or expanded service

In **Ireland**, after data centers consumed 20% of the power in the entire country, regulators imposed a temporary moratorium and now require behind the meter generation.

Despite these efforts, higher power rates for data centers might still not be enough from the perspective of other ratepayers. Wood Mackenzie published a report[11] in 2025 concluding that new specialized rates for data centers may not be high enough to cover the cost of new generation. In other words: unless utilities negotiate even higher rates for data centers, other residential, commercial and industrial ratepayers may end up footing part of the bill. Hyperscalers have responded to the backlash in a number of ways, including self-funded behind the meter generation and long-term PPA agreements to effectively pay for new grid-based generation.

Specialized data center power rates still trail cost of new generation

US$/MWh



Source: Wood Mackenzie, JPMAM, 2025

Not just heat: data center cooling plans

Data center companies are often expected to fund municipal water treatment utilities or deploy closed-loop cooling systems that eliminate potable water use in order to protect local water supply. Under peak use and temperature conditions, a large hyperscaler data center facility could use 1 to 5 mm gallons of groundwater per day in an open loop system, the water usage of 30k-50k people. However…adiabatic dry cooling and chiller options can increase power demand by 10% and by 30% during peak periods

[10] **Curtailment may be harder than it sounds.** While training workloads may be able to be curtailed, this does not describe the majority of data center workloads which are 24/7 inference and cloud-based workloads for which curtailment is a much bigger challenge. Also: many data center backup diesel generators are technically only allowed to run during a limited number of maintenance hours or under a true emergency as defined by the EPA; a peak load event is currently not considered a "federal emergency"

[11] "*Load growth on utility terms: A comparative analysis of large load tariffs*", Wood Mackenzie, April 2025

At least 25 US data center projects were canceled in 2025 following local opposition, four times as many as in 2024. These canceled projects accounted for at least 4.7 GW of electricity demand, a meaningful share of data center capacity projected to come online in the coming years[12]. Cancellations were highest in Virginia and Indiana, followed by Pennsylvania, Wisconsin, Michigan and Georgia.

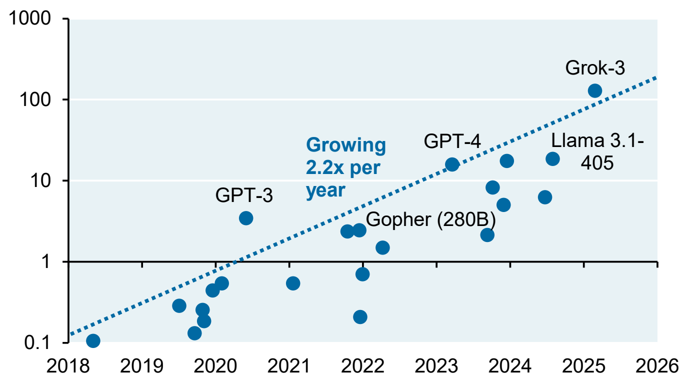
What about chip design/efficiency as a means of reducing data center power demand?

Each year, training AI frontier models requires more computing which drives up AI power demand:

- In 2020, frontier models like GPT-3 only required 3.1 x 10^23 FLOPS and 4-10 MW of power
- By 2025, Grok-3 is estimated to have required 3.5 – 5.0 x 10^26 FLOPS and 150-200 MW of power
- By 2030, training a frontier model could require 10^29 FLOPS and 4 – 16 GW of power

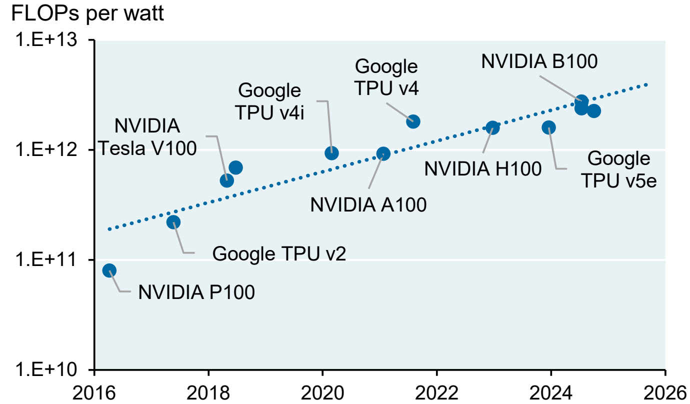
Partial offsets: increased energy efficiency and the increased duration of training runs. From 2020 to 2024, the number of floating point operations per watt of power performed by frontier models increased by 40% per year and the duration of training runs increased by 25% per year. How will these competing forces net out from a power perspective? According to Epoch AI[13], power demand would grow by 4x per year without any mitigating factors. Increased duration of training runs could reduce power demand growth to 3x per year, and improved chip efficiency could further reduce power demand growth to 2.2x per year. That happens to be the pace at which the power required to train frontier models has been growing so far. **Bottom line: computational intensity appears to be outpacing efficiency improvements**, driving projections of rising power demand despite data center utilization rates that are well below 100%.

Power used to train frontier AI models
MW



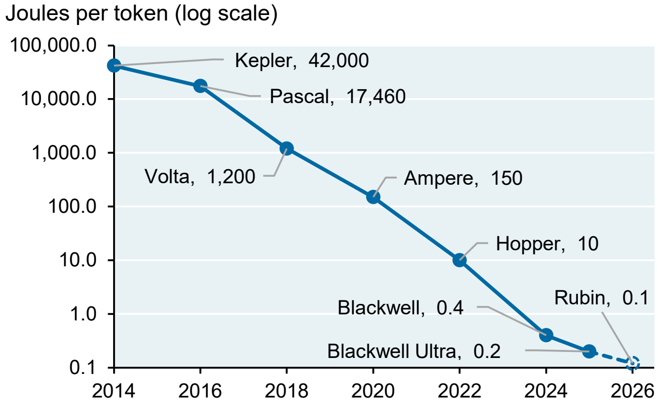
Source: Epoch AI, August 2025

Leading AI hardware energy efficiency
FLOPs per watt



Source: Epoch AI, August 2025

Energy efficiency of chips over time
Joules per token (log scale)



Source: "Building the Backbone of AI", Brookfield, August 2025

Citations of data center utilization rates

Data center utilization rates are not aggregated by the EIA or other agencies. Here are a few citations of prevailing levels in the industry:

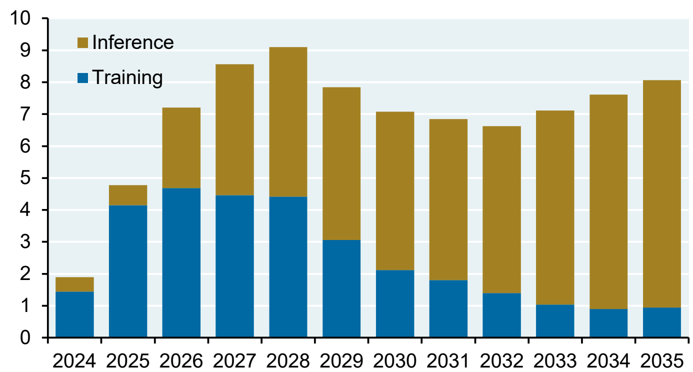
- MIT/NBER (2025): 80%
- LBNL (2024): 80% training, 40% inference
- Innovation Endeavors: 60%-70%

[12] "*Amid Rising Local Pushback, US Data Center Cancellations Surged in 2025*", HeatMap Pro, January 12, 2026

[13] "*Scaling Intelligence: The Exponential Growth of AI's Power Needs*", Epoch AI, August 2025

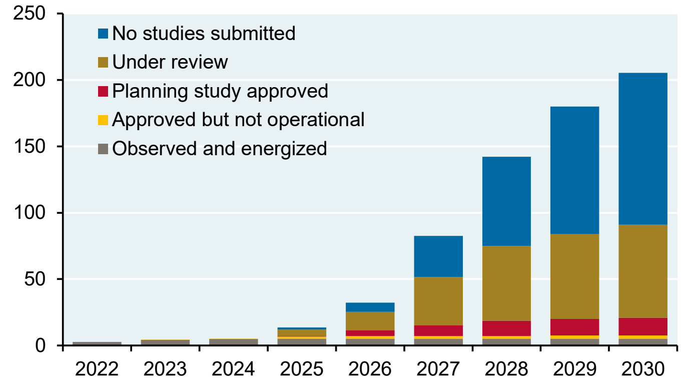
What about the shift from training frontier models to inference usage of these models; won't that reduce power demand? Once models are put into production and accessed by end-users, power demands are often smaller. Brookfield Asset Management which owns over 140 data centers worldwide made some projections of the gradual shift from training to inference, shown below in the first chart. In contrast, OpenAI projects that it will still need more dollars for training than for inference through to 2030, so this issue is far from settled.

Future AI compute demand: training vs inference
Total global absorption,GW



Source: "Building the Backbone of AI", Brookfield, August 2025

ERCOT large load interconnection requests
GW

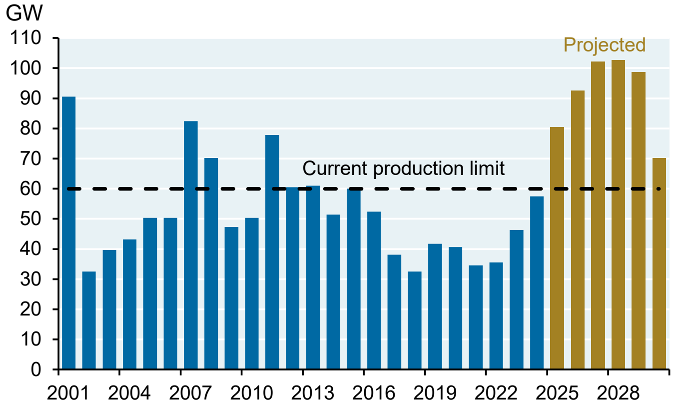


Source: ERCOT, October 2025

In any case, turbine orders are soaring, in part to address data center demand. ERCOT projects 200 GW (!!) of new large load requests (up from 56 GW in 2024), 70% of which is driven by new data centers. And at the 2026 PowerGen conference, midwestern ISO SPP cited 110 GW of projects in its interconnection queue, twice its current maximum load. That partially explains the large power gap projected in the bottom chart.

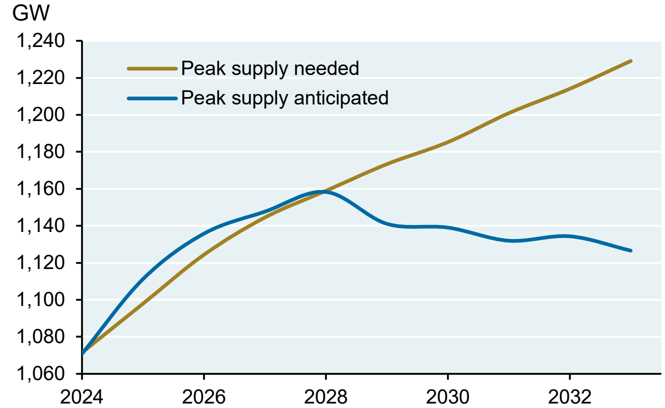
Three companies each have 20%-25% of global turbine market share: GE Vernova, Siemens and Mitsubishi, and each is planning to expand production. Mitsubishi plans to double production capacity within two years; GE Vernova will ramp annual output from 16 GW in 2023/2024 to 22 GW later this year and to 26 GW by mid-2028; and Siemens Energy is investing $1 billion in US manufacturing, lifting its large turbine production capacity by ~20%. It remains unclear if this will be enough to clear backlogs as demand is simultaneously increasing. For example: Germany aims to construct 10-20 new gas-fired plants by 2030, while Japan is considering new gas facilities after reversing a prior view that its power demand was in long term decline. Saudi Arabia aims to add gas-fired plants to boost generation before it hosts World Expo 2030, and Chinese utilities are lobbying for the next five-year plan to sanction ~70 GW of new gas-plant capacity by 2030, roughly equal to Japan's entire fleet[14]. It's a seller's market: turbine suppliers often require non-refundable payments to secure manufacturing slots, a departure from prior procurement norms. Even after ramping up turbine production from 48 per year to 70-80 per year, GE Vernova expects turbine reservations to be sold out through 2030 by the end of this year.

Global gas turbine orders
GW



Source: Bloomberg News, October 2, 2025

Projections of a US power supply-demand gap
GW

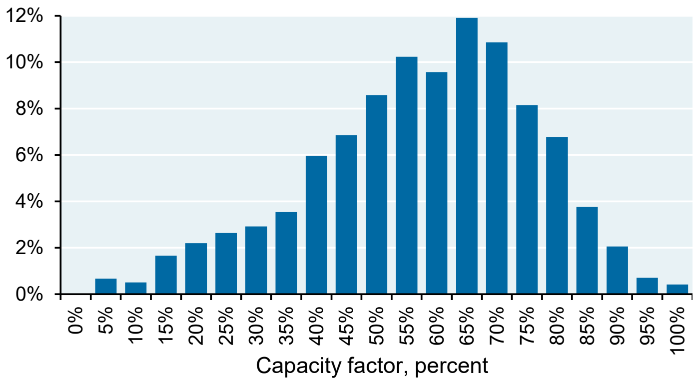


Source: NERC, Schneider Electric, 2025

14 "*AI-driven demand for gas turbines risks a new energy crunch*", Bloomberg, October 2, 2025

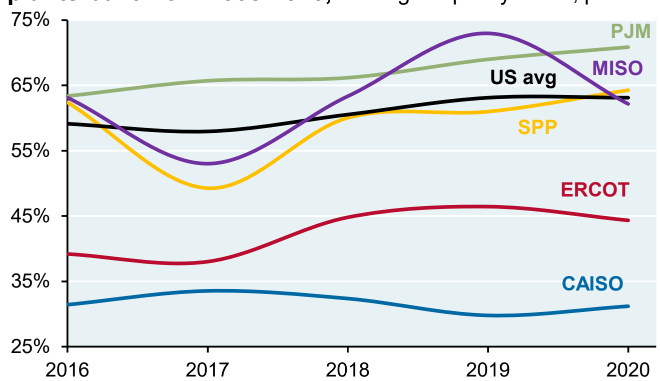
Are large amounts of new gas plants needed to accommodate more data centers? Some analysts believe that if data centers agree to be curtailed at moments of peak demand, there's room for more of them to hook up to the grid since many US combined cycle plants operate well below maximum capacities. The chart on the left shows an aggregation of US combined cycle plant capacity factors in 2024; most clustered between 50% and 75%. The chart on the right shows combined cycle capacity factors by region for the period 2016-2020.

US natural gas combined cycle capacity factor in 2024
Share of total US natural gas combined cycle capacity, percent



Source: EIA forms 923 and 860, JPMAM, 2024

Natural gas combined cycle capacity factor by region, plants built from 2008-2020, Average capacity factor, percent



Source: EIA, May 20, 2021

However, the independent market monitor for PJM wrote in November 2025 in stark terms that new data center loads require new dedicated capacity and that demand response/flexibility is not enough[15]:

- "Large data center load additions have already had a significant impact on other customers as a result of higher transmission costs, higher energy market prices and higher capacity market prices…Continuing to simply accept interconnection of large data center loads that cannot be served reliably because there is not adequate dispatchable capacity is not a reasonable path forward and is not a solution of any kind"
- "Current capacity in PJM is not adequate to meet demand from large data center loads and will not be adequate in the foreseeable future. This is a simple factual issue. **The market solution is to establish a queue for large new data center loads which would not be interconnected until there is adequate capacity to serve them**. This solution to the issues created by the addition of unprecedented amounts of large data center load does not require a massive wealth transfer"
- "The assertion that large new data center loads can be demand side resources and do not require new capacity is a regulatory fiction…PJM does not have the authority to enforce reductions in load from emergency demand resources. Proposals that include the demand side option in place of adding actual generation capacity do not make the demand side option a mandatory condition for interconnection"
- "Implementing a load queue for large new data center loads is the only enforceable way to address the impacts of such loads and to require large new data center loads to pay for a significant part of the costs and risks that they would otherwise impose on other customers"

Some academics and consulting firms disagree with Monitoring Analytics. They argue that by combining flexible grid connections with behind the meter capacity, "data centers can reach full operation years sooner while maintaining reliability and improving affordability for all customers"[16]. I'm not sold on this argument. Google-funded analyses like these can be influenced by (a) hyperscaler and data center companies simply seeking faster data center grid interconnections, and (b) renewable energy advocates fundamentally opposed to development of natural gas resources under any circumstances. The ultimate arbiters will be the utilities and Independent System Operators who oversee the grids and who are accountable to customers.

[15] Monitoring Analytics LLC, "*State of the Market Report for PJM*", November 13, 2025

[16] "*Flexible Data Centers: A Faster, More Affordable Path to Power*", Camus Energy and Princeton University Zero Lab, December 2025. Google provided the financial backing for this research

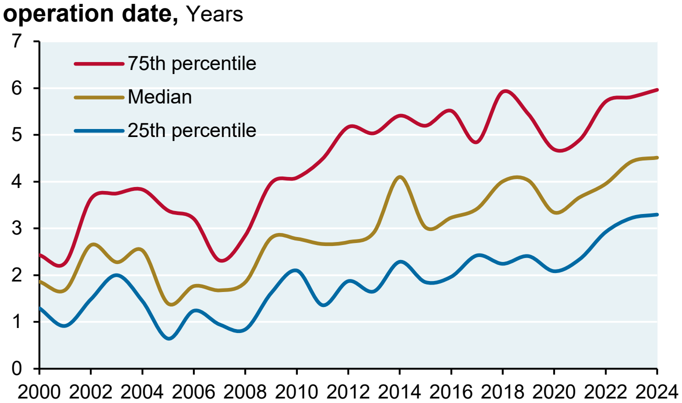
What about BYOG: bring your own behind the meter generation? While very few data centers currently rely on their own onsite generation (less than 1% of their power demand in 2025), a Bloom Energy survey indicates that 38% expect to rely *partially* on their own power by 2030, with 27% expecting to *fully* rely on their own onsite power[17]. Separately, Cleanview published a study showing that 30% of planned data center capacity (56 GW out of 190 GW) in the US now intend to build their own behind the meter generation; long lead times for grid interconnection shown below may explain why. There are several options for onsite generation shown in the table, all with their own costs, lead times and performance characteristics. According to Cleanview, 75% of generation equipment for planned behind the meter data center power relies on natural gas with another 21% in nuclear (i.e., very little reliance on behind the meter renewables + storage).

To be clear, most behind the meter options would be "grid-adjacent", meaning the facility would still have access to the grid for redundancy and load balancing, rather than being a stranded facility completely reliant on its own power. I also think the whole behind the meter craze is going to run into some headwinds since the data centers are competing with utilities, independent power producers and themselves for equipment.

BEHIND THE METER ALTERNATIVES	Size per unit	All-in capex	Lead time	Ramp rate	Land use	Efficiency
Generation type	MW	$/kW	Months	Minutes	MW/acre	%
Aeroderivative gas turbines	30-60	1,500-1,800	18-36	10	30-50	35-40%
Industrial gas turbines	5-50	1,000-1,300	12-36	20-30	20-40	35-40%
Small combined-cycle gas turbines	40-100	1,800-2,500	18-36	30-60	20-30	40-55%
Medium-speed reciprocating engines	7-20	1,700-2,200	15-24	5-10	8-15	40-50%
High-speed reciprocating engines	3-5	2,200-2,800	15-24	5-10	5-10	40-50%
Fuel cells	0.325	3,000-4,000	12-18	Baseload	30-100	50-55%
H-Class combined-cycle gas turbines	600-1000	2,200-2,800	36-60	30-60	20-30	50-60%

Source: SemiAnalysis "How AI Labs Are Solving the Power Crisis: The Onsite Gas Deep Dive", December 30, 2025; JPMAM

Time elapsed from interconnection request to commercial operation date, Years



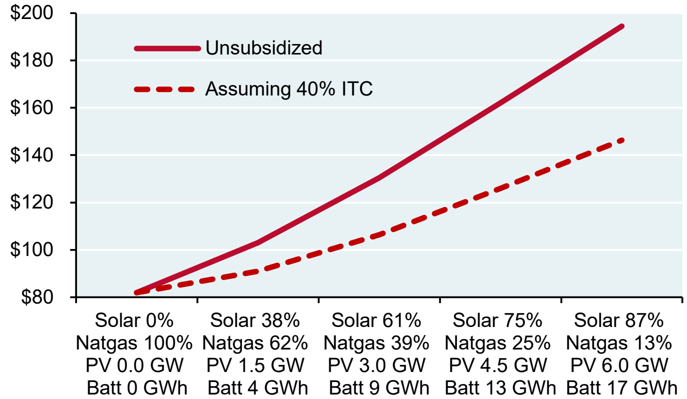
Source: LBNL, 2025

[17] "*Onsite generation expected to fully power 27% of data center facilities by 2030*", Bloom Energy, June 2025 and "*Bypassing the Grid: How Data Centers Are Building Their Own Power Plants*", Cleanview, February 2025

Data centers with onsite power, current & proposed: xAI Colossus 1 and 2, OpenAI/Oracle Stargate, Microsoft Three Mile Island, Equinix, CoreWeave, Meta Socrates South. New entrants in gas fired power: while GE Vernova, Mitsubishi and Siemens dominate this industry, new entrants provide other options. Examples include Doosan Enerbility (S Korea) H class turbines; Wartsila (Finland) modified ship engines; Boom Supersonic (US) jet engines modified into aeroderivative turbines; Caterpillar (US) gas turbines and reciprocating engines

Could behind the meter solar + battery provide baseload power for data centers? Even when including a 40% investment tax credit, solar + battery installations are much more expensive per MWh than single cycle turbines as per our analysis, as shown below. But for operators that are less price-sensitive on power and more focused on getting up and running, solar + storage *might* work; a delay of even a few months to secure power can mean billions in lost revenue for AI infrastructure developers. That is, if they have the land: a 1 GW data center campus might need ~40,000 acres given ~10 acres per MW and a solar capacity factor of 25%.

1 GW data center behind the meter buildout, $ per MWh



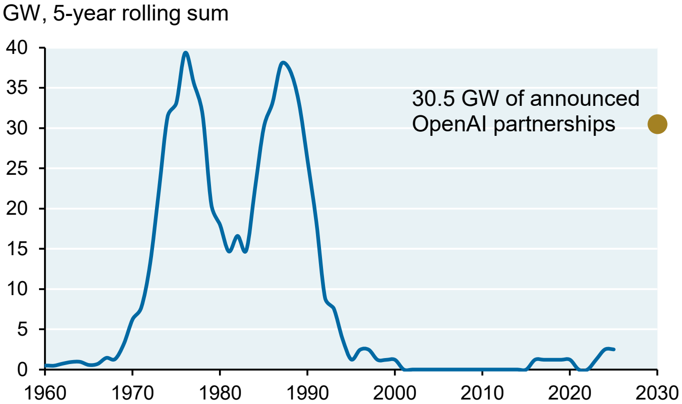
Source: NREL, JPMAM, EIA, December 2025

Most important assumptions

- Solar, battery and single cycle gas turbine capital costs of $923 per kW, $228 per kW and $1,500 per kW; single cycle heat rate 9,142 btu/kWh
- Gas turbine useful life of 25 years; 20 years for solar and battery
- Actual power usage effectiveness 1.15, buildout PUE 1.5 and 30% redundancy
- 7.7% discount rate, gas price $4 per MMBtu
- Other assumptions include solar and battery degradation rates, annual fixed and variable costs and inverter DC-> AC losses

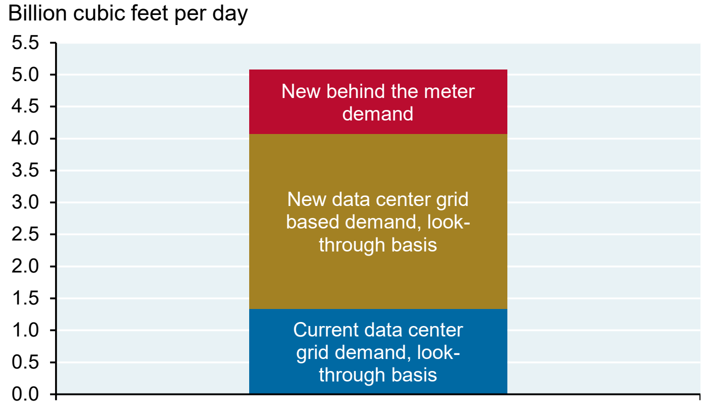
Wrapping up. OpenAI alone announced four partnerships that require 30.5 GW of new power[18]. To put this in context, that's ~75% of peak nuclear GW completions over 5 years during the US nuclear era…just for one company in the AI ecosystem. A power draw of 30.5 GW would also require ~300% of NVIDIA 2025 GPU shipments and more than 100% of current global high bandwidth memory supply[19]. As shown in the bar chart, BNEF projects that data centers may boost US gas demand by 3-4 bn cubic feet per day by 2030. This is a meaningful addition in the context of US dry natural gas production of ~107 bn cubic feet per day in 2025.

US nuclear plants built by year of completion
GW, 5-year rolling sum



Source: Power Reactor System Database, JPMAM, September 2025

Data center natural gas demand by 2030
Billion cubic feet per day



Source: BloombergNEF, JPMAM, November 2025

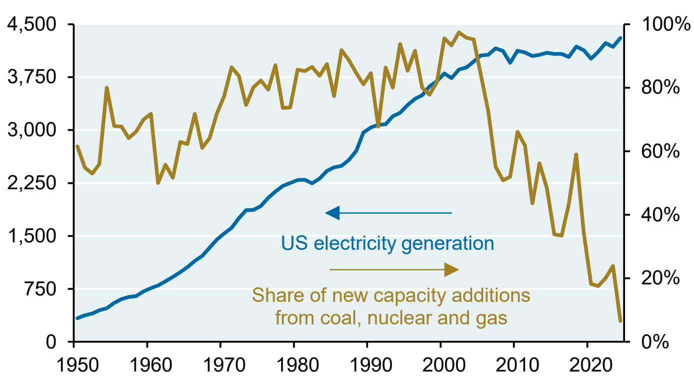
[18] A September 2025 article in *The Information* cited Altman as stating in an internal memo that the ultimate goal is 250 GW (!!!) by 2033, an amount equal to one third of peak US power consumption

[19] Bridgewater Daily Observations, November 10, 2025

After 20 years of flat electricity demand, the US now needs to meet new demand from data centers, EVs and electrification of industrial, commercial and residential heating. While US power generation grew by 2%-4% each year from 1950 to 2006, during that era 70%-90% of new capacity came from a small number of coal, nuclear and gas plants.

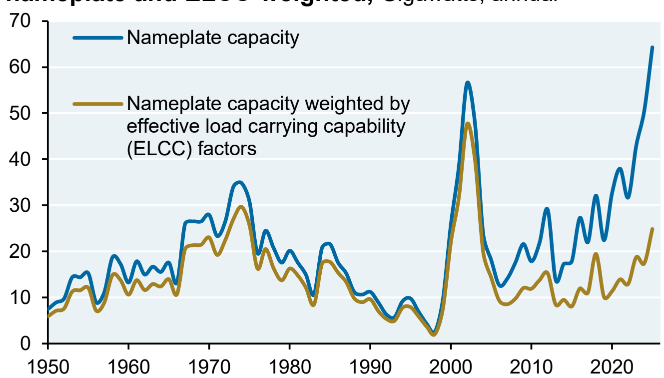
Whether the same pace can be maintained today is another question, particularly given shortages of skilled energy labor, shortages of transformers, breakers and other equipment and tariffs on grid equipment which do not benefit from the kind of exclusions granted to semiconductors and computers. As shown in the second chart, new US power capacity looks like it's surging but is a lot more gradual after adjusting for reliability and intermittency (i.e., derating of solar and wind)[20]. In other words, not all negawatts are created equal.

Generation and capacity additions since 1950



Source: EIA, JPMAM, 2025

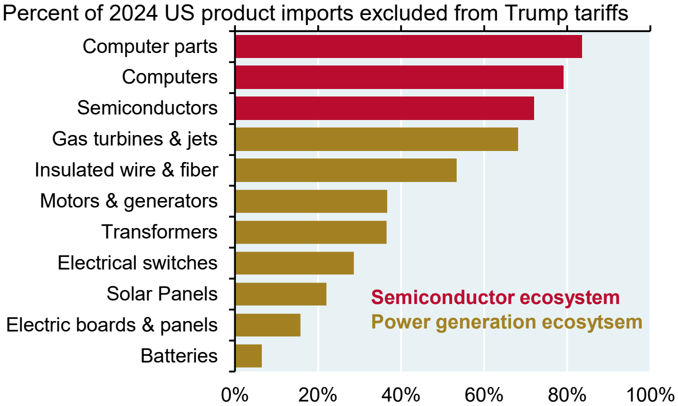
US electricity generation and storage capacity additions: nameplate and ELCC-weighted, Gigawatts, annual



Source: EIA, PJM, MISO, ERCOT, CAISO, Thundersaid Energy, 2025

Power generation vs semiconductor tariff exclusions

Percent of 2024 US product imports excluded from Trump tariffs



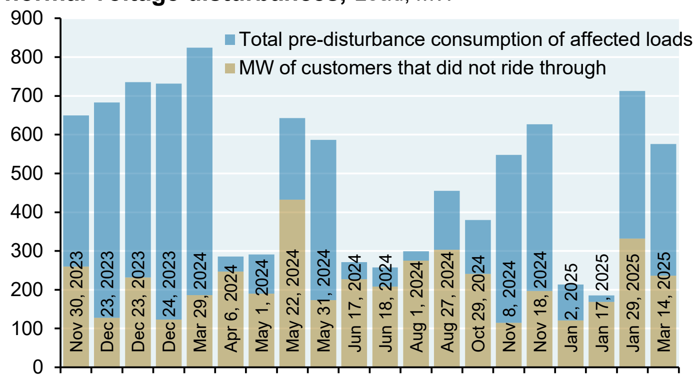
Source: USITC, White House, JPMAM, 2025

[20] We use effective load carrying capability estimates from PJM, MISO, ERCOT and CAISO for the adjusted series. **ELCC** estimates anticipated firm capacity (as a % of nameplate capacity) that a specific resource is projected to supply during the highest net-load hours and reflects its intermittence and reliability

Two manageable data center issues which need attention: ride-through events and harmonic distortion

Large loads that drop suddenly from the grid can be just as problematic as large loads that suddenly appear; both can result in voltage distortions that damage equipment. A **ride-through event** refers to a large load user that opts to stay on the grid despite a temporary voltage blip somewhere in the system. Grid managers are working with customers to increase the frequency of ride-through behavior in the interest of grid stability, since most of the time there's no reason for the large load user to switch to on-site generation or shut down. ERCOT's 2025 Large Load Interconnection report included the chart below showing instances of large loads that suddenly dropped from the grid and did not ride-through. Software and hardware investment should be able to reduce the frequency of these events which ERCOT cites as a growing risk to the stability of grid frequency.

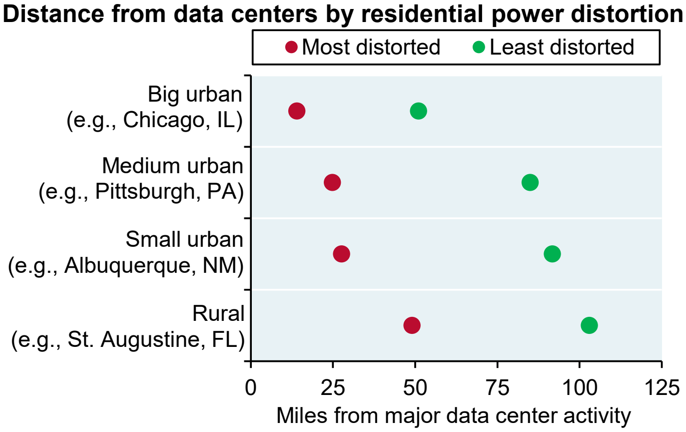
Recent large electronic load ride-through behaviour during normal voltage disturbances, Load, MW



Source: Electric Reliability Council of Texas, October 20, 2025

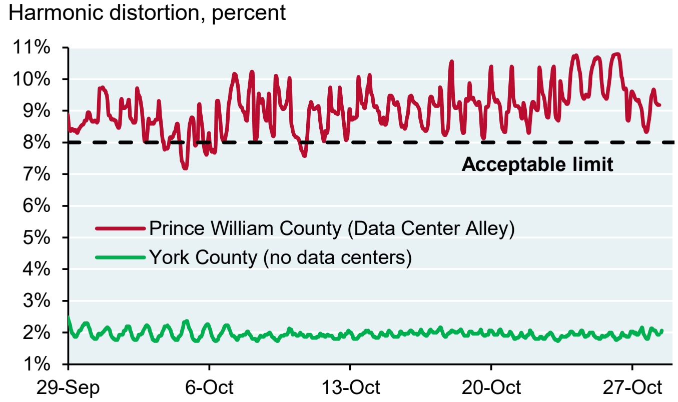
Harmonic distortions. In 2024, Bloomberg Technology issued a report citing higher levels of grid distortions the closer one gets to large data centers. Such distortions could theoretically damage commercial, industrial and residential appliances and power equipment (although we have seen no reports of this actually happening). Using residential sensor data from Whisker Labs, Bloomberg found that 75% of highly distorted power readings were within 50 miles of significant data center activity, with the highest distortions within 20 miles. The chart on the right shows harmonic distortions in October 2024 for Prince William and York counties; the former is part of data center alley. The highest distortions tended to take place at night when data centers are a larger share of energy use. While Commonwealth Edison disputed Whisker Lab readings since they don't directly measure grid harmonics and measure harmonics inside homes, readings were similar across multiple sensors in the same area. Distortions were also highest in data center alley in Northern Virginia. **Potential solutions include requiring data centers to have their own substations and transformers, and greater use of filters/capacitors**.

Distance from data centers by residential power distortion



Source: Bloomberg Technology, Whisker Labs, DC Byte, December 2024

Grid harmonic distortions in Virginia counties, 2024
Harmonic distortion, percent

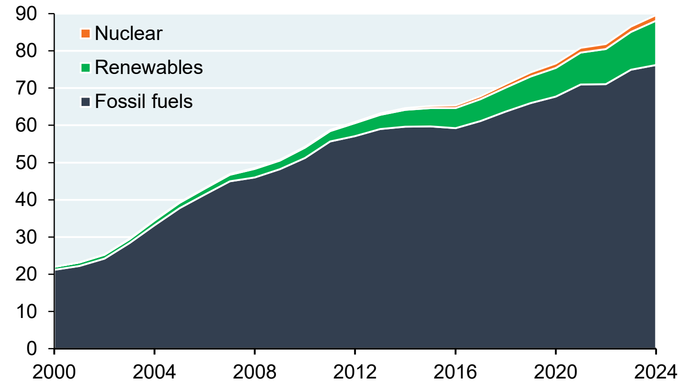


Source: Bloomberg Technology, Whisker Labs, DC Byte, December 2024

The Chinese energy behemoth: Everything, Everywhere, All at Once…including Environmental Damage

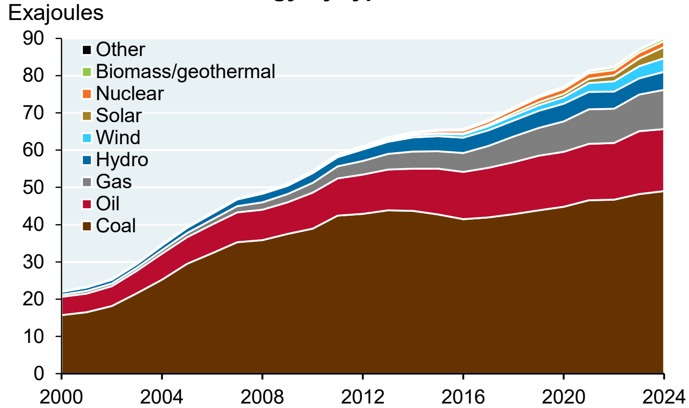
China's energy consumption exceeds the US and Europe combined, and China also represents 50% of the entire increase in global generation since 2010. When I say that China is adding everything, I mean **everything**: solar, wind, coal, hydro, gas and nuclear fission; related industries such as EVs, battery storage and heat pumps; electrification of energy consumption; mandated co-location of data centers with renewable capacity; critical minerals mining and processing; and experimental nuclear fusion.

China useful final energy by type
Exajoules



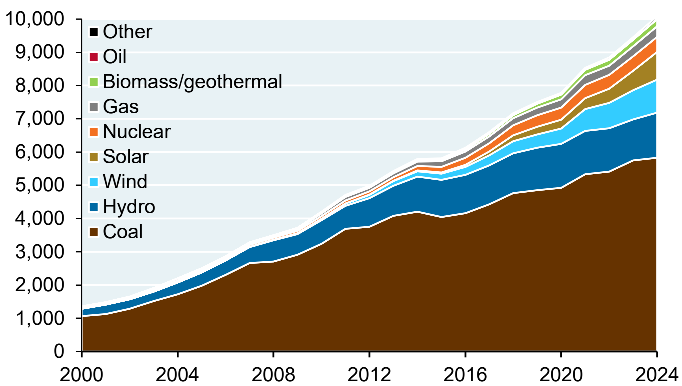
Source: Energy Institute, JPMAM, 2025

China useful final energy by type
Exajoules



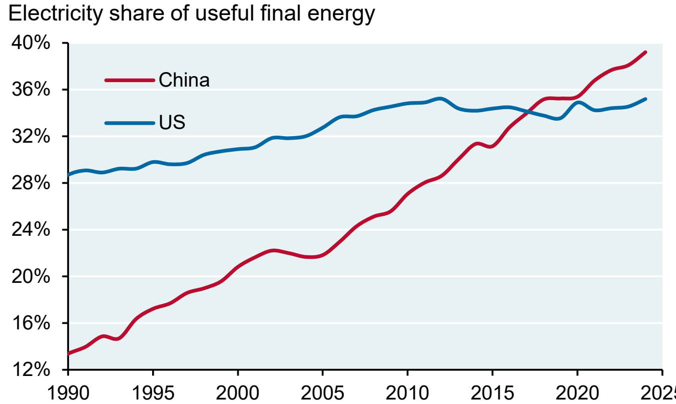
Source: Energy Institute, JPMAM, 2025

China electricity generation by source
Terawatt-hours



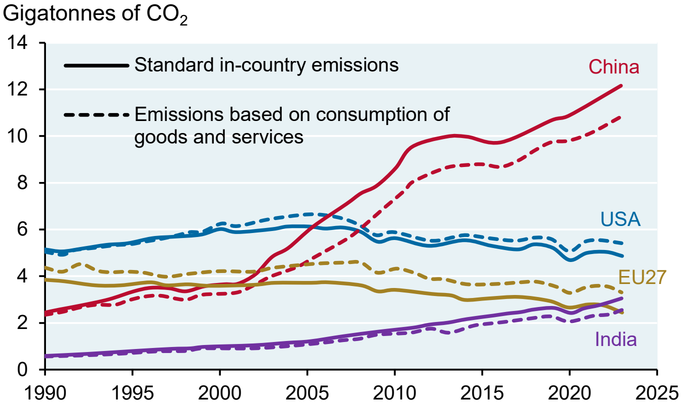
Source: Energy Institute, JPMAM, 2025

Electrification
Electricity share of useful final energy



Source: Energy Institute, IEA, JPMAM, 2025

Annual territorial vs consumption-based emissions
Gigatonnes of CO_2



Source: Global Carbon Project, November 13, 2025

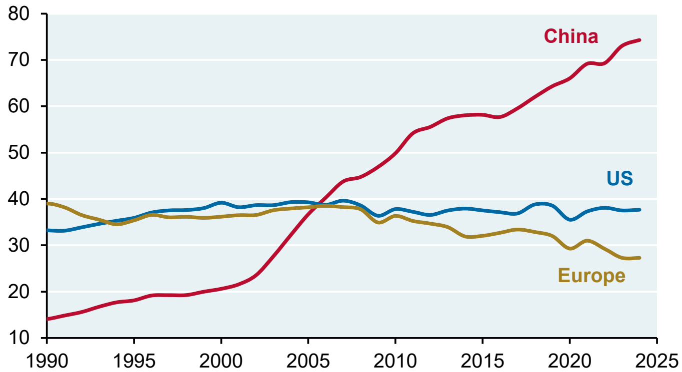
How much of China's rising energy use is due to Western outsourcing? Not very much

China's emissions footprint doesn't change much using a consumption-based approach instead of standard measurements of in-country emissions. As shown on the left, China and India CO_2 emissions only decline by ~10% when using an approach that allocates emissions based on where goods and services are consumed. In other words, Western outsourcing is part of the reason for rising Chinese emissions but only a small part.

Is China approaching an emissions plateau? While Carbon Brief reports that China coal-fired power generation declined in 2025 by 1.6% (the first decline since the 1970's), **electricity only accounts for 55% of Chinese coal consumption; the remainder is coal used for thermal heat, and China is still building coal plants at a breakneck pace**. It's still unclear exactly how China CO_2 emissions will stack up for 2025. It does seem like China might be approaching a CO_2 emissions plateau; how long this plateau would persist before declining is hard to predict, particularly given the expansion of China's coal-to-liquids facilities used to produce synthetic natural gas.

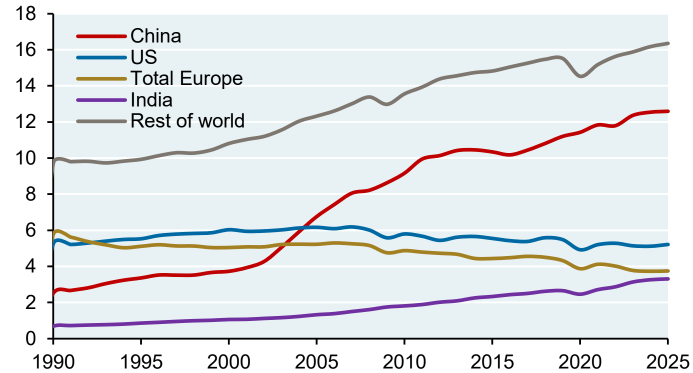
One silver lining: China has become the world's largest carbon *remover* from land use change (mostly from reforestation efforts) after being the second largest land use *emitter* fifty years ago. A recent paper in Nature cites China carbon sinks from reforestation as being underestimated from 1981-2020[21]. That said, such removals are small in context; China's land use removals of 0.25 GT CO_2 per year are pretty small compared to its energy related emissions of 12.3 GT CO_2 per year.

Fossil fuel useful final energy
Exajoules



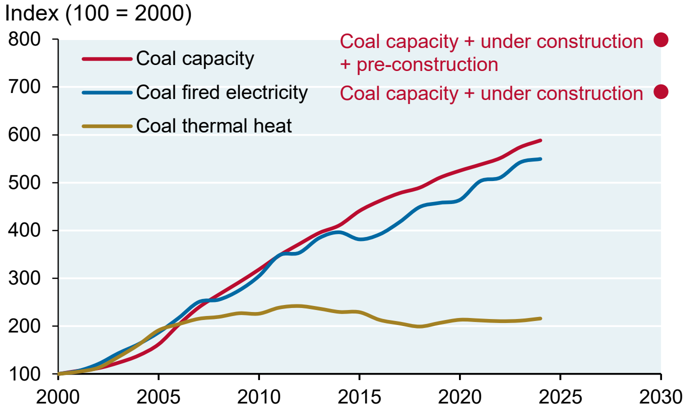
Source: Energy Institute, IEA, JPMAM, 2025

Global CO_2 equivalent emissions from energy, process emissions, methane & flaring, Billion tons



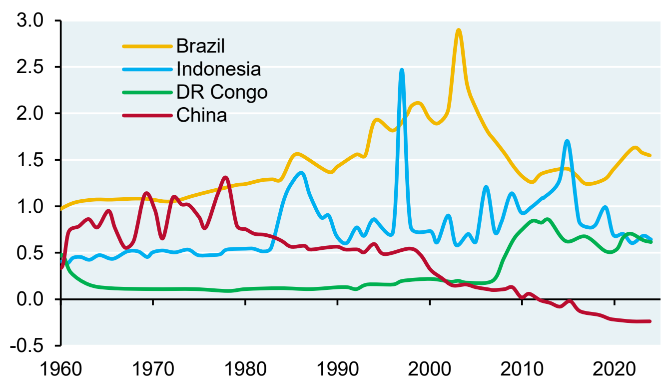
Source: Energy Institute, Global Carbon Project, JPMAM, 2025

China coal tracker
Index (100 = 2000)



Source: Energy Institute, Global Energy Monitor, JPMAM, 2025

Annual CO_2 emissions from land-use change
Gigatonnes of CO_2

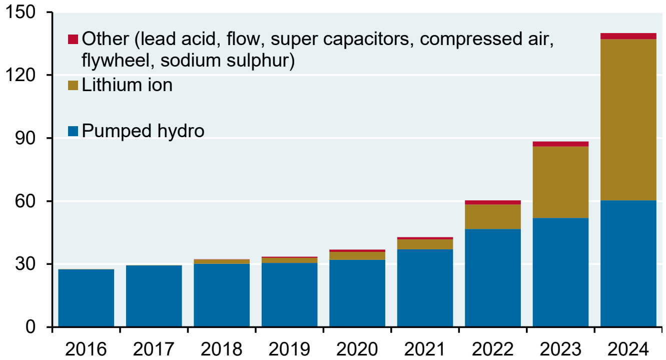


Source: Global Carbon Project, November 13, 2025

[21] "*China's carbon sinks from land-use change underestimated*", Nature Climate Change, Yuan et al, April 2025

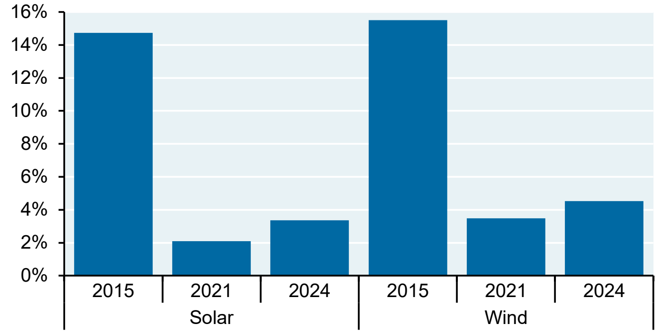
The charts below illustrate the primary drivers of China's renewable additions: energy storage capacity which has reduced solar/wind curtailment since 2015 despite growth in renewable power; the rollout of electric heat pumps; solar module production which represents 75% of global output; the rising EV share of vehicle sales; rising installations of offshore wind; and the addition of high voltage direct current lines.

China energy storage capacity
GW



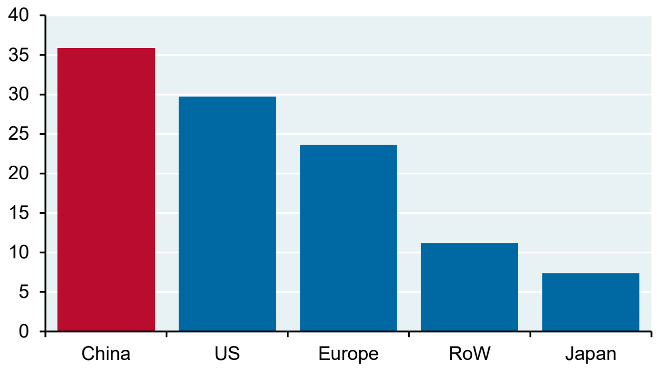
Source: China Energy Storage Association, EMBER, September 2025

China solar and wind curtailment rates
Percent



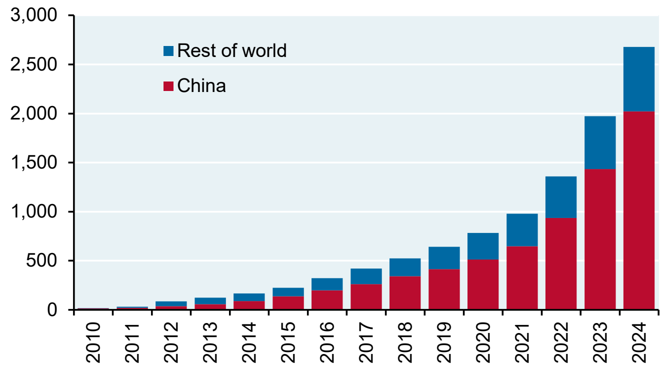
Source: Chinese Renewable Energy Industries Association, EMBER, September 2025

Heat pump sales, 2024
GW



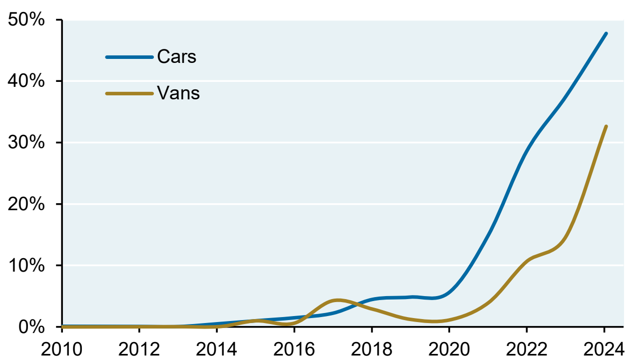
Source: IEA, EMBER, September 2025

Cumulative production of solar modules since 2010
GW



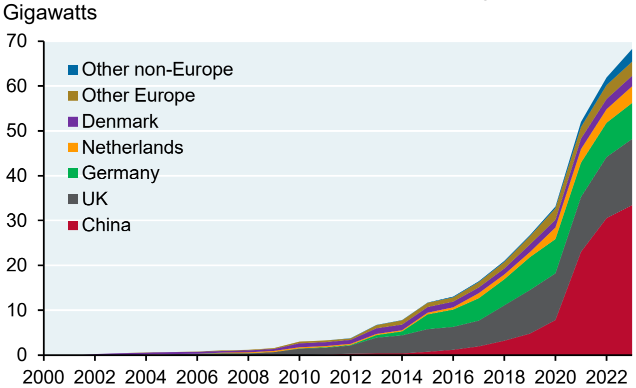
Source: MIIT, IEA, Jäger-Waldau, Fraunhofer, EMBER, September 2025

China electric vehicle share of sales
Percent



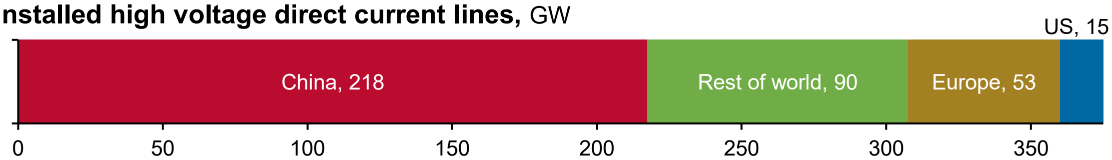
Source: IEA, EMBER, September 2025

Offshore wind cumulative installed capacity
Gigawatts



Source: "Offshore Wind Market Report 2024 Edition", NREL

Installed high voltage direct current lines, GW



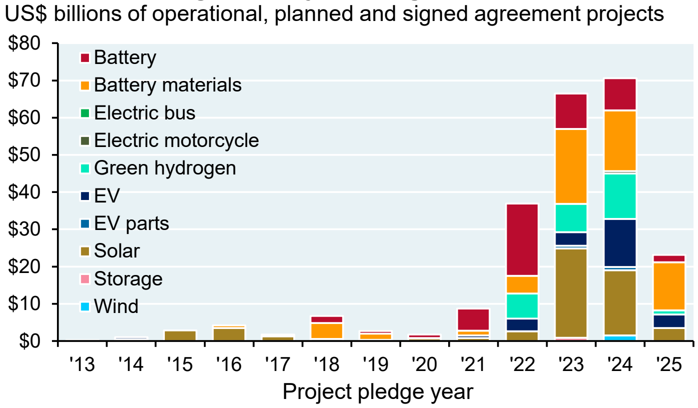
Source: Global Transmission Report, 2024

Exporting the transition

China's exports of solar modules, batteries and EVs are flooding parts of the developed and developing world. Chinese firms have pledged US$225 - $250 billion to green manufacturing projects outside of China, an amount that now surpasses the inflation adjusted value of US aid during the post-WWII Marshall Plan[22]. The chart on the right illustrates how China's production capacity for solar modules, wind turbines, EV battery cells and EVs was much higher than its actual production in 2024. These are startling figures that are (a) encouraging if your perspective is global decarbonization and (b) terrifying if your perspective is the CEO of competing companies elsewhere in the world that are exposed to Chinese competition.

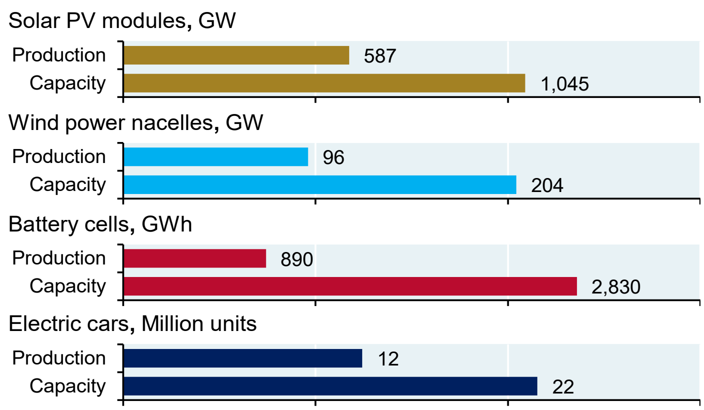
Importing Chinese technology can come with hidden risks. Chinese "Volt Typhoon" hackers hijacked hundreds of routers and used them to infiltrate US transport, telecom, water and electricity networks. Chinese cargo cranes used at US ports were also found with embedded technology that could allow Beijing to remotely control them. Former FBI Director Chris Wray[23]: "China's hackers are positioning on US infrastructure in preparation to wreak havoc and cause real-world harm to US citizens and communities, if and when China decides the time has come to strike"[24].

China overseas green project pledges
US$ billions of operational, planned and signed agreement projects



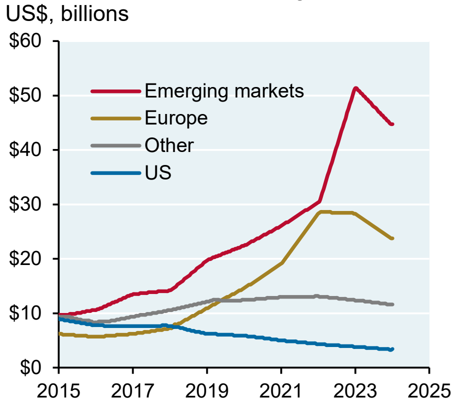
Source: Xue and Larsen (Net Zero Industrial Policy Lab), June 2025

China manufacturing capacity vs production, 2024



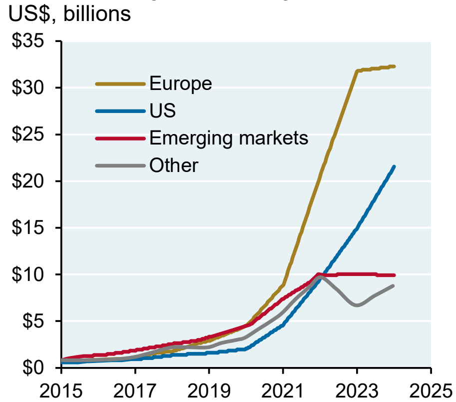
Source: IEA, 2025

China solar PV exports by destination
US$, billions



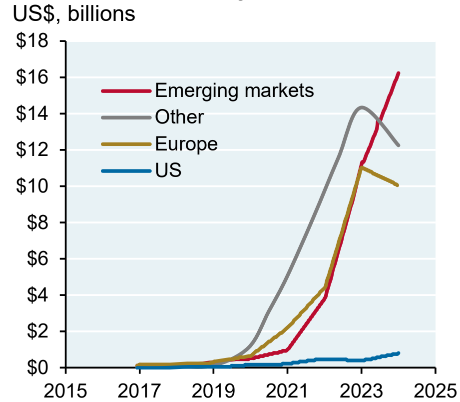
Source: EMBER, September 2025

China battery exports by destination
US$, billions



Source: EMBER, September 2025

China EV exports by destination
US$, billions



Source: EMBER, September 2025

[22] *"China's green leap outward: the rapid scale-up of overseas Chinese clean-tech manufacturing investments"*, Net Zero Industrial Policy Lab, September 2025

[23] Trump fired Christopher Wray in favor of Kash Patel. One lone Republican Senator, Mike Rounds (R-SD) who serves on the Armed Services Committee and Cybersecurity Subcommittee, spoke up in Wray's defense in December 2024 before Wray resigned.

[24] *"Chinese hackers aim to wreak havoc on US critical infrastructure"*, NPR, January 31, 2024

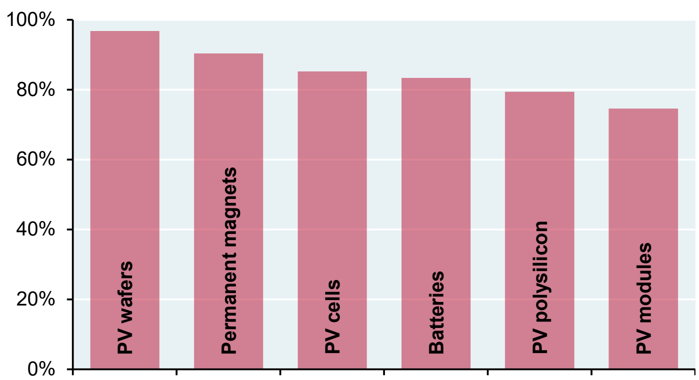
Chinese domination of renewable and critical mineral supply chains

This is widely known but it's worth showing just how dominant China is with respect to production of renewable technology (PV wafers/cells/modules, batteries and magnets), and mining/processing of strategic minerals including rare earths. Another China advantage: as shown in the third chart in the last four stacked bars, some of China's laterite rare earth basins contain a broader mix of minerals than rare earth basins in the US or Russia.

In April 2025 China temporarily cut off rare earth exports to the US. In October, China broadened the scope of its rare earth export controls to require licenses for any product containing more than 0.1% in value of Chinese rare earths, or manufactured using equipment containing Chinese rare earths or related magnets. The regulations include a presumption of denial for military end-uses and close scrutiny on uses related to high-end semiconductor production. The new rules expand the number of specific rare earth minerals covered and also limit the export of rare earth mining and manufacturing equipment from China. China's rare earth rules match what the US imposed for high end chips and semiconductor equipment: a "foreign direct product rule" that controls not only direct exports of a targeted product, but other countries exports that embed that product. If such controls were implemented, impacts would be felt in semiconductor, automotive, electronics, aerospace, defense, robotics, medical imaging, medical equipment and telecom industries[25].

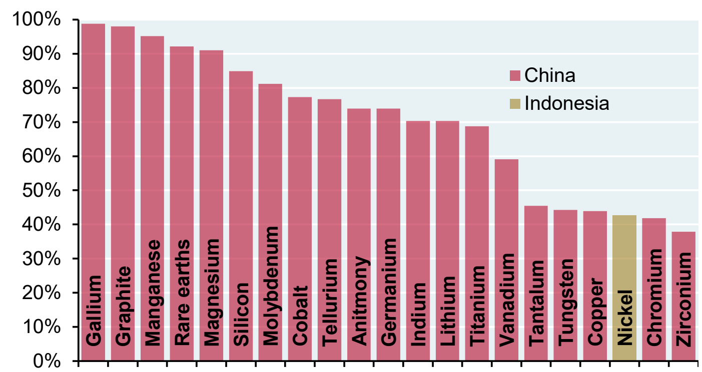
In late October China **paused implementation of rare earth controls** (other than those linked to foreign militaries) in exchange for a reduction in the US fentanyl tariff from 20% to 10% and easing of chip controls, but is still only providing 6 month licenses. China's goals may include further relaxation of controls on US high-end chip exports/manufacturing equipment to China, and rules that would safeguard Chinese foreign investments.

China share of manufacturing capacity by product
Percent



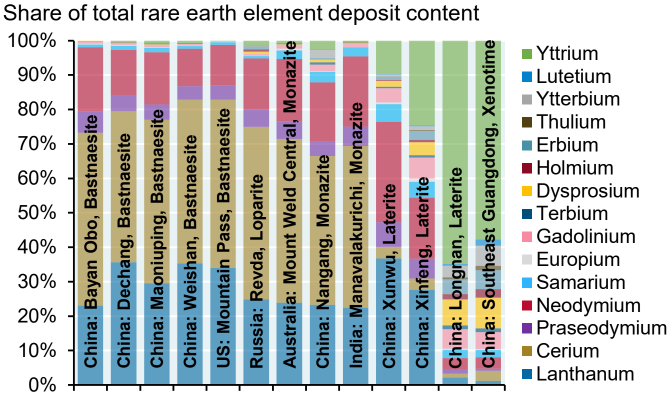
Source: "Global Critical Minerals Outlook 2025", IEA, JPMAM, May 2025

Top producer share of refined strategic mineral output
Percent



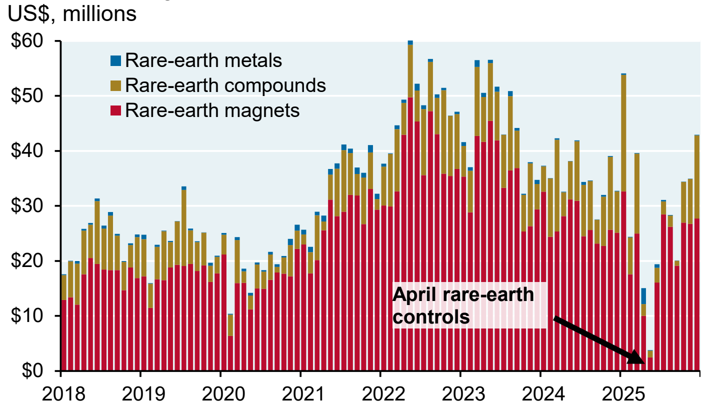
Source: "Global Critical Minerals Outlook 2025", IEA, CRM Alliance, May 2025

Major rare earth element deposits by element
Share of total rare earth element deposit content



Source: US Geological Survey, JPMAM, 2022

China monthly rare earth exports to the US
US$, millions



Source: General Admin. of Customs of China, JPMAM, December 2025

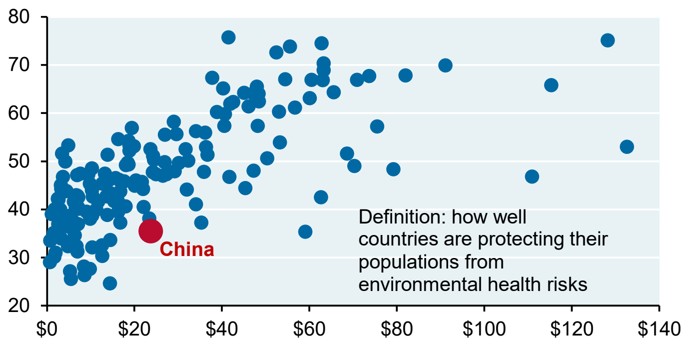
25 There are demonstration projects in the US at Sandia Labs and the DoE National Energy Technology Lab using water, supercritical CO_2 and mild acids to leach rare earth minerals from coal fly ash

It's important not to gloss over the environmental price China pays for critical mineral dominance. Examples include a 4-mile lake of toxic sludge in Northern China that dries out each winter and spreads dust contaminated with lead, cadmium, thorium and other heavy metals, and spreads the same materials into groundwater in the summer. China's cabinet concluded in 2012 that "excessive rare earth mining resulted in landslides, clogged rivers, environmental pollution emergencies, major accidents and disasters, causing great damage to people's safety and health and the environment" [26].

The Big Picture: China has among the worst environmental health scores in the world for a country at its level of economic development. In other words, compared to countries with similar levels of per capita GDP, China's scores are terrible (red dots in the charts). The second chart refers to metallic elements and metalloids that are highly toxic at low concentrations and include lead, mercury, cadmium, chromium, arsenic and thallium. These elements have high density and high atomic weight, leading to their persistence and bioaccumulation in the environment. Heavy metal accumulation in Chinese soil is partially the byproduct of non-ferrous metal mining and other activities related to renewable supply chains. The map shows Chinese cropland concentrations of cadmium; in five provinces (including southern rice growing areas), cadmium levels are well above the 0.5 mg per kg generally accepted safety level for agriculture soil concentrations. On the right: a table of cadmium and lead uptake in rice and wheat crops by province.

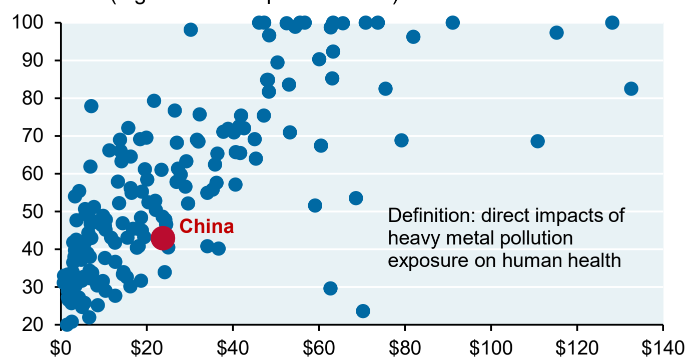
It is jarring to see many green energy advocates so vocal in their admiration for China's progress on renewable energy and EV production while never mentioning this inextricably related issue at all.

China: environmental health score
EPI score (higher = better performance)



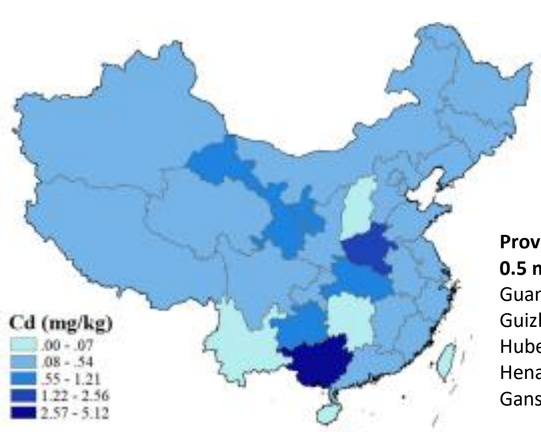
Source: Yale University, CIA Factbook, JPMAM, 2025

China: heavy metals exposure score
EPI score (higher = better performance)



Source: Yale University, CIA Factbook, JPMAM, 2025

Cadmium cropland concentrations by province



Provinces > 0.5 mg/kg:
Guangxi
Guizhou
Hubei
Henan
Gansu

Sichuan University, 2021

Chinese crop heavy metal concentrations

		Cadmium mg/crop kg	Lead mg/crop kg
	Standard	**0.20**	**0.20**
Zhengzhou, Henan	Rice	0.02	**0.53**
Zhengzhou, Henan	Wheat	0.02	**0.99**
Beijing	Wheat	0.04	0.17
Anhul	Rice	**0.21**	0.06
Hebel	Wheat	0.02	0.15
Balyin, Gansu (a)	Wheat	**0.61**	**1.29**
Balyin, Gansu (b)	Wheat	**0.75**	**9.96**

Source: Sichuan University, 2021. Pollutants > standard are bolded

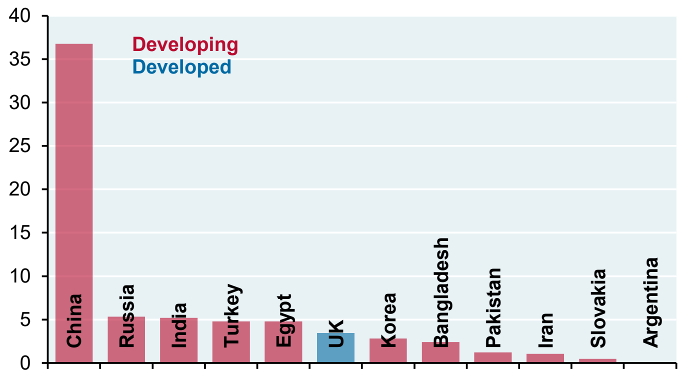
[26] "*China Has Paid a High Price for Its Dominance in Rare Earths*", NYT, June 5, 2025

China and nuclear

China is now the world leader in nuclear power development[27]:

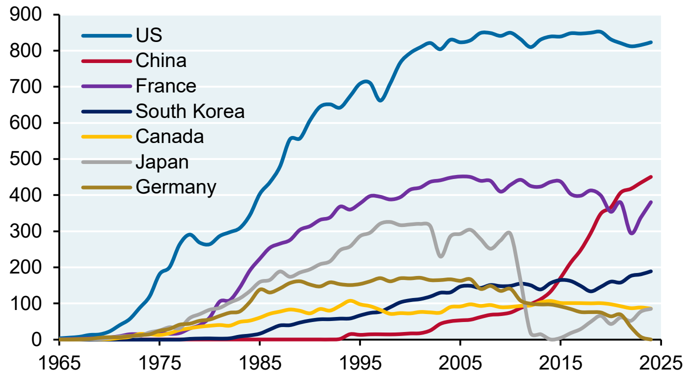
- China has 32 reactors under construction, expects to build 6 to 8 new nuclear plants per year in the future and is on target to surpass the US in nuclear-generated electricity by 2030
- China's most recent plants were completed at 15%-35% of the cost of nuclear plants in the West, and nearly every Chinese project entering into service since 2010 was completed in 7 years or less
- In 2023, China commenced operation of the world's first fourth-generation nuclear plant, the 200 MW gas-cooled Shidaowan-1 in Shandong province, with 90% of required technology developed in China. Reactors such as Shidaowan-1 feature passive systems that don't need to rely on electricity or pumps to shut down in case of failure; use coolants other than water (such as helium); operate at higher temperatures than other reactors, permitting them to generate electricity and hydrogen; and generate less waste
- **To be clear, China's existing plants are based on US expertise**: most of its fleet consists of third-generation reactors initially designed by Westinghouse in the late-1990s which transferred its technology and designs to China in 2008 as part of a contract to build four Chinese reactors. However, China's nuclear success is based on more than just voluntary technology transfer. **What China could not obtain legally, it reportedly stole**: in 2010, hackers working with the Chinese military penetrated Westinghouse's computer systems and stole confidential proprietary technical and design specifications for Westinghouse's AP1000 reactor[28]
- China provides its nuclear industry with low-interest financing, feed-in tariffs and other subsidies, streamlined permitting, accelerated regulatory approval and faster environmental impact assessments

New nuclear plants under development with estimated grid connection dates between 2025-2030, GW of capacity



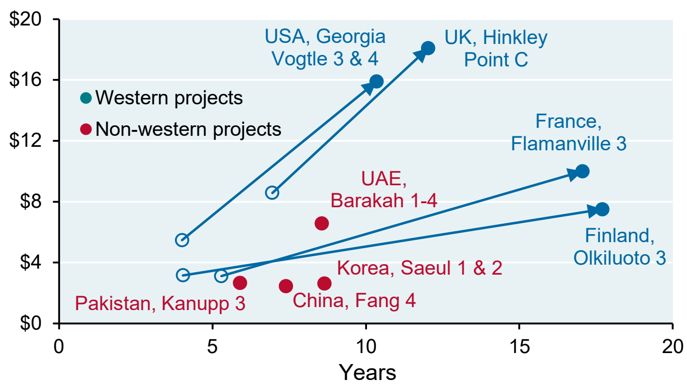
Source: World Nuclear Association, JPMAM, 2025

Nuclear generation by country
Terawatt-hours



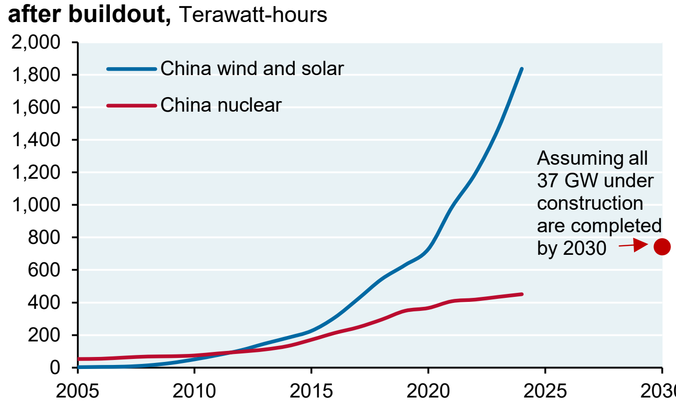
Source: Energy Institute, JPMAM, 2025

Capital cost and construction time of nuclear plants
US$ millions / MW



Source: IEA, Power Reactor System Database, JPMAM, 2025

China nuclear will be a fraction of wind and solar even after buildout, Terawatt-hours



Source: Energy Institute, JPMAM, 2025

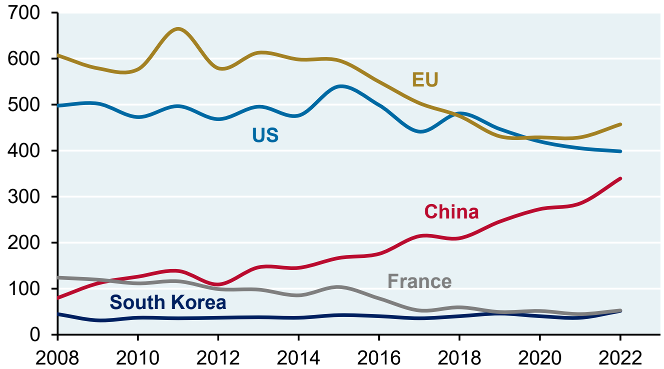
27 *"How Innovative is China in Nuclear Power"*, Information Technology & Innovation Foundation, 2024

28 US Dep't of Justice Press Release, May 19, 2014; "*What were China's hacker spies after?*" CNN, May 19, 2014

Other Chinese **nuclear fission** projects include:

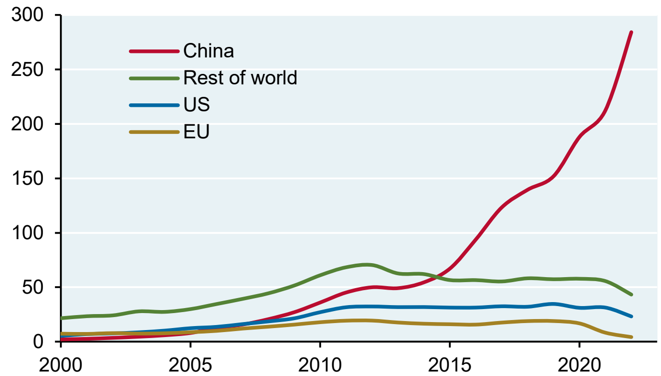
- launch of a molten salt/thorium reactor in the Gobi desert; the 2 MW demonstration plant is reportedly the only operating example in the world to successfully load and use thorium fuel
- a floating nuclear reactor designed to endure a once-in-10,000 years weather event and power oil rigs in the Bohai Sea
- fast neutron reactors designed to produce more plutonium than the uranium and plutonium they consume
- China's Betavolt New Energy Technology Company claims to have developed a miniature atomic battery that can generate electricity for 50 years without charging or maintenance[29]. Such atomic energy batteries utilize energy released by decay of nuclear isotopes and convert it into electrical energy. If successful, such batteries could provide long-lasting power in aerospace, AI equipment, medical equipment, micro-electromechanical systems, advanced sensors drones and robots

Nuclear science and engineering research by country
Count of publications in top 10% of most-cited publications



Source: "How innovative is China in nuclear power", Stephen Ezell, ITIF, 2024

Annual clean energy patent applications by country
Thousands



Source: IRENA, JPMAM, 2025

And on **fusion**[30], China created the China Fusion Corporation to lead development efforts which include 25 government-owned companies, four universities and one private company. Some early milestones:

- China set up the state-owned China Fusion Energy Co. with over $2 billion in funding. Chinese fusion labs aim to replicate the temperatures and pressures inside a nuclear detonation without an actual detonation, making it easier to research and test new weapons materials and systems
- In January 2025, the Experimental Advanced Superconducting Tokamak in China maintained steady-state high-confinement plasma operation for 1,066 seconds, a record subsequently broken by a reactor in France. To be effective, a fusion device must achieve stable operation at high efficiency for thousands of seconds to enable the self-sustaining circulation of plasma that would (in principle) generate continuous power
- In March 2025, China's HL-3 Tokamak successfully maintained an ion temperature of 117 million degrees Celsius. Since atomic nuclei are positively charged and naturally repel one another, extreme heat over 100 million degrees Celsius is needed to give nuclei enough kinetic energy to overcome this repulsion and fuse
- China has developed a fusion research center that's around 50% larger than its US counterpart. China also built the largest known radiation-proof robot designed to maintain fusion reactors. The robot can handle 60 tons of weight with 4 mm positioning precision, something most robots cannot do under radiation conditions

[29] World Nuclear News, January 16, 2024

[30] **Commercialized fusion is still too far away to assess its ultimate cost or feasibility**. Nine Western fusion companies raised capital of $7.5 billion and are trying different things: high temperature superconducting magnets, beam injection to heat and stabilize plasma, magneto-inertial confinement, high current electric pulses to generate intense magnetic fields, sheared-flow-stabilized Z-pinch methods, stellarator designs etc. When a company appears close to sustainable fusion with auditable costs, we will get into the details

China R&D on sodium ion batteries[31]

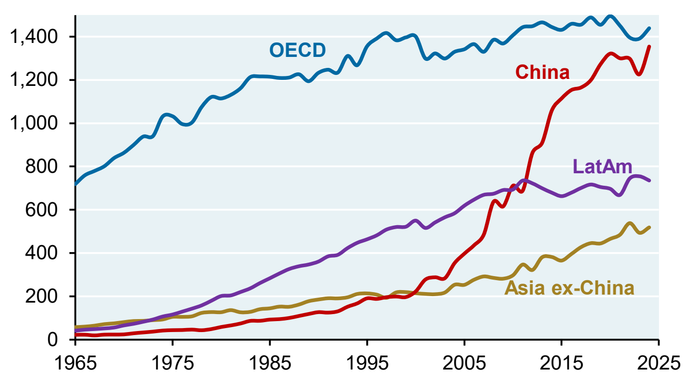
Everything in a sodium ion battery (anode, cathode, current collectors, separator, electrolyte) is geologically abundant. However, the 80% decline in lithium prices since January 2023 shelved some sodium ion efforts (i.e., Stanford spin-out Bedrock Materials). Nevertheless, China is powering ahead:

- China's CATL now offers sodium-ion Naxtra batteries with energy densities of 175 Wh/kg (up from 100-120 Wh/kg 12-18 months ago), nearly equivalent to Li-Ion phosphate batteries. In EVs these batteries can reportedly provide 500 km on a full charge and operate at temperatures of -40°C to +70°C for 10,000 cycles, with both temperature ranges and cycles representing an improvement over Li-Ion and at lower cost
- China Southern Power Grid has commissioned the world's first grid-forming sodium-ion battery system with capacity of 200 MW/400 MWh, cycling up to 580 GWh annually and powering 270,000 households
- To be clear, independent validation of CATL battery performance under real-world conditions has not been established. Lab testing protocols may not accurately reflect field performance degradation, particularly for new chemistries lacking extensive deployment history

From energy sources of the future (fusion, sodium ion) to one of the oldest: hydropower, which generated power for customers in Appleton, Wisconsin as far back as 1882. China has been a large driver of hydropower growth since 1995, a period during which OECD hydropower generation flat-lined.

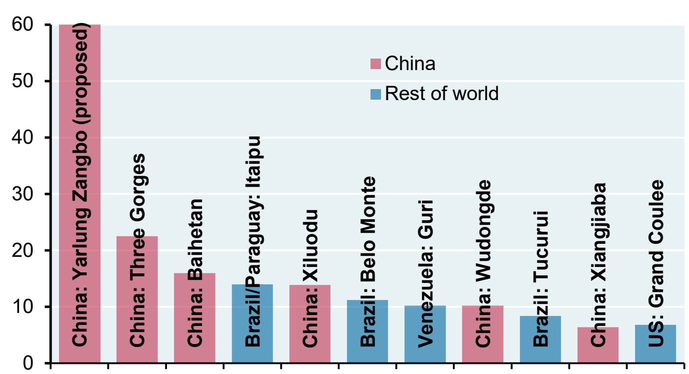
China is preparing to take it up a notch: the mammoth 60 GW Yarlung Zangbo project in Eastern Tibet. China is planning a "run of river" scheme in which part of the river's flow is diverted through a series of 36 km tunnels and turbines before the water rejoins the river further downstream at an elevation that's 2 km lower[32]. China has built similar projects before such as the Jinping II project in Sichuan; this new project is much larger in scale. When completed, the Zangbo project could meet 2%-3% of China's entire electricity consumption each year.

China accounts for 60% of global hydropower growth since 1995 while OECD is flat, Terawatt hours



Source: Energy Institute, JPMAM, 2025

Largest hydroelectric power stations by installed capacity
GW



Source: JPMAM, 2025

[31] *"Sodium-ion battery technology: So near and yet so far"*, S&P Global, June 5, 2025; *"CATL's $19/kWh Sodium-Ion Claims Face Reality Check in $1.82 Billion Market"*, Energy News, September 15, 2025; *"Advanced Energy Storage Market Analysis & Forecast: 2025-2032"*, Coherent Market Insights, June 27, 2025

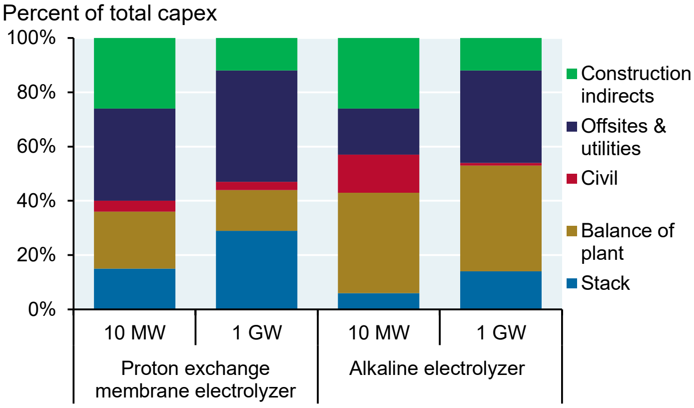
[32] Gavekal Research, "*Trade Deals and Energy Dominance*", August 1, 2025

What about China and green hydrogen? China dominates global production of alkaline electrolyzers with an 85% share and currently operates a small 600 MW fleet of renewable-powered electrolyzers. Some press reports refer to Chinese green hydrogen costs of just $3 per kg[33]. **However, we have reason to believe that real-world green hydrogen costs in China are much higher than that**. The primary reason: balance of plant, engineering and other construction costs can dwarf costs of the electrolyzer stack and are often either excluded or underestimated in hydrogen cost analyses. A quick review of electrolytic hydrogen production:

- Before the process begins, water must first be purified via reverse osmosis to remove minerals. In the case of alkaline electrolysis, pure water is added to a strong potassium hydroxide solution (an electrolyte). Since some water and electrolytes are lost in purge streams to remove contaminants, electrolytes are added to make up for these losses. In PEM units the electrolyte is a solid membrane (and not a liquid solution)
- The electrolysis process which separates water into hydrogen and oxygen is an imperfect one. After the process is complete, water and oxygen in the hydrogen stream must be removed which requires capital equipment (deoxygenation systems and dehydration systems) and the energy to run them
- Around 30% of the electricity used in the electrolysis reaction ends up as unwanted waste heat rather than as hydrogen. The electrolysis process runs best at 70-80 degrees Celsius so any waste heat above that level must be removed, which involves more engineering costs to avoid damage to equipment

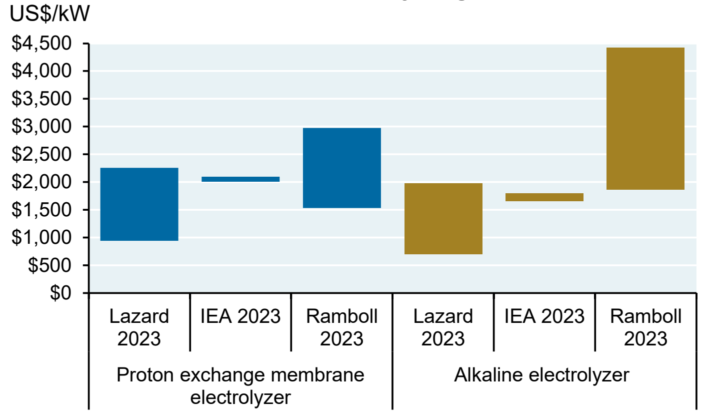
These processes are understood by industrial engineers but some hydrogen cost analyses may not properly reflect them. According to engineering firm Ramboll, **the electrolyzer stack may only account for 5%-30% of electrolyzer capital costs;** note how Ramboll capital cost estimates are much higher than Lazard and the IEA. Using our assumptions, China's all-in green hydrogen costs are closer to $6 per kg than $3[34].

Ramboll capex breakdown estimates, hydrogen plants
Percent of total capex



Source: Ramboll, November 2023

Capex estimates, 10 MW - 1 GW hydrogen plants
US$/kW



Source: Ramboll, November 2023

China's cost of production is not the only obstacle impeding its ability to promote hydrogen adoption at home and abroad. Given difficulties in transporting hydrogen in liquefied form (safety issues and cost of refrigeration) or as ammonia (energy conversion penalties), China's impact on global clean hydrogen adoption may be limited. Around 99%+ of all hydrogen is still produced via fossil fuels; ~99% of all hydrogen is still used as a chemical (for ammonia) or for oil refining rather than for transport, power generation or commercial heating; and most hydrogen is produced where it is consumed given the difficulty of moving it around.

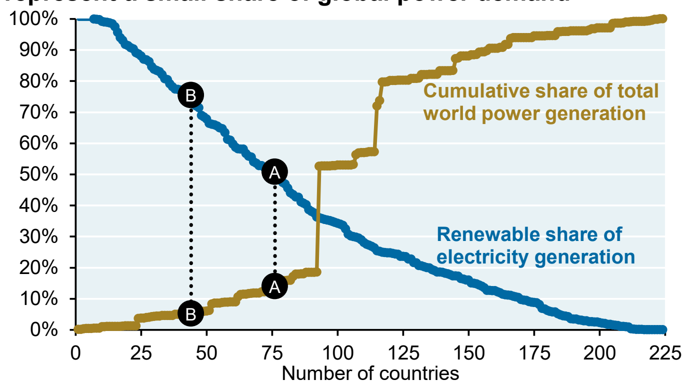
[33] "*Major leap seen for H_2 energy industry*", China Daily, December 9, 2024

[34] Stack capital cost $200 per kW, stack share of total capital cost 15%, 20-year operating life, 7% discount rate, 55 kWh per kg of H_2, 65% annual plant utilization rate, electricity cost of 6 cents per kWh, operating & maintenance costs of 10% of capital cost, stack replacement every 60,000 hours

PUNIs and PIEs: the bizarre fascination with small country transitions with limited relevance for large ones

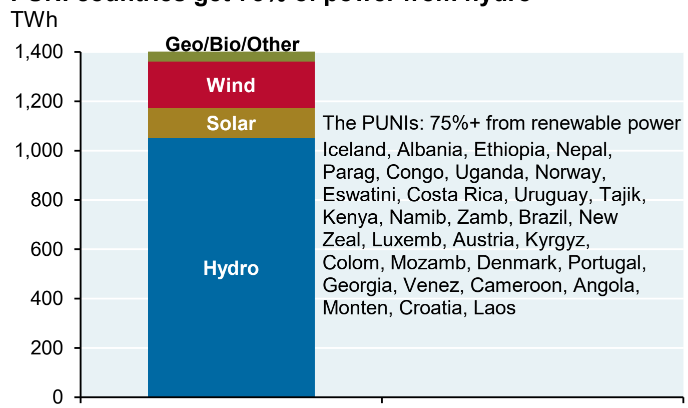
Let's shift from China, the world's biggest energy user, to the some of the smallest. Two years ago I showed the first chart on electricity consumption sorted by renewable generation shares. For example: there are 76 countries with renewable shares over 50% but they only represent 14% of global generation [pt A]. If we narrow the focus to countries with 75%+ renewable shares, they represent just 5% of global generation [pt B]. Hence the "PUNI" acronym for this latter group: countries like Paraguay, Uruguay, Norway and Iceland do not merit the coverage often given to them. One reason for their limited relevance to larger countries: PUNIs get ~75% of their renewable energy from hydropower which is not a boilerplate solution other countries can easily mimic.

PUNI update: countries with high renewable shares still represent a small share of global power demand



Source: EMBER, IRENA, JPMAM, November 2025

PUNI countries get 75% of power from hydro



Source: EMBER, IRENA, JPMAM, November 2025

Within the PUNIs, there's another problem: some are also PIEs, or **Parasitically Irrelevant Examples**. Here's what I mean: countries like Denmark and Portugal don't rely heavily on hydropower and have large shares from wind and/or solar. BUT…**they're also small countries that import large shares of power from neighboring large country grids.** The table on the left shows countries with 50%+ renewable shares and import shares > 25%; for example, Denmark imported 77% (!!) of its gross power needs in 2024. Countries with a lot of intermittent renewables often rely on the kindness of strangers to provide 24/7 power and absorb excess generation. Bigger countries have no such luck; the average import/export reliance of the 15 largest electricity generating countries is **just 1%-2%. Bottom line:** when you see articles and social media posts on the PUNIs and the PIEs, admire their progress but remember their limited relevance to larger countries and the global energy picture.

The PIEs: Parasitically Irrelevant Examples
Countries with >50% renewable power and >25% import reliance, 2024

				Shares of renewable generation			
Country	Renew share of power	Imports share of consump	Exports share of consump	Hydro	Solar	Wind	Geotherm/ Biomass/ Other
Albania	100%	**28%**	41%	97%	3%	0%	0%
Eswatini	99%	**71%**	0%	62%	7%	0%	31%
Namibia	90%	**69%**	6%	76%	23%	1%	0%
Luxembourg	87%	**105%**	21%	4%	36%	39%	21%
Austria	87%	**29%**	40%	66%	16%	14%	3%
Mozambique	84%	**61%**	88%	99%	0%	0%	0%
Denmark	83%	**77%**	66%	0%	16%	71%	14%
Portugal	82%	**28%**	8%	31%	25%	36%	8%
Georgia	81%	**34%**	40%	99%	0%	1%	0%
Montenegro	76%	**199%**	231%	73%	9%	18%	0%
Croatia	76%	**60%**	51%	46%	13%	32%	9%
Latvia	71%	**63%**	47%	68%	17%	5%	9%
Lithuania	68%	**83%**	37%	5%	29%	64%	3%
Switzerland	66%	**46%**	71%	82%	17%	0%	0%
Zimbabwe	65%	**26%**	2%	97%	1%	0%	2%
Estonia	58%	**86%**	41%	0%	38%	46%	16%

Source: EMBER, IRENA, IEA, JPMAM, November 2025

15 largest electricity generating countries

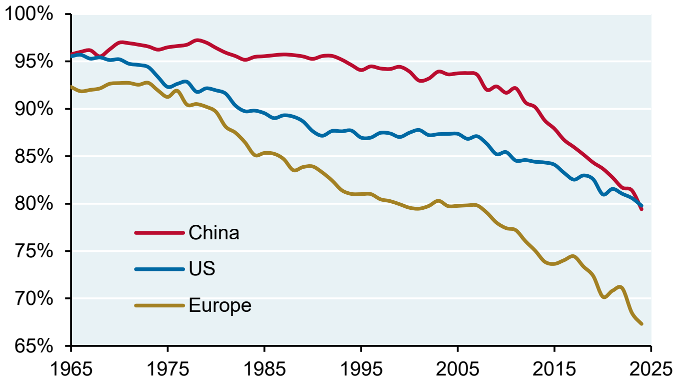
Country	Total elec generation (TWh)	Imports share of consump	Exports share of consump
China	10,341	0%	0%
United States	4,486	1%	0%
India	1,821	0%	1%
Russia	1,154	0%	2%
Japan	965	0%	0%
Brazil	699	2%	0%
Canada	625	4%	6%
South Korea	590	0%	0%
France	522	4%	25%
Germany	481	17%	12%
Saudi Arabia	441	0%	0%
Turkey	354	1%	1%
Mexico	352	1%	1%
Vietnam	316	2%	0%
Taiwan	284	0%	0%

Source: EMBER, IRENA, IEA, JPMAM, November 2025

The primary energy fallacy, the quest for better measures of energy consumption and the future of the EIA

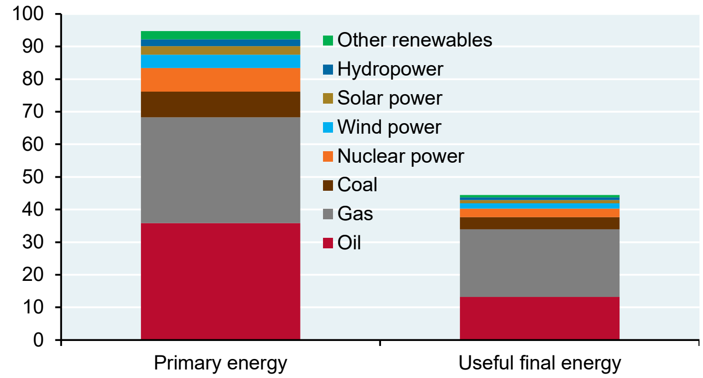
Many analysts use primary energy figures to assess the pace of the energy transition. Primary energy measures the raw energy content in coal, gas, oil and biomass and also measures the heat content in a nuclear reactor or geothermal facility before conversion to electric power. Primary energy is often shown in joules[35], allowing for aggregation and comparison across energy sources. One example: the gradually falling fossil fuel share of primary energy consumption shown on the left, with faster declines in China and Europe than in the US.

Fossil fuels as a share of primary energy
Percent



Source: Energy Institute, JPMAM, 2025

Primary vs Useful Final Energy, US, 2024
Exajoules



Source: Energy Institute, IEA, JPMAM, 2025

The problem: most fossil fuel primary energy is lost as waste heat in conversion, overstating the amount consumed by end users. Energy is lost as waste heat in conversion of fuel energy to motion in internal combustion engines, and in conversion of heat to electricity. For example, if you use primary energy to estimate how much electric power is needed to replace oil in passenger cars, you would overestimate the power needed since electric motors are 80%-90% efficient at converting electricity to motion compared to 18% efficiency for gasoline cars (efficiency is modestly higher for diesel trucks, planes and ships). A better approach: estimate the energy net of waste heat that is actually consumed by end-users; this would help avoid overly high projections of fossil fuel demand in a more electrified world due to this "primary energy fallacy".

A few years ago I constructed a measure of useful final energy (UFE) that I use for my energy charts:

- Determine the amount of oil, gas and coal used for transport, electricity generation and heat by country in primary energy terms (in joules)
- Subtract the joules of waste heat lost from each fuel's primary energy based on their respective energy conversion efficiencies (i.e., account for waste heat lost in passenger car, truck, plane and maritime internal combustion engines, gas and coal turbine plants, gas boilers and furnaces, coal boilers and furnaces, etc)
- Subtract the joules of energy used in the extraction, refining and distribution of oil, coal and natural gas
- Subtract the joules of energy used in the transmission and distribution of electricity
- Subtract the joules of energy used by balance of plant functions in nuclear plants

With this approach we can get **closer**[36] to useful final energy actually consumed by end users (see Appendix I for details). One example: as shown above, the US consumed 45 exajoules (EJ) of useful final energy in 2024 compared to 95 EJ of primary energy. We compute useful final energy for countries representing 87% of global energy consumption. This effort is certainly a better use of my time than the virtue signaling I see on LinkedIn from people who copy and paste Sankey diagrams to prove that they understand the concept of heat loss.

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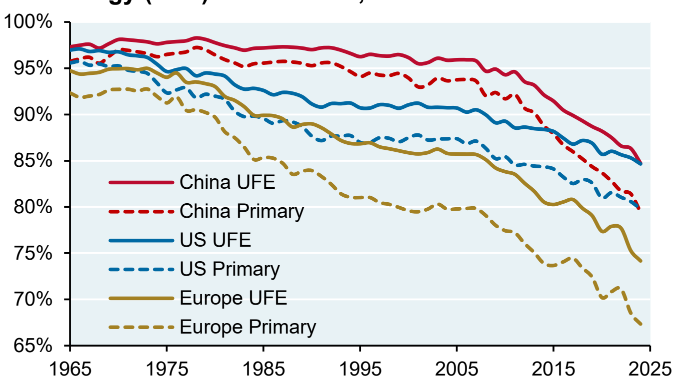
[35] A joule is equivalent to the work done by a force of one newton that moves an object one meter, and is also equal to the energy used by a 1-watt device for one second

[36] Note that I said "**closer**" and not "all the way there". There are more second and third derivative adjustments that could also be made. For the manufactured outrage crowd: I look forward to seeing your version of this concept applied to 87% of global energy consumption if you think this one is not good enough

So…how different is that first chart on the fossil fuel share of energy consumption when using useful final energy instead of primary energy? **Not that different, as shown below**. How can this be? The answer is simple: when the Energy Institute and other aggregators compute primary energy by fuel, they typically gross up electricity from renewables and nuclear power to an "input-equivalent" assuming ~40% conversion efficiency of electricity generation in turbines. **In other words, instead of scaling fossil fuels *down* to useful final energy (my approach), they scale renewable and nuclear power *up* to be more comparable with fossil fuels in primary energy terms.** It's a simplistic assumption since fossil fuels are used for more than just power generation, but it's one way of capturing the fact that a lot of fossil fuel primary energy is lost as waste heat in conversion. I wonder how many "primary energy fallacy" zealots have ever stopped to notice this.

Bottom line: primary energy overstates the energy required in a more electrified world. **BUT**: statistics based on primary energy can still convey useful information if waste heat assumptions are made… which is exactly what most published fossil fuel primary energy ratios do. Decarbonization of energy use is proceeding at roughly the same pace whether you use a primary energy lens or a useful final energy lens, with a faster pace of decline in China and Europe than in the US.

Fossil fuel shares using primary energy and useful final energy (UFE) calculations, Percent



Source: Energy Institute, IEA, JPMAM, 2025

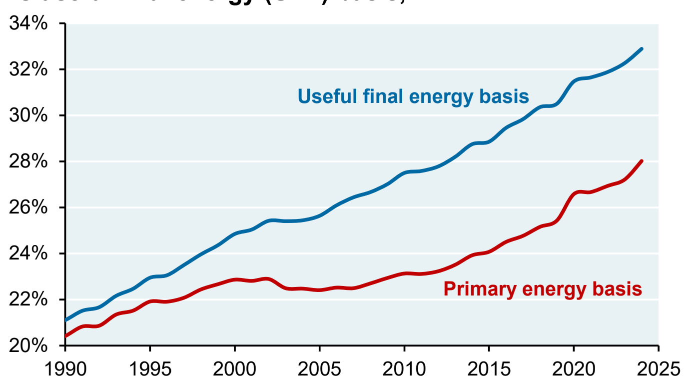
If you're concerned about misleading energy data, be careful when reading anything from Marc Jacobson at Stanford. Jacobson claimed that in California, "wind-water-solar electricity exceeded 100% of demand for a record 98 out of 116 days" from March to June 2024. Sounds great, but Jacobson included in his count of 98 days any day when wind-water-solar accounted for 100% of demand for as little as 5 minutes (!!) during that day, with an average of ~5 hours per day over his entire time sample. **OK, but what about the need to meet power demand during the other 19 hours in the day?** Jacobson's methodology is the equivalent of a vegan who swears off meat but only in between meals. If Jacobson's misleading approach were used by a company in the context of its GAAP financial statements, I imagine they might be reported to the SEC.

Does that mean that useful final energy figures aren't telling us anything new or different? Not at all; there's something important that useful final energy figures show, and it has to do with electrification and a social media post by US Energy Secretary Chris Wright.

A solar tweetstorm. In August 2025, Secretary Wright posted something to the effect that covering the world in solar panels would only generate 20% of world energy needs. Energy analysts pounced from all corners since taken at face value, Wright's statement made little sense. Energy density[37] shows that an area the size of New Mexico would need to be entirely covered with solar panels to produce enough *electricity* to meet global needs, and that an area the size of Venezuela would need to be covered with solar panels to produce enough *final energy* to meet global needs, assuming the extreme hypothetical that all energy uses were electrified somehow. Billions of dollars in above-ground and undersea HVDC transmission investment would be needed to get power to final users, but you get the point.

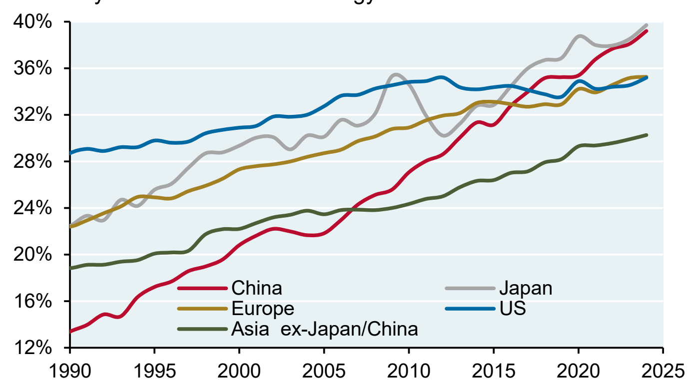
The broader issue Wright was trying to raise is that all the solar power in the world won't radically change things if electricity is just 20% of total energy consumption. Using a primary energy lens, I can see why Wright thinks that (although our primary energy electrification figure is higher at ~28%). But when using a useful final energy lens, the electrification of global energy use is higher at ~32% and rising. Bottom line: I agree with Secretary Wright that there should be more focus on total energy consumption and not just power generation since the latter is still just one third of the former. But as shown on the right, China and Japan are now making faster progress on electrification than the US. And of the 25 countries with the largest useful final energy consumption, the US ranks #22 with respect to the increase in electrification since 2010; only Germany, Canada and South Africa saw smaller gains.

Electrification of global energy use, primary energy basis vs useful final energy (UFE) basis, Percent



Source: Energy Institute, IEA, JPMAM, 2025

Electrification: China and Japan power ahead
Electricity share of useful final energy



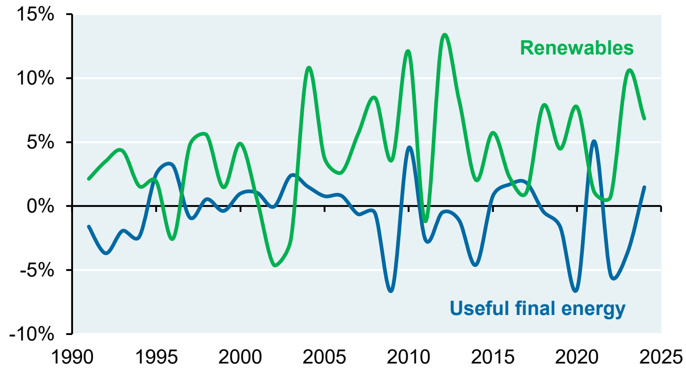
Source: Energy Institute, IEA, JPMAM, 2025

[37] The most important assumption required is **solar power energy density** which Lawrence Berkeley National Laboratory estimated at 394 MWh per acre per year in 2022 for solar PV tracking. The LBNL sample consisted of 736 plants totaling 36 GW-DC that went online from 2007-2019 across 38 US states. The sample included 92% of all utility-scale PV plants that became operational over this 13-year period.

Nuclear fission energy density is 50,000 to 90,000 MWh per acre and dwarfs that of solar power. But when it comes to the real-world cost per MWh of sustainable baseload power, nuclear still faces challenges on that front in Western countries, a topic which we discuss every year

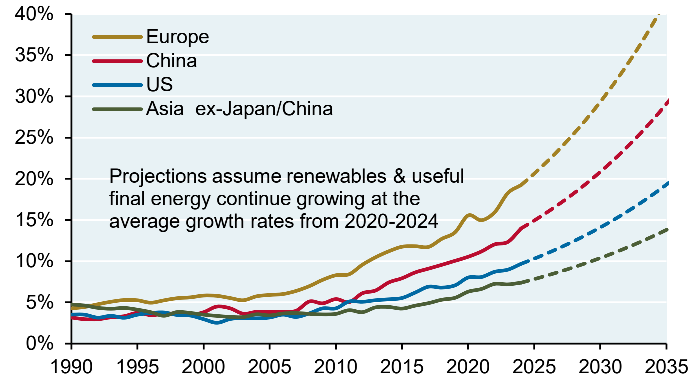
How quickly might the renewable share of useful final energy rise over the next decade? In Europe, renewable energy is growing much faster than usable final energy as shown on the left. If the pace of both remained roughly the same, Europe would increase its renewable share of useful final energy from 20% in 2025 to 40% in 2035, with China at 30% and the US at 20%.

Europe renewables vs useful final energy: annual growth
y/y growth, percent



Source: Energy Institute, IEA, JPMAM, 2025

Renewable share of useful final energy
Percent

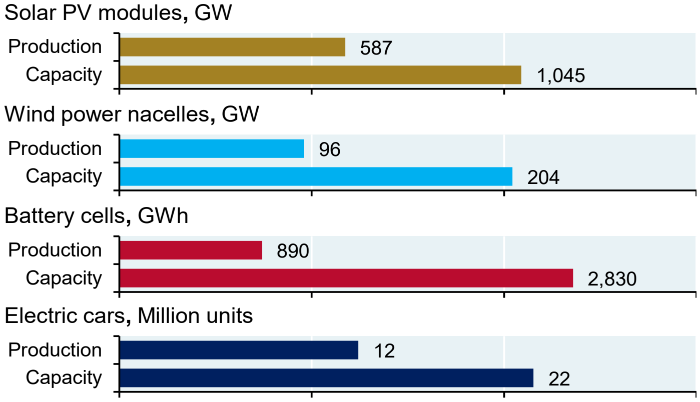


Source: Energy Institute, IEA, JPMAM, 2025

Are we at a tipping point of a faster transition? China is exporting transition technology to the rest of the world given its excess capacity shown on the left. The trend is also global: of all power capacity additions in 2024 and 2025, 90%+ have been renewable rather than fossil fuels, as shown on the right.

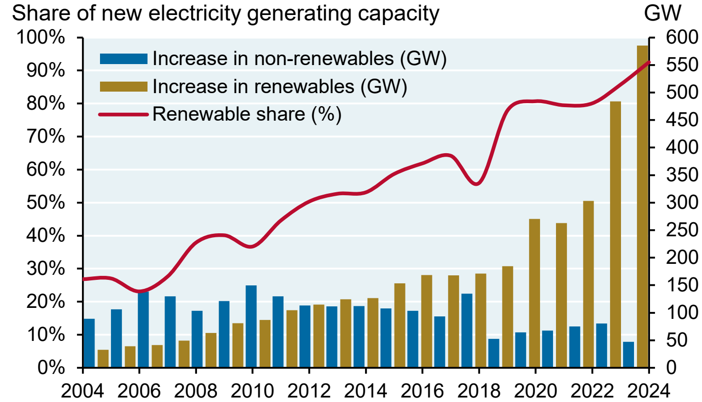
Rapid energy transitions can occur but normally require large improvements in cost, time and energy. Example: the shift in steel production from open hearth furnaces to basic oxygen furnaces and electric arc furnaces. This transition accelerated during the 1970's when energy prices soared and took place in just 20 years. The catalyst: new technology cut steel production times to **less than a tenth** of open-hearth furnaces, allowing for 80%-90% energy savings[38]. The lack of such cost/time savings this time around is why trillions of dollars in subsidies are needed to keep the global transition moving given the general absence of a carbon tax[39].

China manufacturing capacity vs production, 2024



Source: IEA, 2025

Renewable share of annual power capacity expansion
Share of new electricity generating capacity



Source: IRENA, Clean Technica, March 2025

[38] "*Energy Use and CO_2 Emissions in the Steel Sector in Key Developing Countries*", LBNL, April 2001, Table 1; "*Steel production and energy*", Encyclopedia of Energy, Volume 5, 2005

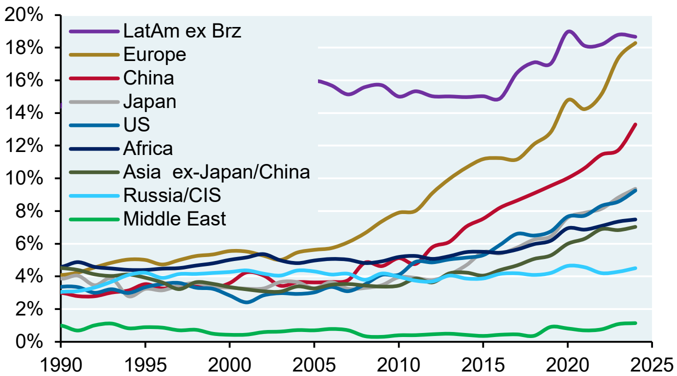
[39] While 28% of global CO_2 emissions are covered by carbon taxes or some kind of emissions trading system, after all the exemptions and carveouts, the emissions-weighted carbon price in countries with carbon taxes/ETS is only $19 per tonne (Source: World Bank 2025 carbon pricing report)

No matter what side you're on, we all need good data from places like the EIA

Primary energy fallacy and useful final energy debates are important since they touch on a third rail topic: how much investment countries still need in natural gas production/distribution or imports, and the related issue of stranded asset risk. I believe that natural gas investment is still needed based on the pace of change shown in the first chart below but I can see why some people disagree. No matter what side you're on, we all need good data on which to base our assessments but I fear that might get harder.

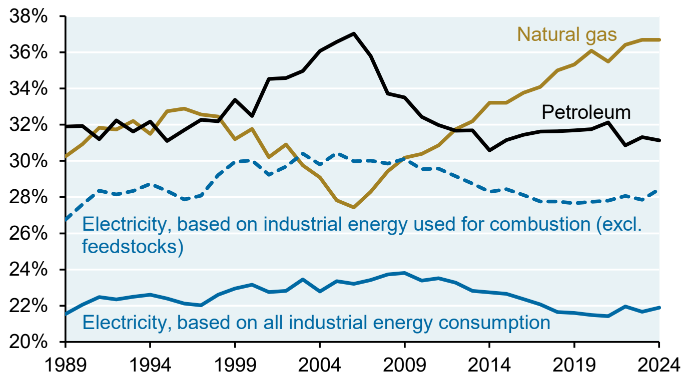
DOGE reduced the EIA workforce by one third as of August 2025, and the EIA also came under fire from the Administration for some of its projections. The right-of-center *National Interest* published a piece expressing support for the EIA[40], widely known as the gold standard for energy statistics. I agree: the second chart shows the slow pace of electrification of US industrial energy use, a chart that would be impossible to create without EIA researchers and databases. I suspect that some people who indiscriminately cut EIA funding are opposed to distribution of information since like in the Dark Ages, their passions and convictions would rule the day instead. Or in the case of DOGE, agencies that are defunded can appear linked to whom they were regulating[41].

Decarbonization has been a mostly linear industrial transition since 2010, Renewable share of useful final energy



Source: Energy Institute, IEA, JPMAM, 2025

Energy shares of US industrial final energy consumption
% of total



Source: EIA, JPMAM, 2024

One example of why the EIA matters: I need all these EIA tables to produce the chart on the right
Monthly Energy Review, Table 2.4: Industrial sector energy consumption
Monthly Energy Review, Table 7.2c: Electricity net generation: commercial and industrial sectors
Monthly Energy Review, Table 7.3c: Consumption of selected combustible fuels for electricity generation
Monthly Energy Review, Table 1.13b: Heat content of non-combustion use of fossil fuels
Monthly Energy Review, Tables A3-A5: Approximate heat content of petroleum, gas and coal
Electric Power Monthly, Table 1.2D: Net generation by energy source, industrial sector

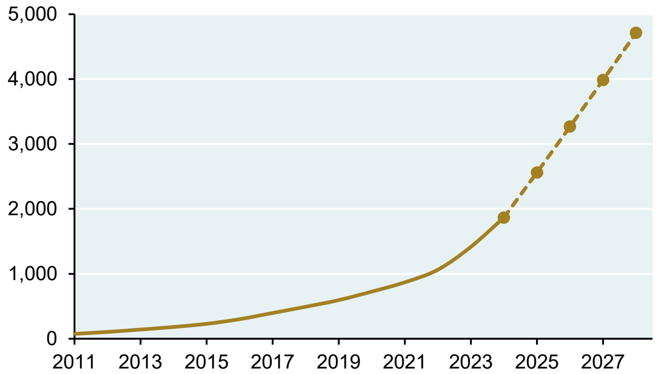
40 "*A Death of Energy Statistics We Can Trust*", National Interest, former EIA Director Adam Sieminski, July 2025

41 DOGE cut staffing at the EPA which regulates Tesla; DOGE cuts to the National Highway Traffic Safety Administration disproportionately targeted the division which oversees autonomous vehicles like Tesla's; and USAID had launched an investigation into its relationship with Starlink before it was effectively dismantled. Other agencies affected by DOGE cuts that were also investigating Musk according to a February 13, 2025 House Judiciary Committee press release include the Dept's of Labor, Transportation, Agriculture, Interior, Justice and Defense, the Consumer Finance Protection Bureau and the Securities and Exchange Commission

Heliocentrism update: solar adoption continues to rise, courtesy of unprofitable Chinese solar companies

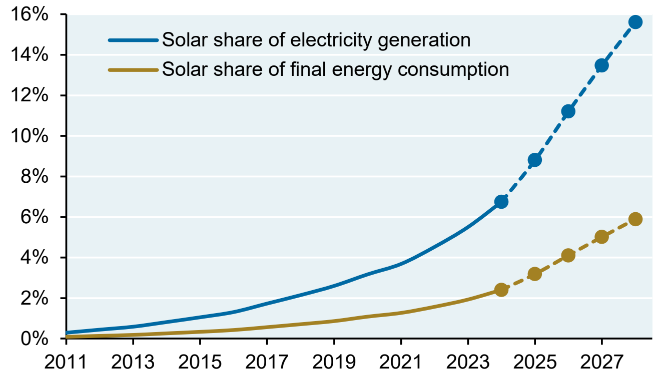
Last year's energy paper was titled "Heliocentrism" and focused on rising global solar capacity and generation. Solar adoption continues to climb as illustrated below. While solar capital costs have declined everywhere, the third and fourth charts highlight how costs are much cheaper in China. The last chart illustrates the increased pairing of solar power with battery storage in the US.

Global solar capacity
GW



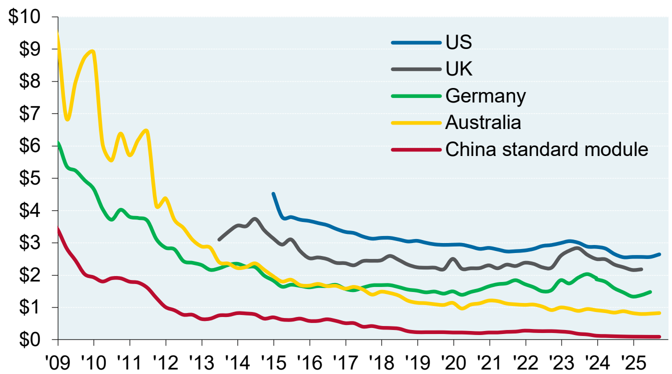
Source: Energy Institute, BloombergNEF, JPMAM, 2025

Solar shares of global electricity and useful final energy
Percent



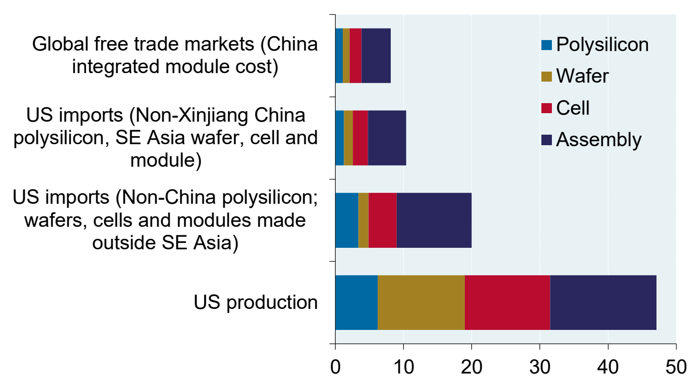
Source: Energy Institute, IEA, BloombergNEF, JPMAM, 2025

Residential solar capital costs
US$ per watt (DC)



Source: BloombergNEF, Q3 2025

Estimated pre-subsidy costs for US, China and Southeast Asia-made modules, end of 2025, US$, cents per watt

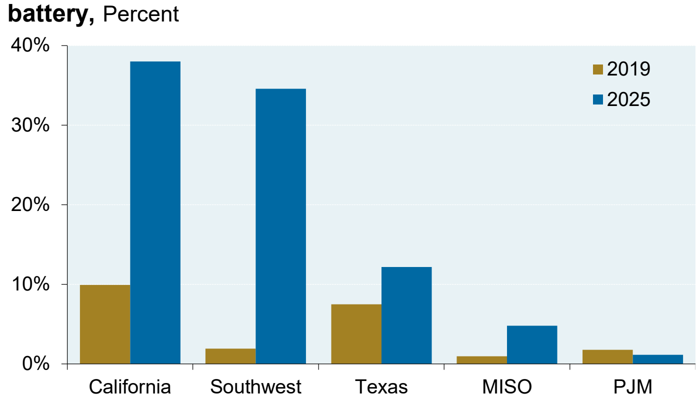


Source: BloombergNEF, Q3 2025

Solar grade polysilicon price
US$ per kilogram

Source: Bloomberg, JPMAM, February 11, 2026

Share of cumulative utility scale PV capacity paired with a battery, Percent

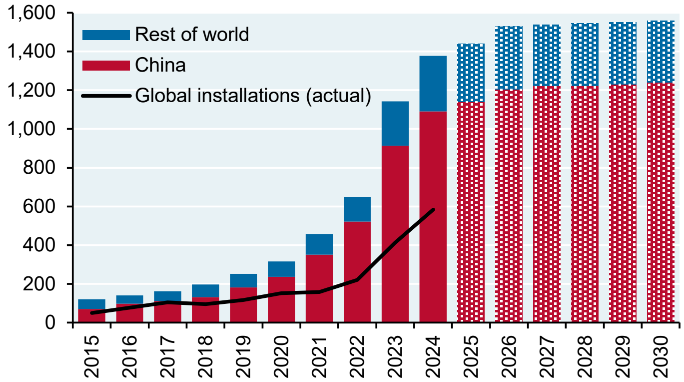


Source: BloombergNEF, April 2025

The solar surge looks set to continue given Chinese overcapacity. China's solar economics would not last long in most Western countries given the negative margins involved; the chart on the right shows solar profitability by company, and Chinese ones are all in the red besides DMEGC and CSI Solar. This bears watching; as shown in the third chart, Chinese solar stocks began to rise in October 2025 amid discussions that authorities would enact capacity controls due to distress in the solar sector. If so, Chinese overcapacity may not be permanent.

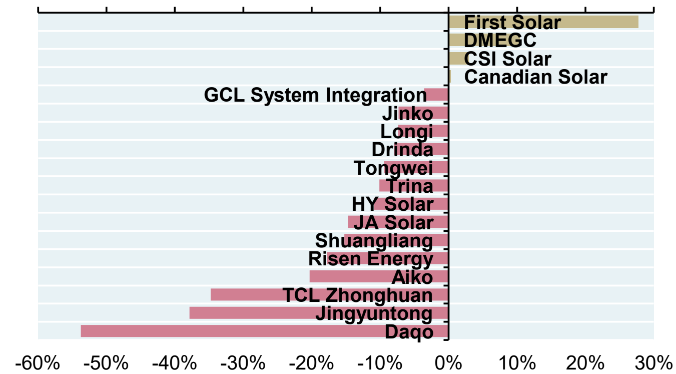
The US installed 35 GW of utility scale solar capacity in 2025, slightly less than in 2024. While the US now has operational capacity to produce polysilicon and to assemble modules from cells, the US still relies substantially on cell imports from Chinese-owned factories in Vietnam, Malaysia, Thailand and Cambodia.

Global solar manufacturing capacity vs installations
GW



Source: EMBER, 2025

Net profit margin of select listed solar companies
Percent, trailing 12 months

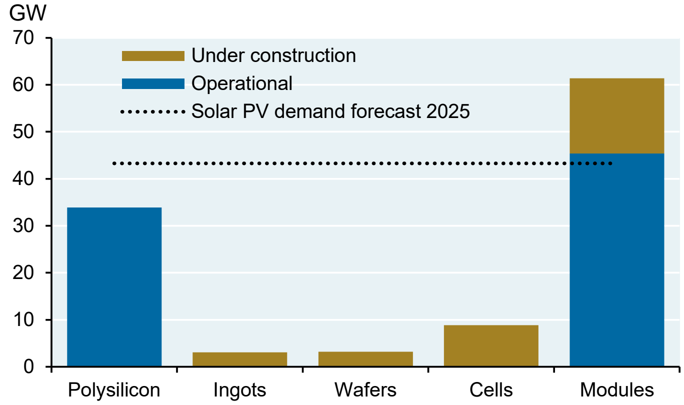


Source: Bloomberg, JPMAM, Q3 2025

China CSI photovoltaic stock index
Index (1,000 = December 2012)

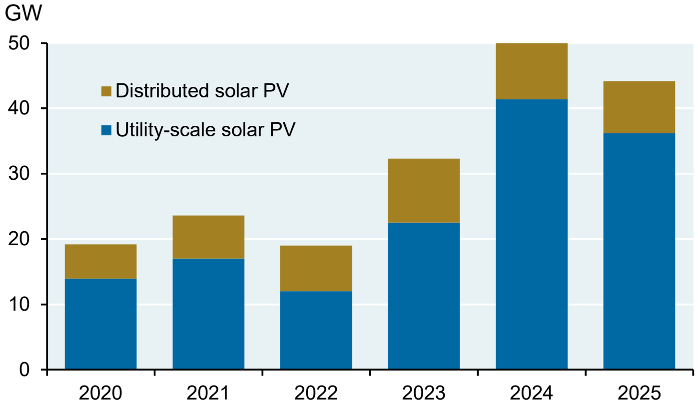
Source: Bloomberg, JPMAM, January 2026

US solar manufacturing capacity
GW



Source: SEIA, S&P Global Commodity Insights, October 2024

United States net solar capacity additions by type
GW

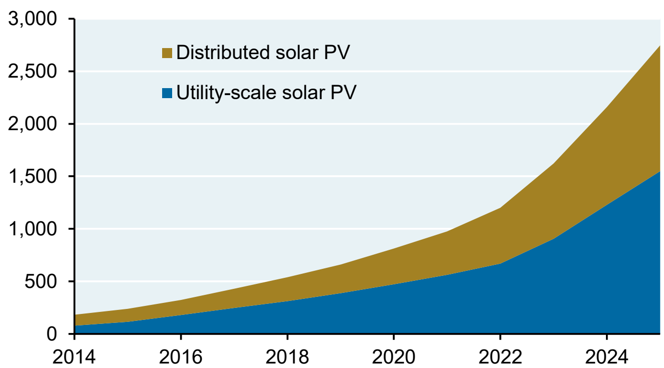


Source: IEA, JPMAM, 2025

The important undercurrent taking place: distributed (rooftop) solar power is keeping pace with installation of utility scale applications. The first chart shows the increase in distributed and utility scale capacity, the second shows the latest breakdown by country while the third chart shows the pace of investment tilting to distributed solar.

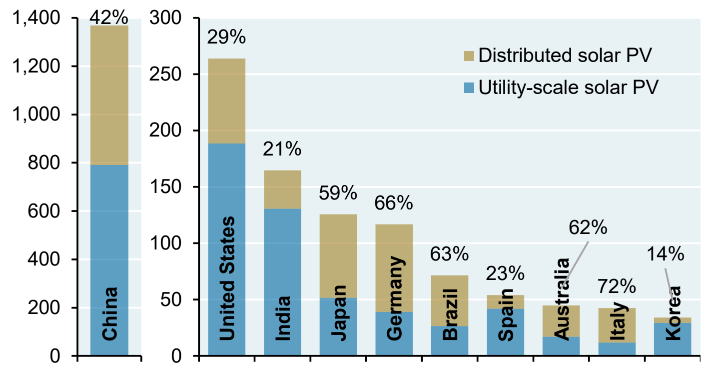
The fourth chart shows best-in-class efficiency of standard silicon multi-crystalline and heterostructure solar cells relative to silicon cells layered with **perovskite**. While cells with perovskite more efficiently convert sunlight to electricity at low extra cost, this benefit is offset by faster degradation from photo-bleaching, heat and humidity, reducing the panel's lifespan and energy generation potential[42]. It takes a PV cell with perovskite less than a year to degrade to 80% of its starting efficiency compared to the industry standard of ~20 years for commercially sold silicon cells[43]. Shorter lifespans increase cost of ownership due to the need for frequent replacements or repairs, a problem that is preventing perovskite cells from being widely adopted[44].

Global solar capacity by type
GW



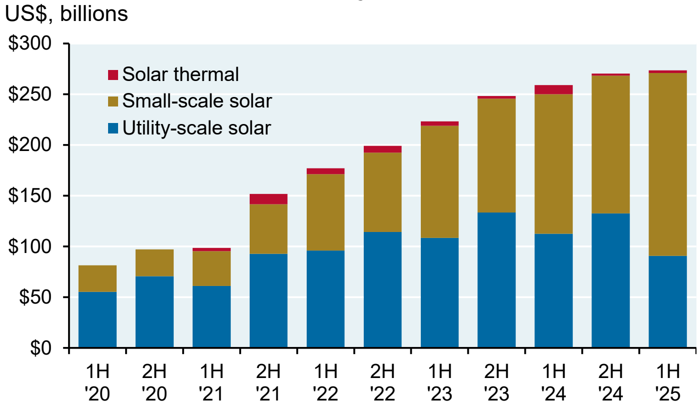
Source: IEA, JPMAM, 2025

2025 solar capacity by top ten solar capacity countries
GW, with % share of distributed solar PV



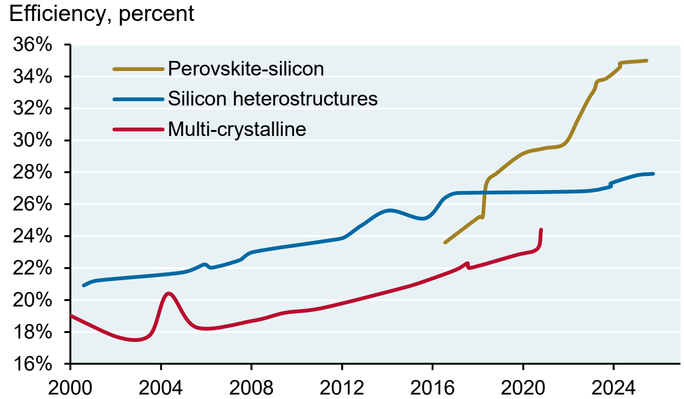
Source: IEA, JPMAM, 2025

Global investment in solar projects
US$, billions



Source: BNEF, JPMAM, 2025

Best in class solar research-cell efficiency
Efficiency, percent



Source: National Laboratory of the Rockies, DOE, JPMAM, 2025

Note: PV cell efficiency measures the ability to convert sunlight to power. This differs from capacity factors which measure the amount of generation over a given period compared to its maximum potential according to nameplate capacity. LBNL's 2025 Utility Scale Solar report cites median capacity factors for tracking panels of 23% in third quartile irradiance locations and 29% in top quartile irradiance locations.

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[42] *"Durability is more important than record-breaking solar cell efficiencies",* Solar Power World, Nov 21, 2024

[43] "*How ISOS protocols are used to assess perovskite solar stability*", Fluxim, March 11, 2022; "*Perovskite solar cell efficiency, stability and scalability*", Khatoon et al, Materials Science for Energy Technologies, May 8, 2023

[44] *"Major challenges for commercialization of perovskite solar cells",* Energy Reports, June 2025

The jury is still out: the quest for affordable small modular reactors, the war on science and Germany's regret

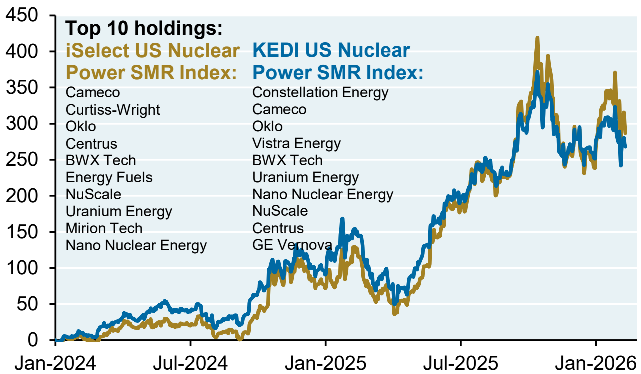
This section could either have been 30 pages or 3 pages given all the complexities, so I opted for 3 since we're analyzing something for which there's no economic proof of concept yet. With enough money, time and regulatory approvals, SMRs can certainly be built. **The question is whether they would be affordable which I define as levelized costs of $125 - $130 per MWh in current dollars**. For context, the levelized cost of a combined cycle gas plant run at 90% utilization would range from $55 per MWh ($2,500 per kW, $3.5 gas and 7.7% discount rate) to $85 per MWh ($3,000 per kW, $5.0 gas and 11% discount rate).

Latest developments: investors are convinced SMRs can deliver

Investors are optimistic about SMR prospects; even after the 2025 correction in SMR stocks, two different SMR indexes still more than doubled over the year. The SMR sector raised $1.3 billion in funding in 2025 through June; 50%-60% has been raised in the US since 2020. The largest rounds were TerraPower's $650 mm Series C, X-Energy's $200 mm Series C and its $700 mm D round in Q4. The remainder are a mix of seed, pre-seed, early-stage and late-stage investments.

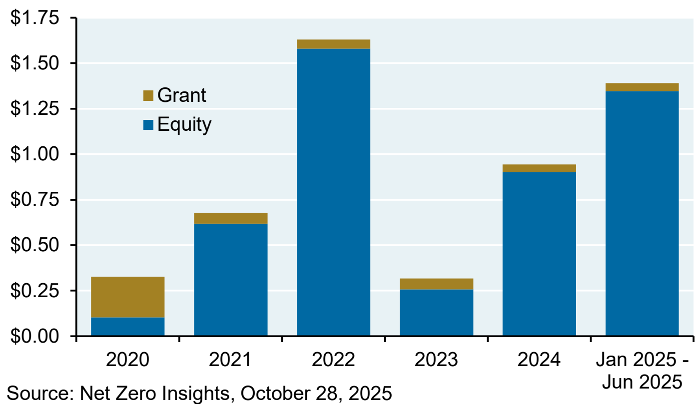
Last December 2025, the US DoE announced $800 mm in cost-shared funding for two SMR projects: TVA's GE Vernova/Hitachi BWRX-300 reactor in Tennessee, and Holtec's two 300 MW SMR's at the old Palisades nuclear site in Michigan (Holtec has no prior experience in nuclear plant development and will partner with Hyundai).

US small modular reactor equity indices total returns
Index (0 = Jan 2024)



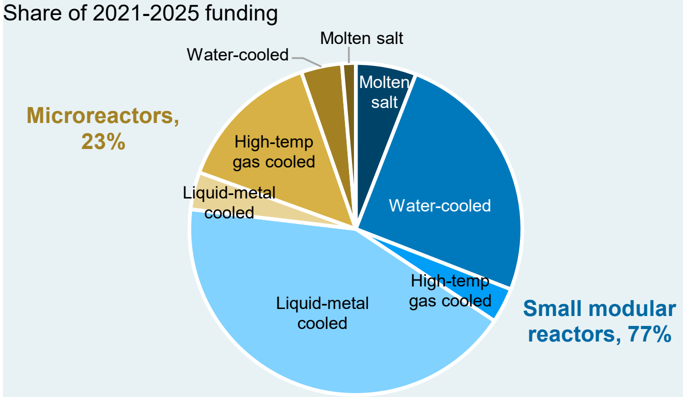
Source: Bloomberg, JPMAM, February 11, 2026

SMR and microreactor annual venture funding
US$, billions



Source: Net Zero Insights, October 28, 2025

SMR and microreactor funding by technology
Share of 2021-2025 funding



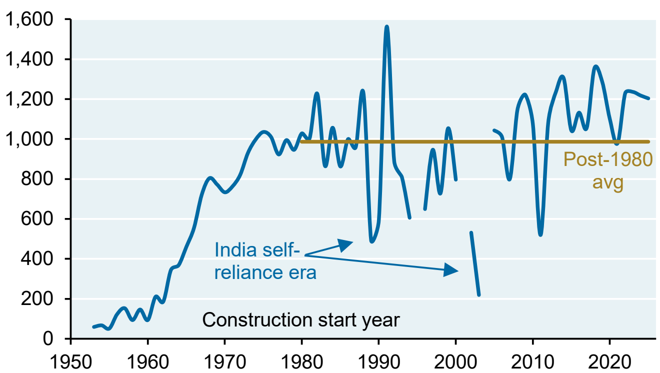
Source: Net Zero Insights, JPMAM, 2026

What is an SMR? SMRs generally refer to reactors less than 300 MW produced via modularity, factory fabrication and serial production. Four main types are being pursued: light water reactors, fast neutron reactors, graphite-moderated high temperature reactors and molten salt reactors. Light water reactor technology has existed for decades and is used in > 90% of the global nuclear fleet. At the end of 2025, the NRC approved the first US sodium cooled fast reactor (SFR) with a molten salt based energy storage system (TerraPower); there are also a handful of SFRs in operation in Russia, China and India. As of early 2026 the NRC has not fully approved the X-energy Xe-100 high temperature gas-cooled reactor but the project is in the licensing and review process, and in February 2026 the NRC approved the first license for a facility to produce fuel for these reactors

The burden of proof for economic viability still lay with the SMR industry:

- **SMRs are a reverse learning curve in motion**. When nuclear was commercialized in the 1950s, utilities and project engineers realized that given large fixed capital costs, it made sense to *increase* project sizes from 100 MW to 1 GW by 1980, a size which has been the global average ever since (see chart below)
- A 2025 paper from the former chair of the US Nuclear Regulatory Commission reviewed four SMR types and estimated SMR levelized costs of $200 to $400 per MWh (even higher for Xe-100 reactors)[45]. The authors concluded that capital and O&M costs for SMRs may surpass standard large LWRs due to diseconomies of scale; and that learning, modularization and reducing construction times may not reduce costs significantly
- The Tennessee Valley Authority analyzed SMRs in its 2025 Integrated Resource Plan[46]. TVA noted that its estimated first-of-a-kind SMR cost of $18k per kW was higher than industry averages, a reflection of its experience exploring the potential for SMRs at its Clinch River site and of cost risks experienced with new nuclear builds in the industry. Using TVA assumptions shown below, first-of-a kind SMR levelized costs would be $196 per MWh, possibly falling to $150 per MWh assuming a 30% future decline in capital costs[47]
- Studies prepared for some corporate clients show SMR costs per MWh at 2.5x – 5.5x grid cost levels
- China's first SMR, a high-temperature gas cooled 200 MW reactor, had an energy availability factor of just 30% in 2024 vs the US light-water reactor fleet of 87%[48]. In 2021 China started building a second SMR, the 125-megawatt ACP100 reactor. China's National Nuclear Corporation conceded in 2021 that its cost per kilowatt is 2x higher than its larger plants and that its cost per kilowatt-hour is likely to be 50% higher[49]. The US DoE came to similar conclusions in its September 2024 Advanced Nuclear Pathways report
- From what we can tell, most SMR contracts such as Oklo's with Switch and prior NuScale contracts were non-binding, allowing buyers to exit under certain conditions based on final project costs

The original learning curve led to larger nuclear plant sizes
Average capacity of global nuclear plants, gross MW



Source: Power Reactor System Database, JPMAM, September 2025

Estimating the cost of a first-of-its-kind SMR using TVA assumptions	
Capital cost	$18,000 per kW
Useful life	60 years
Capacity factor	95%
Fixed O&M	$147 per kW-year
Variable O&M	0.0011 per kWh
Heat rate	10713 btu per kWh
Fuel cost	$0.85 per mmbtu
Discount rate	7.7%
Cost escalation	2.25%
Levelized cost	$196 per MWh

[45] "*Challenges of small modular reactors: A comprehensive exploration of economic and waste uncertainties associated with US small modular reactor designs*", Macfarlane and Kim, Progress in Nuclear Energy, Aug 2025

[46] Integrated Resource Plan 2025, Tennessee Valley Authority, September 2024

[47] "*NuScale wants to sell 72 reactors to a company based in a WeWork office shared with NuScale*", Iceberg Research, November 14, 2025

[48] *"Fleet-Scale Nuclear: The Case For Large Modular Reactors",* Penney and Hilly, Foundation for American Innovation, November 2025

[49] "*Impact of core power density on economics of a small integral PWR*", Nuclear Engineering and Design, December 15 2021 and the 2022 World Nuclear Industry Status Report

A change in nuclear regulatory oversight: be careful what you wish for

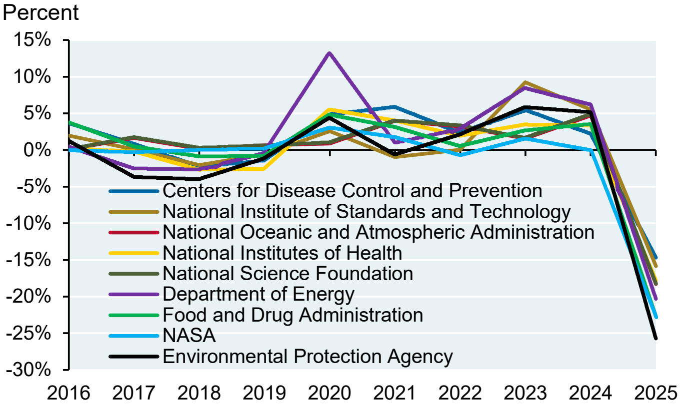
While the Administration is supportive of advanced nuclear designs like SMRs, changes in nuclear regulatory oversight might make investors, utilities and other private sector actors nervous about the consequences. Trump's February 2025 executive order stripped independent oversight authority of the US Nuclear Regulatory Commission and gave the OMB the power to review agency actions to ensure consistency with the President's policies and priorities. According to a former NRC chair, "**the executive order implies that there are no longer independent regulators free from political and industry influence**"[50].

An article in the March 2025 issue of Scientific American came to a similar conclusion: "we foresee that this proposed regulatory capture by the Executive Office of the President, where decisions are made for political reasons and not for the benefit of people served, will severely increase the risk of expensive, unexpected nuclear accidents"[51]. Regulatory capture was at the heart of the 2011 Fukushima meltdown in Japan: the country's parliament concluded that "the TEPCO Fukushima Nuclear Power Plant accident was the result of collusion between the government, the regulators and TEPCO, and the lack of governance by said parties. They effectively betrayed the nation's right to be safe from nuclear accidents"[52].

With respect to SMRs, since so much is riding on cost cutting and efficiency, modularization approaches need very close scrutiny. For example: in 2023, physicist Edward Lyman voiced safety concerns over NuScale's SMR cost-related design choices and that project didn't even introduce new nuclear technology[53]. Another issue: some nuclear analysts believe that due to compact cores, SMRs can leak more neutrons than conventional reactors, leading to more complex damage to reactors and different radioactive waste streams[54].

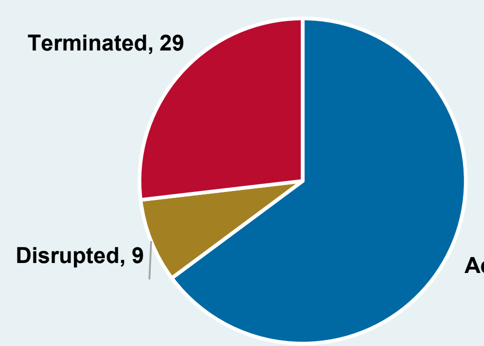
The big question: is an Administration enacting large workforce reductions in multiple agencies responsible for science, energy and public health/safety[55], and terminating independent scientific advisory committees, positioned to oversee and regulate development of power generation sources that can result in catastrophic outcomes if something goes wrong?

Change in agency staff levels from previous year
Percent



Source: Nature, January 22, 2026

Disruptions and terminations of independent federal advisory committees at science agencies, January 2025 to June 2025



Agencies include: NSF, EPA, HHS and USDA
Source: GSA FAC Database, Union of Concerned Scientists, June 30, 2025

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50 "*Trump just assaulted the independence of the nuclear regulator. What could go wrong?*", Allison Macfarlane (Chair of US Nuclear Regulatory Commission, 2012-2014), Bulletin of the Atomic Scientists, February 21, 2025

51 "*Killing a Nuclear Watchdog's Independence Threatens Disaster*," Scientific American, Huff et al, March 6, 2025. Authors: former DOE assistant secretary for nuclear energy, chair of the University of Wisconsin/Madison department of nuclear engineering and engineering physics, former president of the American Nuclear Society

52 "*Fukushima: A Manmade Disaster*", Science.org, July 5, 2012

53 "*Small Nuclear Reactor Contract Fails, Signaling Larger Issues in Nuclear Energy Development*," Dr Edward Lyman, Union of Concerned Scientists, November 9, 2023

54 "*Why Small Modular Reactors Won't Save Nuclear Power*", A. Gundersen, The Energy Mix, December 24, 2025

55 "*US Science After a Year of Trump*", Nature, Max Kozlov, Jeff Tollefson and Dan Garisto, January 20, 2026

Why isn't the fleet of US nuclear submarines a good proxy for what the private sector can do?
One obvious starting point is that the military is not price sensitive. Cost estimates for the Virginia-class nuclear submarine are now ~$4 billion compared to $500 mm for Japan's new Sorgu submarines which rely on Air Independent Propulsion and Korea's KSS-III submarines at $845 mm (the US military relies entirely on nuclear submarines rather than diesel-electric versions other countries use). The primary difference: the incremental cost of nuclear propulsion. Let's round the nuclear cost difference to $3 billion and measure that against the 210 MWt of power that a Virginia class submarine gets from its S9G nuclear reactor; the cost is $14.2 mm per MWt. How expensive is that? Vogtle reactors 3 and 4, one of the most expensive white elephant power projects in US history, cost $5.4 mm per MWt. So: military reactors are ~2.5x more expensive than one of the most expensive commercial nuclear reactors ever built.
Note: MWt measures thermal capacity, which is the heat content in the reactor core. That is the necessary unit of comparison since nuclear submarines use reactor energy for propulsion as well as on-board power

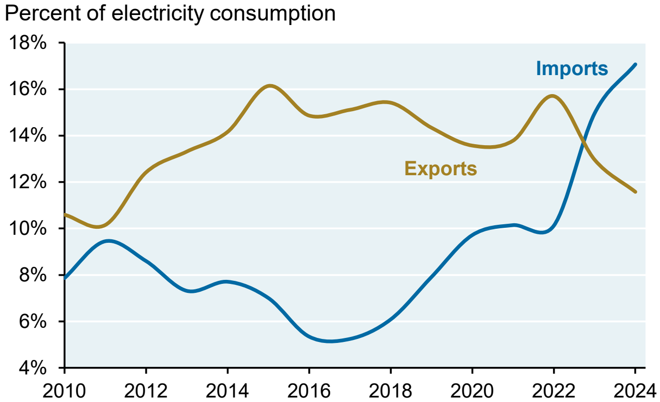
Nuclear Entscheidungsreue in Germany

That long word refers to "regretting a decision" and can be ascribed to German Chancellor Merz who said in January that Germany's shutdown of nuclear power was a "**serious strategic mistake**". Merz: "So we're now undertaking the most expensive energy transition in the world; I know of no other country that makes things so expensive and difficult as Germany". And this: "To have acceptable market prices for energy production again, we would have to permanently subsidize energy prices from the Federal Budget. We can't do this in the long run"[56]. Germany could in theory restart decommissioned plants, but it wouldn't be cheap. According to Radiant Energy Group, the cost of restarting Germany's Class 2 reactors could be $1 to $3 billion each[57].

In 2024 we estimated that had Germany not decommissioned nuclear power after the Fukushima accident, it would have needed 50% less electricity generation from fossil fuels, 84% less generation from imported natural gas, 27% less fossil fuel capacity and 42% less natural gas capacity[58]. Another road less traveled: Germany's electricity prices in 2024 were almost 25% higher than they would have been had the country kept its nuclear power online[59]. And as shown below, Germany might not have experienced such a sharp increase in its electricity imports which are 2x higher than a decade ago as a share of consumption.

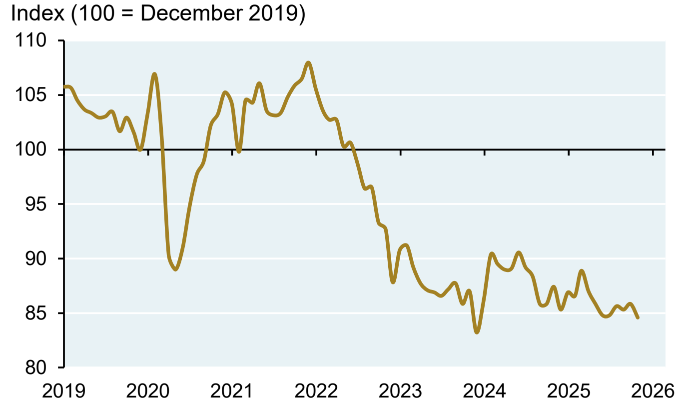
More nuclear shutdown repercussions: Germany's industrial power prices were 3x higher than the US and China in 2024, and part of the reason why Germany has been experiencing the deindustrialization shown on the right.

German electricity imports and exports
Percent of electricity consumption



Source: IEA, JPMAM, 2024

German energy intensive manufacturing output
Index (100 = December 2019)



Source: German Federal Statistical Office, JPMAM, November 2025

56 "*Germany's shutdown of nuclear plants was a huge mistake, says Merz*", Brussels Signal, January 15, 2026
57 "*Restarting Germany's reactors: feasibility and schedule*", Radiant Energy Group, May 2025
58 2024 Eye on the Market Energy paper, page 27
59 "*Germany: What have been the consequences of the closure of the nuclear power plants*", PwC, 2025

Do renewables raise or lower power prices? Depends on whom you ask, and what you leave out

Consistent with the cover art, the impact of renewables on power prices is a hotly debated topic. I find most analyses to be incomplete since they don't look at differences between generation costs and transmission/grid resilience costs, or they don't account for taxpayer subsidies (i.e., you can finance new power via higher electricity prices and/or more taxpayer subsidies, so power prices alone don't tell you enough). On the tax subsidy question, imagine a world with a 100% PTC/ITC for wind and solar; the transition would look very cheap to *ratepayers*, **but that would tell you nothing about the cost to *taxpayers* and the true economy-wide cost of the transition**. Here are two examples of subsidies that illustrate the point. Imagine if these costs were shifted from taxpayers onto ratepayers instead; a lot of analyses about the transition's impact on power prices would look much different:

- The energy subsidies in the Inflation Reduction Act were originally projected to cost taxpayers $341 billion over ten years in the form of tax subsidies and grants, with a later Goldman Sachs analysis estimating a 10-year cost of $1.2 trillion[60]
- From 2015 to 2023 the European Union provided $700 billion in taxpayer subsidies and grants related to solar, wind, hydro, biomass and other renewable energy sources[61]

In any case, here are differing views on the impact of renewables on power prices (which to reiterate I think are incomplete given the tax subsidy omission):

Renewables LOWER power prices: "*Clean energy isn't driving power price spikes*", Energy Innovation, 2024; "*Have renewables decreased electricity prices? Empirical evidence in the US over the past 24 years points to yes*", Zeke Hausfather, Breakthrough Institute, 2025; "*Power generation mix and electricity prices*", Stringer et al, in Renewable Energy, 2024

Renewables RAISE power prices: "*Electricity prices are soaring: It's time to hold the energy transition accountable*", American Experiment, 2024; "*Increasing renewables will reshape electricity prices*", Oxford Economics, 2025; "*The Renewable Energy Honeymoon: starting is easy, the rest is hard*", Centre for Independent Studies, 2025

Mixed results: "*Factors influencing recent trends in retail electricity prices in the US*", LBNL, October 10, 2025. Primary finding: when market forces drive renewable adoption they lower power prices but when RPS standards drive adoption, they increase power prices

The latter LBNL study analyzed wind and solar growth, natural gas exposure, renewable portfolio standards, system interruption frequency, load growth and prior price trends as potential explanatory factors for recent spikes in power prices (California needed its own dummy variable). While LBNL's analysis was thoughtful, I don't see it as the final answer to the question of what drives power prices or power price increases. **There are other factors that could have been included as well and which are illustrated on the next page.**

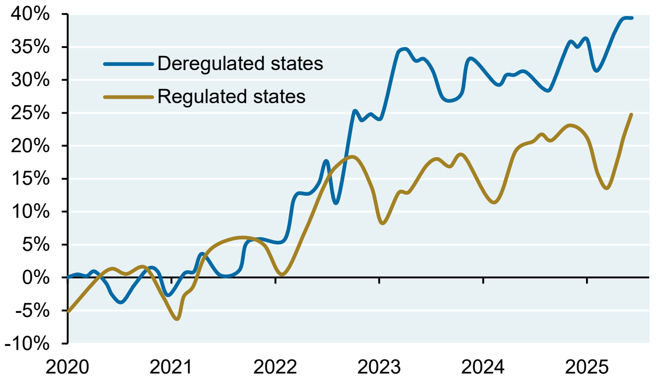
60 "*Inflation Reduction Act: Here's What's In It*", McKinsey Public Sector Practice, October 2022; and "*The US is poised for an energy revolution*", Goldman Sachs, April 2023

61 "*Report from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions: 2024 Report on Energy Subsidies in the EU*", January 28, 2025. This sounds like a meeting one would have read about in TASS during the USSR Brezhnev era

What about the impact of nuclear/hydro, wealth, politics, taxation and the ease of doing business?

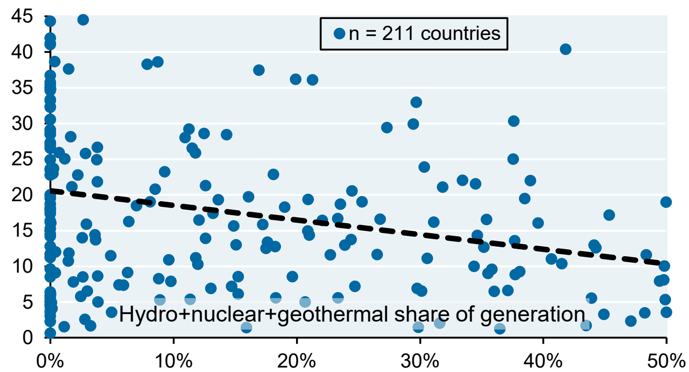
Residential power prices are also affected by (a) whether the US state is regulated (unregulated: higher price increases), (b) the share of existing hydro and nuclear power (more nuclear/hydro: lower power prices), (c) per capita GDP (more wealth: higher power prices), (d) the political orientation of the state (Democratic states have higher power prices) and (e) the cost of doing business and tax competitiveness (lower rankings: higher power prices). On the latter: California, New York, New Jersey, Massachusetts and Connecticut are simply difficult and costly places to conduct business, whether it's power generation or anything else.

Residential electricity prices in regulated vs deregulated states, Percent change in electricity prices since 2020



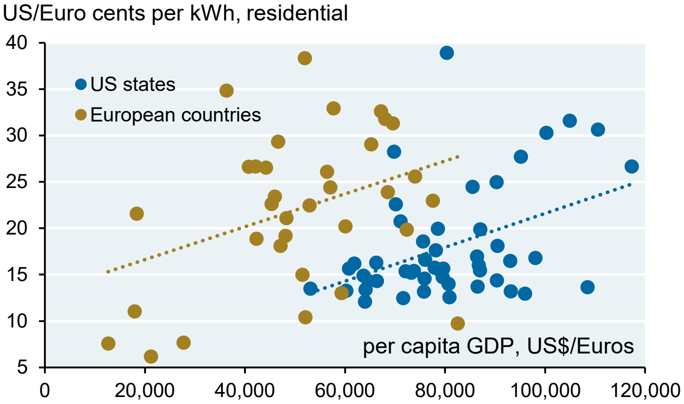
Source: William Blair, EIA, October 2025

More hydro and nuclear: lower electricity prices
US cents per kWh, residential prices



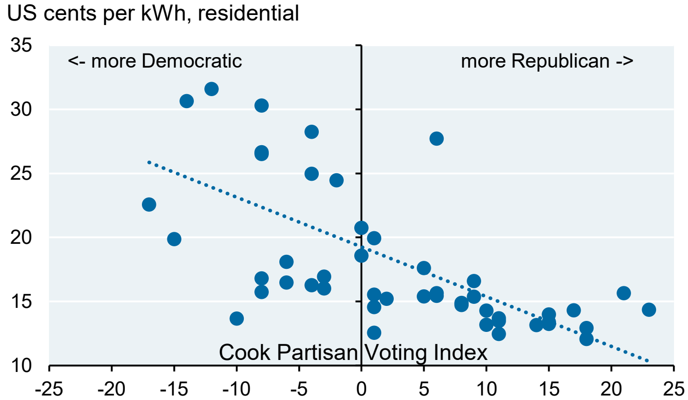
Source: IRENA, Thundersaid Energy, JPMAM, 2025

Higher wealth: higher power prices
US/Euro cents per kWh, residential



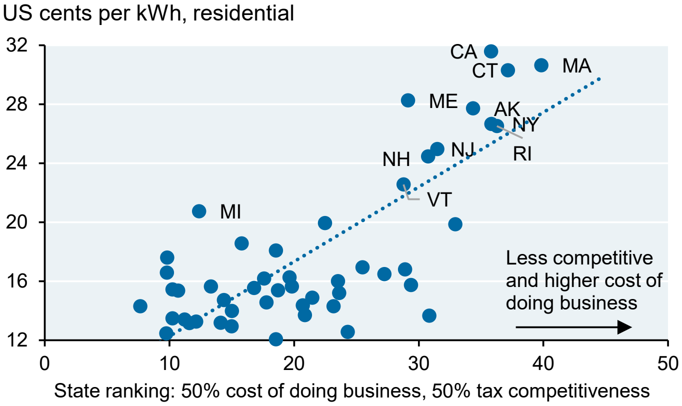
Source: Eurostat, EIA, JPMAM, 2025

More Democratic states: higher power prices
US cents per kWh, residential



Source: Cook Political Report, EIA, JPMAM, 2025

Lower business rankings: higher power prices
US cents per kWh, residential



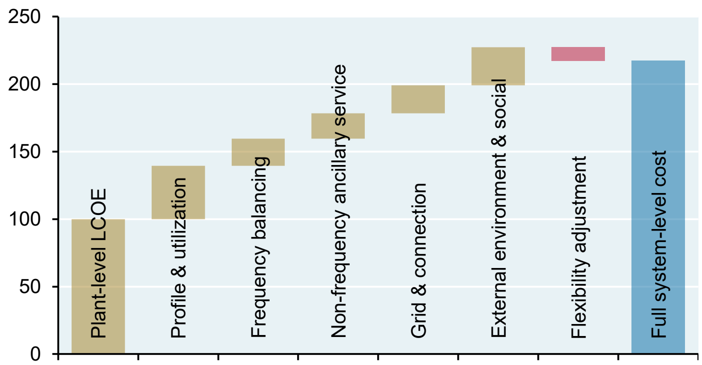
Source: Tax Foundation, CNBC, EIA, JPMAM, 2025

A rebuttal: on levelized costs and EMBER's assessment of solar/storage costs vs gas as baseload power

I've frequently stated that LCOE for intermittent energy sources like wind and solar is the cocktail napkin of energy math[62]. What matters more is **systemwide levelized cost,** something increasingly acknowledged by energy analysts. One example: the Clean Air Task Force concluded that LCOE is not an appropriate tool for long-term planning and policymaking for deep decarbonization[63] since it doesn't consider energy generation profiles such as dispatchability and inertia; it often does not account for full system costs necessary to deploy generators at scale including transmission and distribution costs; and does not assess the existing penetration of renewable energy and thus ignores the economic value a new project adds to the system.

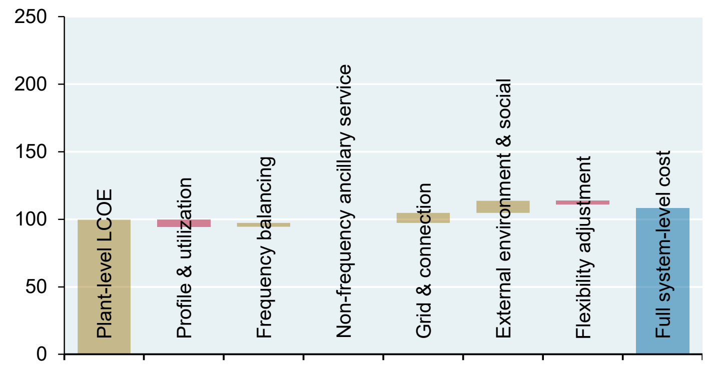
CATF has plenty of company. The consultancy Quantified Carbon prepared an analysis for the UN Commission for Europe that helps illustrate the problem[64]. The first chart shows that for variable renewable resources, **plant-level LCOE may only represent half of the overall associated system cost**. For non-variable resources the same factors apply but their incremental impact on system cost is minimal, as shown on the right.

LCOE & overall system cost for variable renewable energy
Index (100 = plant-level LCOE)



Source: Quantified Carbon, 2025

LCOE & overall system cost for non-variable energy
Index (100 = plant-level LCOE)



Source: Quantified Carbon, 2025

In a similar vein, another recent study analyzed the LCOE of a 1 GW off grid data center[65]. The estimated LCOE of a solar+battery configuration doubles as its required load factor increases from 40% to 90%. In other words, **the true cost of solar when used to replicate baseload power doubles** when it includes necessary overbuilding of solar capacity plus the battery capacity to handle periods with less solar irradiance (i.e., winter months and all nights). In other words, solar marginal LCOE is largely irrelevant when dealing with real world systems.

That's why Independent System Operations, utilities, FERC, NERC, consultancies like Brattle and E3 and other agencies apply concepts like effective load carrying capability (ELCC) and summer/winter expected share of nameplate capacity when analyzing reserve margins and grid reliability. Even Lazard now tries to adjust for this although their approach is belated, insufficiently disclosed and lower than our estimates. If LCOE for wind and solar really meant what its adherents claim, alternative measures wouldn't be needed in the first place.

That brings me to a recent report from EMBER which found that the cost of solar generation + battery storage is only modestly higher than all-gas systems in places like Las Vegas. I decided to give EMBER's report a full endoscopy; my medical diagnosis was quite a bit different, as we discuss next.

62 See 2023 energy paper pages 14-18 and 2024 energy paper page 29

63 "*Beyond LCOE: A Systems-Oriented Perspective for Evaluating Electricity Decarbonization Pathways*", Clean Air Task Force, May 2025

64 "*Understanding the Full System Costs of Electricity*", Quantified Carbon/UNECE, 2025

65 "*Powering Hyperscaler AI data centers*", Browning, Prasad and Yan, University of Delaware Departments of Chemical and Mechanical Engineering, December 15, 2025

The EMBER endoscopy: is solar+storage really cost-competitive with natural gas in the US?

EMBER's report found that solar plus storage can meet a 1 GW hourly load in sunny places like Las Vegas for 97% of the hours in the year at a cost that's only 38% higher than a gas system, a premium EMBER describes as "cost-effective" and "affordable"[66]. This would be a paradigm shift; places with high solar irradiation like Hawaii and Lebanon currently get just 20%-30% of their power from solar.

For Las Vegas, EMBER assumed 6 GW of solar capacity and 17 GWh of battery storage, a configuration they claimed would meet 97% of the city's annual power needs at a cost of $104 per MWh. EMBER assumes for the sake of simplicity that grid managers need to meet a constant 1 GW load in every hour of the year; in real life the contour of power demand is variable within days and across months, but let's work with their assumption for now. We need a laundry list of other assumptions, most of which we source from EMBER. If you disagree with EMBER's capital cost assumptions, be patient: we iterate on those later.

Assumptions: Las Vegas utility scale grid configuration analysis

Solar			*Storage*			*Natural gas*		
Useful life	20	years	Capital cost	$165	$ per kWh	Capital cost	$1,400	$ per kW
DC->AC ratio	1.35		Operating cost	$5.51	$ per kW-yr	Useful life	40	years
Capital cost (incl. inverter)	$436	$ per kW	Useful life	20		Fixed costs	$13.73	$ per kW-yr
Operating cost	$12.50	$ per kW-yr	Annual degradation	2.60%		Variable costs	0.0021	$ per kWh
Solar degradation rate	0.50%	per year	Round trip efficiency	100%		Fuel cost	$3.50	$ per mmbtu
Grid connections	$76.0	$ per kW solar	Peak and minimum buffer size	5%		Heat rate	6370	btu per kWh
Solar generation profile			DC-DC conversion losses in/out of battery	1.80%		Color key		
Single axis bifacial panels, 1-axis backtracking							EMBER	
System losses [shading, soiling, wiring]	10.06%						NREL	
Inverter			*Cost of capital*				Lazard	
DC->AC loss	2.00%		Discount rate	7.7%			EIA	
Useful life	20						JPMAM	

Source: NREL, EMBER, JPMAM, July 2025

A few comments before we proceed:

- While EMBER sources solar generation data from a European Commission database, we use NREL's well-known PVWATTS system for specific locations
- Round-trip efficiency of lithium ion batteries is obviously not 100%; EMBER states that round trip efficiency is inherently embedded in some of their other assumptions
- EMBER did not explicitly state their natural gas capital costs so we derived their implicit assumption as follows: on page 33 of EMBER's report, they source Lazard's 2024 natural gas LCOE so we obtained Lazard's gas capital cost per kW, updated for 2025
- In energy modeling for this kind of simplified grid example, the size of the required gas system is the largest MW of demand in any hour of the year not met by solar generation or by battery draws
- Systemwide levelized cost refers to the cost of the entire system divided by the total MWh of load, and represents a **levelized cost of firm generation** (excluding the cost of transmission & distribution, which we assume is similar for gas and solar/storage for the sake of simplicity). We also exclude any necessary redundancy or reserve margin since they would be similar across most configurations we studied

Why do so many news outlets accept energy claims like EMBER's so uncritically?

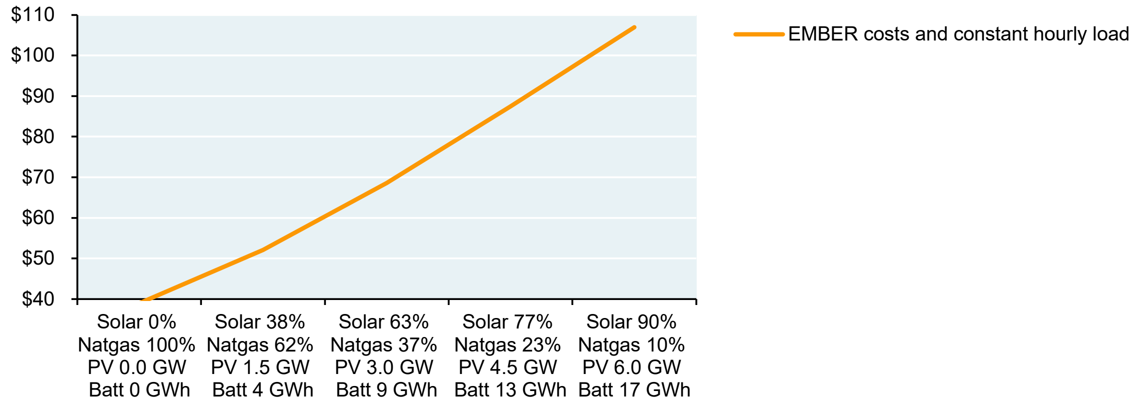
An informal study of the 70-person Wall Street Journal energy reporting pool found no reporters with degrees in chemical engineering, electrical engineering, petroleum engineering, mechanical engineering, physics or chemistry; the only STEM backgrounds were two reporters with BAs in computer science. Also: of the entire pool of WSJ energy reporters, not a single one had ever worked in oil, power, pipeline, auto manufacturing, solar, battery or aviation sectors.

Source: "*Caveat Lector: Gell-Mann Amnesia and WSJ Energy Reporting*", Nick Deiuliis, January 2026

[66] "*Solar electricity every hour of every day is here and it changes everything*", EMBER, June 21, 2025

Here are the results using mostly EMBER assumptions. The curve shows the increase in systemwide levelized cost as more solar is added to the grid, starting on the left with an all-gas system of 1 GW. At maximum solar penetration levels, the system requires 6 GW of solar, 17 GWh of storage and 1 GW of gas (since there are hours in the year with no solar or available battery storage). **Our systemwide levelized cost of $108 per MWh for the max solar+battery system is close to EMBER's $104 result even when including the cost of a gas system which meets 10% of the load**[67]. While we agree with EMBER's levelized cost results using their assumptions, whether a $60 per MWh premium for solar + storage over an all-gas system is "affordable" is open to debate.

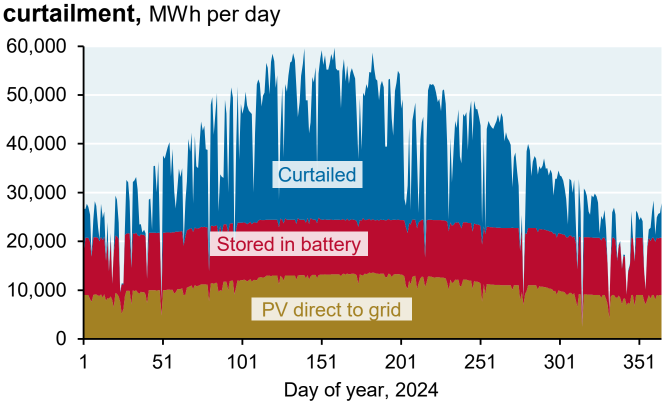
Las Vegas utility scale grid configurations, $ per MWh of system levelized cost



Source: NREL, EMBER, JPMAM, July 2025

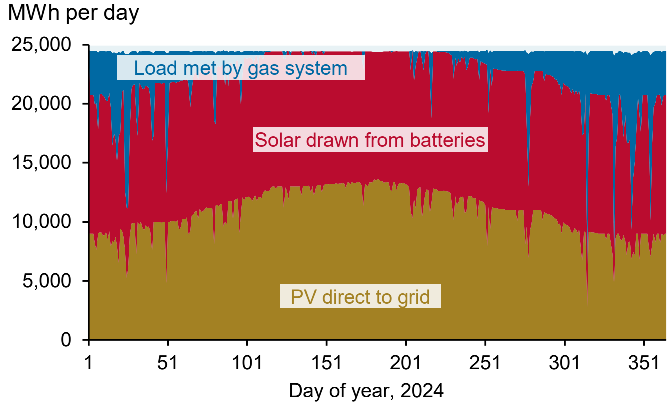
Also: massive amounts of solar power are curtailed (unused) in EMBER's maximum solar/battery scenario, ~40% of total generation as shown in the chart on the left. More storage could be added but its additional cost would outweigh the benefit of reduced gas system utilization. As per the second chart, solar+ storage meets almost the entire load during the late spring and summer, with gas required in fall and winter months due to declining solar irradiance.

How solar is used: grid demand, battery storage and curtailment, MWh per day



Source: NREL, EMBER, JPMAM, July 2025

How daliy loads are met: solar, batteries and gas
MWh per day



Source: NREL, EMBER, JPMAM, July 2025

EMBER's implicit daily load assumption is 24,000 MWh. Note that when using real world loads for a place like Las Vegas, daily demand would range from 20,000 MWh in winter to 30,000 MWh in summer months due to air conditioning demand with spikes as high as 35,000 MWh on select days. That would have obvious implications for the required backup thermal system, as we discuss next.

[67] Analysts sometimes overestimate the cost of backup thermal power; combined cycle gas plant capital costs can be amortized over 40 years, and variable/fuel costs are low in a high-renewable system since the gas system is rarely used. In our analysis the maximum penetration solar system meets 90% of the city's power rather than EMBER's 97%, a gap we attribute to minor differences in solar generation profiles/assumptions

Adjusting the analysis to reflect assumptions on capital costs, operating costs and real world loads[68]:

Real world loads: instead of assuming constant hourly loads, we derive a more realistic hourly load profile for Las Vegas for the entire year by using hourly load data from CAISO for scaling purposes

Solar: we use a capital cost of $923 per kW plus 21% in indirect costs (based on the NREL/Department of Energy Photovoltaic System Cost model PVSCM)[69]; fixed costs of $18.5 per kW-year; and annual degradation of 0.75%. EMBER's solar cost of $436 per kW is a global figure **heavily weighted to Chinese installations**. Obviously, such costs would not be available to developers in US cities; we double checked our solar capital cost figures with multiple industry sources. We were very surprised to see EMBER use a China-weighted figure for a US city.

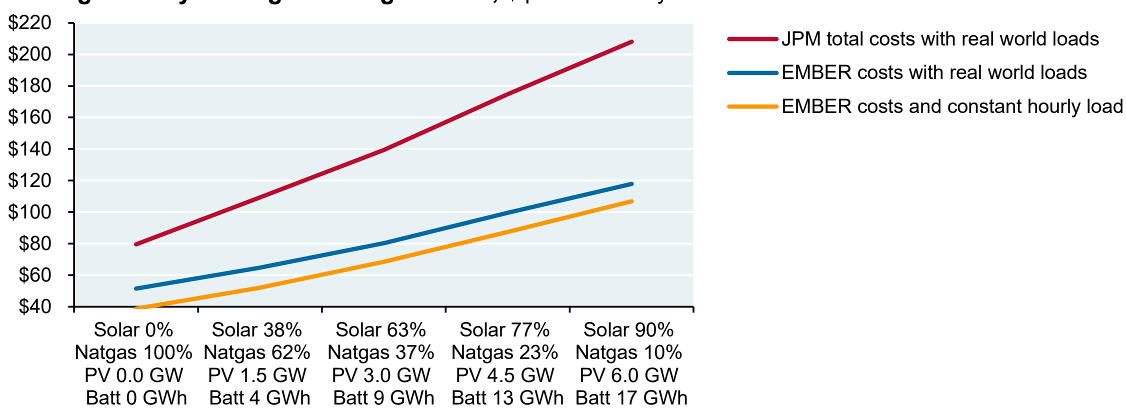
Inverter: 1% losses

Storage: capital cost of $228 per kWh; round trip efficiency 92%; annual degradation of 3.6%

Natural gas combined cycle plant: $2,500 per kW capital cost plus 21% for indirect costs

While the adjustment for a realistic load profile is modest (blue curve), our other assumptions result in a much more expensive and steeper tradeoff (red curve)[70]. The estimated cost for a deeply decarbonized solar+storage system is ~$210 per MWh, even higher than the $170-$180 per MWh cost of the white elephant Vogtle Unit 3 nuclear plant completed in Georgia in 2023.

Las Vegas utility scale grid configurations, $ per MWh of system levelized cost



Source: NREL, EMBER, JPMAM, July 2025

While natural gas looks cheaper on a systemwide cost basis, that doesn't account for time it takes to acquire it. Backlogs are currently 3-7 years for combined cycle turbines, although as explained on page 12, major gas turbine manufacturers are planning to expand production. Meanwhile, solar and storage can be installed more quickly. New US battery installations were 4 GW in 2022, 7 GW in 2023, 11 GW in 2024 and 13 GW in 2025 as of November; and for new utility-scale solar, 11 GW in 2022, 20 GW in 2023, 31 GW in 2024 and another 22 GW in 2025 as of November[71].

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68 We reviewed and confirmed our solar, inverter and battery assumptions with **NREL** and with **Tyba Energy**, a software platform that enables energy companies to develop and operate projects that maximize financial returns while supporting grid decarbonization

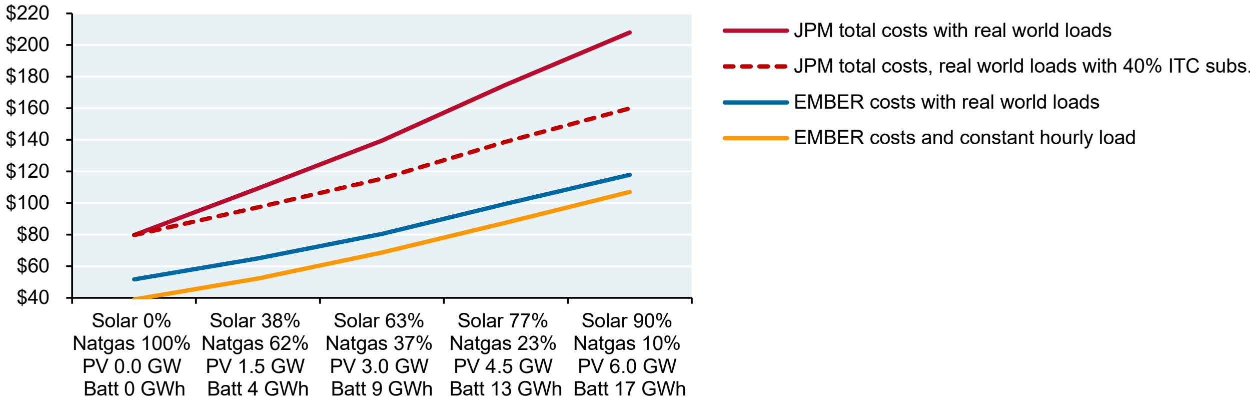
69 Other NREL capital cost estimates for solar were even higher at $1,400 per kW (NREL ATB 2025), but we use the lower figure to give EMBER's analysis the benefit of the doubt

70 We also ran the analysis using a longer operating life for solar of 30 years and a modestly shorter 15-year operating life for the battery; the results were practically identical to the red line curve in the chart

71 Solar and battery capacity additions as per EIA Form 860M

What about solar subsidies? Their future in the US is uncertain and secondly, we prefer to look at systemwide cost per MWh excluding subsidies since *someone* is paying for them. Even Lazard shows baseline LCOE figures gross of subsidies. But if you're curious, the red dotted line shows the results with the benefit of a 40% ITC (30% base rate plus 10% bonus credits for siting in coal states/low-income communities or using US manufactured products). Solar+storage: still more expensive than an all-gas system, even with subsidies.

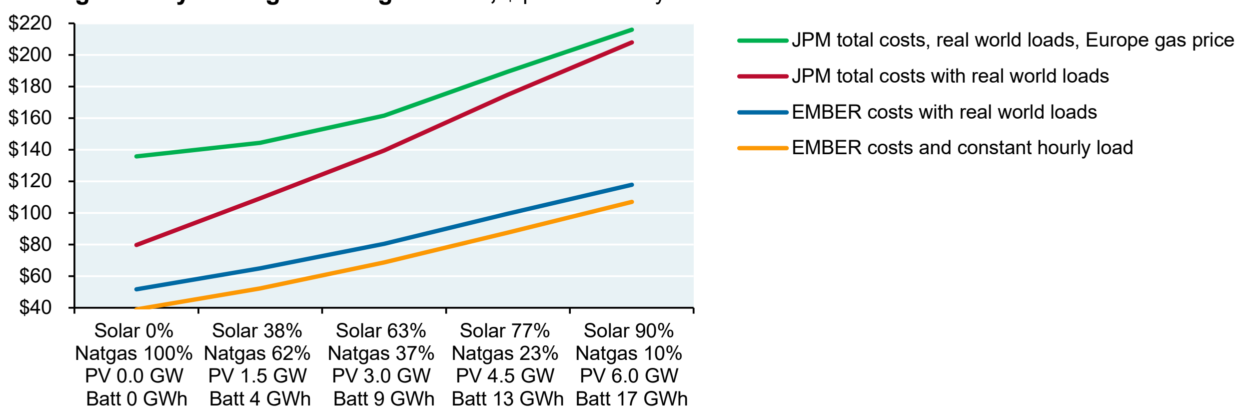
Las Vegas utility scale grid configurations, $ per MWh of system levelized cost



Source: NREL, EMBER, JPMAM, July 2025

What does the curve look like if natural gas prices rise? The green line shows the impact of a European gas price of $12.30 per mmbtu. The gas-heavy front end of the curve rises a lot, but the curve is still not quite flat.

Las Vegas utility scale grid configurations, $ per MWh of system levelized cost

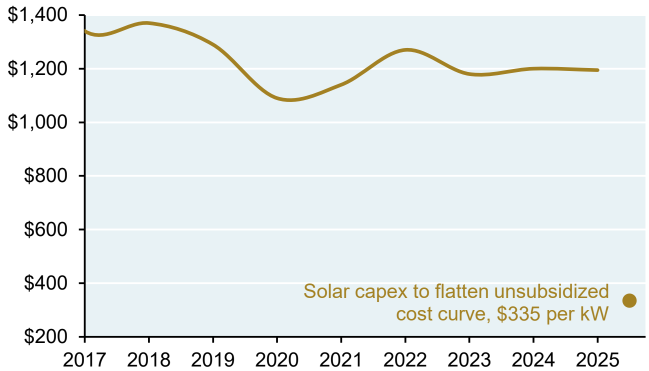


Source: NREL, EMBER, JPMAM, July 2025

What would it take for the unsubsidized cost curve to be flatter, implying a more even economic tradeoff between an all-gas system and the max penetration solar+storage system? Something like this: gas prices rise to $8 per mmbtu, AND solar capital and operating costs fall by 70%, AND 4-hour storage capital costs fall by 70%. While learning curves have been steep, $335 per kW for solar and $68 per kWh for storage seem a long way off, at least in the US. The impact of US tariffs raises the uncertainty further.

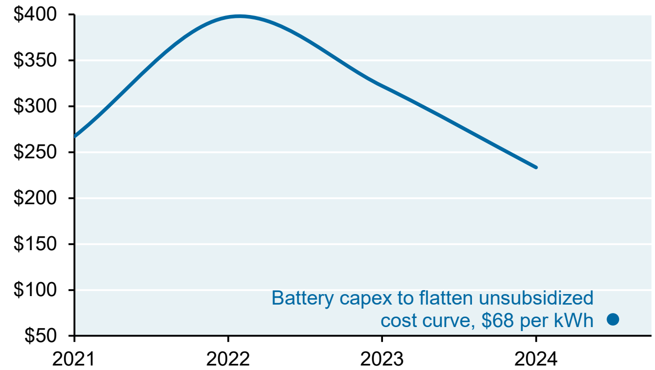
Bottom line: our analysis mostly rejects EMBER's thesis and finds that their report understates the economic tradeoffs of deeply decarbonized solar + storage systems in cities like Las Vegas. On this kind of topic, stick to peer-reviewed pieces in publications like *Joule*. EMBER's article is more a reflection of the world the authors want to exist rather than the world as it really is.

US solar capital costs
2024 US$ per kilowatt



Source: BloombergNEF, JPMAM, August 2025

US 4-hour energy storage capital costs
2024 US$ per kilowatt-hour

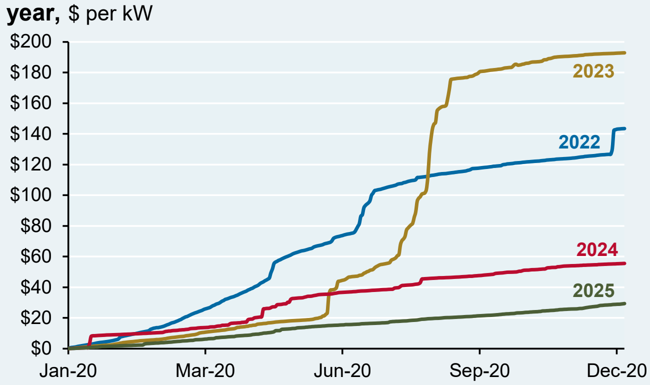


Source: BloombergNEF, JPMAM, December 2024

Related topic: why did ERCOT battery arbitrage revenues collapse in 2025?

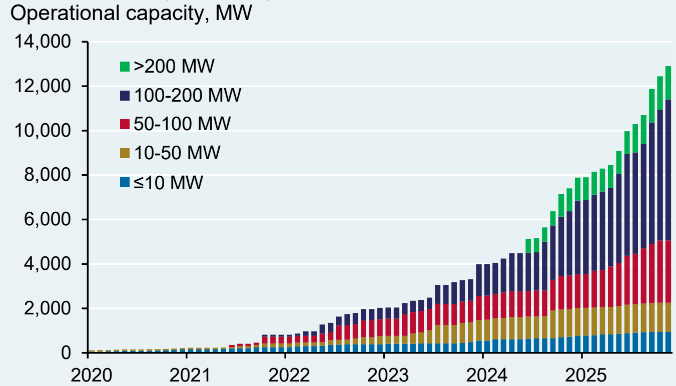
Two years ago I met with the JP Morgan team that makes tax equity wind and solar investments for the firm's balance sheet. We discussed battery arbitrage investing in energy-only markets like ERCOT. I did not understand how battery arbitrage investors would be protected from a flood of new entrants that would eventually lead to a collapse in diurnal arbitrage revenue. They agreed with my concerns, which have now been confirmed by the chart below on ERCOT battery revenues by year. Even after controlling for temperature differences vs prior years, 2025 was a bad year for battery revenues. The reason: 9 GW of new battery capacity in ERCOT saturated Ancillary Services and pushed storage into diurnal energy market competition, compressing spreads across the grid and increasing storage capacity by 70x since 2020. How could Texans that lived through multiple real estate cycles not have seen this one coming?

Cumulative ERCOT battery energy arbitrage revenues by year, $ per kW



Source: Modo Energy, February 2026

ERCOT battery capacity
Operational capacity, MW



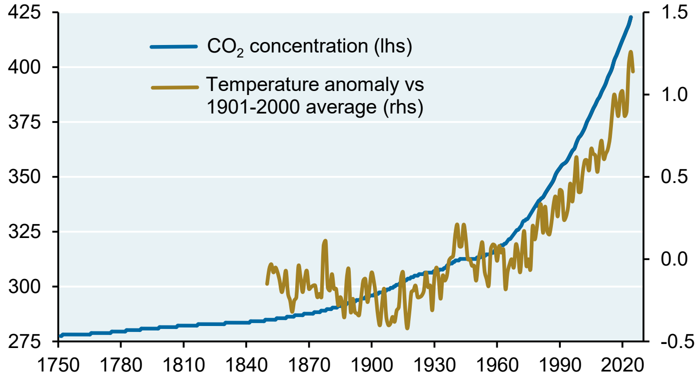
Source: Modo Energy, November 2025

Climate charts: new highs on CO_2 concentrations, ocean heat content and temperature anomalies

These charts speak for themselves. As a personal observation, I started swimming in a saltwater lagoon in the southern Mexican Yucatan in 1991. It was full of fish, crabs, sea urchins, coral, sea fans and other sea life at the time. Today it's almost barren and looks like the Forbidden Zone from the 1975 Planet of the Apes movie.

Atmospheric CO_2 and global temperatures

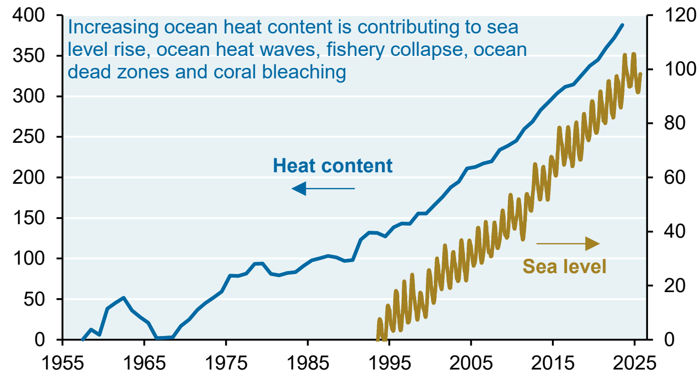
Parts per million | Temperature anomaly, ºC



Source: NOAA, JPMAM, 2025

Ocean heat content and sea level

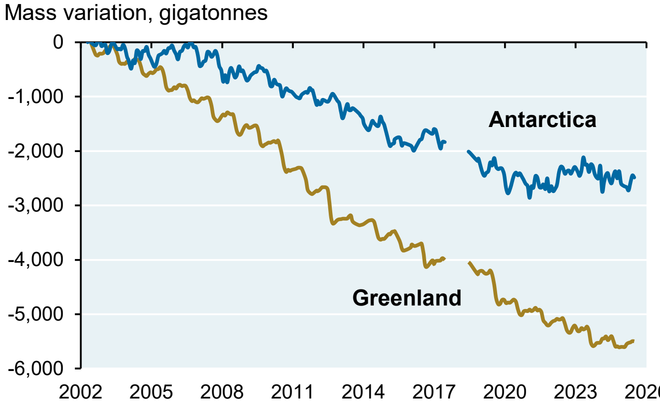
Zettajoules, vs 1957 baseline | Millimeters, vs 1993 baseline



Source: NASA/NOAA, JPMAM, July 2025. 1 ZJ = 10^{21} joules

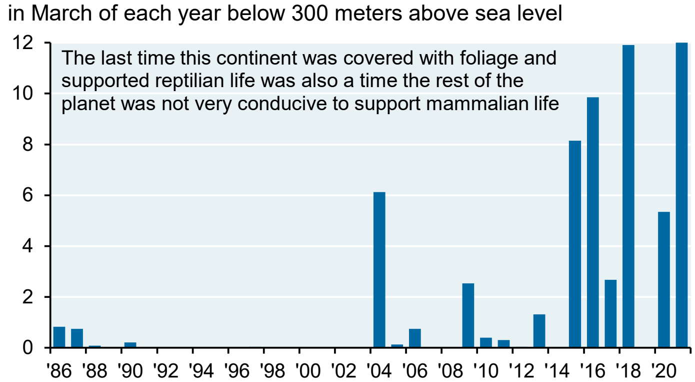
Antarctica and Greenland ice sheet mass

Mass variation, gigatonnes



Source: NASA, JPMAM, July 2025

The greening of Antarctica, Square km of green vegetation cover in March of each year below 300 meters above sea level

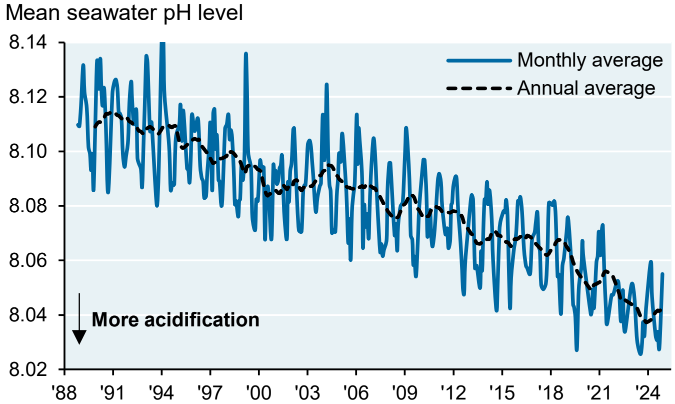


Source: "Sustained greening of the Antarctic Peninsula observed from satellites", Roland et al, Nature, October 2024

Ocean acidification is the process by which the pH of the ocean decreases due to absorption of CO_2 from the atmosphere, and which kills off the building blocks of ocean life (plankton) and impedes the ability of calcifying organisms to build and maintain shells and other calcium carbonate structures (negative impacts on coral reefs, mollusks and other marine life).

Hawaii ocean acidification

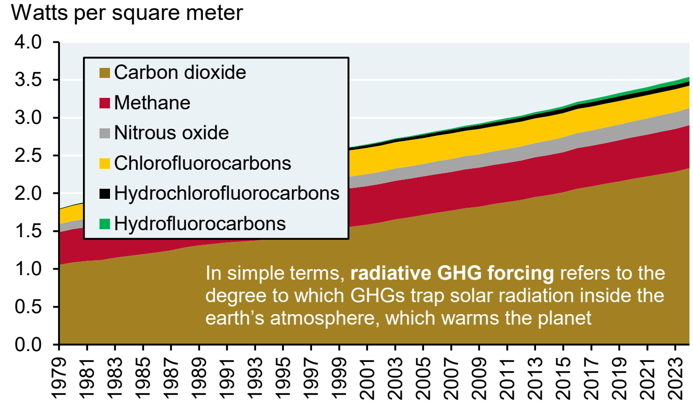
Mean seawater pH level



Source: University of Hawaii SOEST, December 2024

Greenhouse effect: radiative forcing by GHG

Watts per square meter



Source: NOAA Global Monitoring Laboratory, 2024

Bloom solid oxide fuel cells: a real-world alternative to gas turbines and gas engines

If SMRs are slow to develop, grid connections can take years and natural gas turbine delivery times are extended (even for simple cycle turbines), what's a data center operator to do? One commercially available option is Bloom Energy's solid oxide fuel cell which uses natural gas to produce electric power, and which competes with open-cycle small gas turbines and gas engines. Bloom's order book[72] and stock price have been rising, so I decided to take a closer look.

Solid oxide fuel cell power generation is still pretty small; Bloom cites current global generation of ~7 TWh per year from ~1 GW of installed fuel cells; that's just 0.02% of global electricity generation. Bloom Energy's solid oxide fuel cells, once marketed with 90-day deployment timelines, now require 16-18 months for delivery, installation and commissioning of 50+ MW installations according to industry estimates.

How it works:

- **Short version**: solid oxide fuel cells induce gas and air to interact with specialized solid ceramic materials at high temperatures, and a series of chemical processes converts the gas into CO_2 and electricity
- **Longer version**: solid oxide fuel cells use electrochemical reactions to convert natural gas into electricity, water, CO_2 and heat without the use of combustion. The natural gas must first be desulfurized using static sulfur absorption beds which are periodically removed and sent offsite for regeneration, since unlike gas turbines, fuel cells are very sensitive to the presence of sulfur. Bloom fuel cell anode tail gas is ~62% CO_2 with the balance in carbon monoxide and hydrogen once all water is removed; that compares to ~5% CO_2 concentrations for gas turbine flue gas. If CCS is not attempted, the entire tail gas stream is sent to an oxidizer where the heat of combustion of the CO and H_2 is used to improve operational efficiency (such as preheating the combustion air being fed to the fuel cell)

Background and cost. Solid oxide fuel cells are not new; they have been considered expensive and were limited to niche applications that prioritized reliable on-site power during grid outages. They were often hampered by short lifetimes with fuel cell stacks sometimes requiring replacement after just a few years of continuous use. Bloom claims to have solved cost and durability challenges, rendering them suitable for baseload power. A December 2025 piece from SemiAnalysis cites capital costs of $3,000 to $4,000 per kW for Bloom fuel cells[73], which is higher than all other behind the meter alternatives shown on page 14. But to reiterate, for many data center operators a faster connection can offset the economic cost of more expensive generation capacity.

Partnerships. In addition to the order book cited below, Bloom announced a $5 billion partnership with Brookfield Asset Management, one of the world's largest data center operators. These projects are designed to bring power directly to data centers without the need for new grid connections or connections to old ones.

Energy efficiency and carbon emissions. Bloom cites energy efficiency for newer fuel cells of ~55% on an LHV basis (i.e., excluding the energy value of latent heat stored in water vapor produced during combustion), which is consistent with the ~800 lbs of CO_2 per MWh figure cited in its publicly available materials. Such efficiency rates are modestly lower than CCGT power plants and considerably better than either reciprocating engines or open cycle gas turbines. Also, since Bloom emissions are only CO_2, permitting is often simpler and faster than gas plants which also emit nitrogen oxides, sulfur dioxide and volatile organic compounds.

[72] New orders based on Bloom Energy 2024-2025 press releases:

- Deal with Oracle Cloud Infrastructure (OCI) to bring fuel cells to OCI data centers
- Increased order from Equinix for over 100 MW of fuel cell power for data centers
- 100 MW order from American Electric Power (AEP) as part of a 1 GW agreement to power AI data centers
- 80 MW deal to power ecoparks in South Korea
- Order from FPM Development to provide 20 MW of power to commercial sites in Los Angeles
- 150% expansion of Bloom's agreement with Quanta Computer to support tech hardware manufacturing

[73] "*How AI Labs Are Solving the Power Crisis: The Onsite Gas Deep Dive*", SemiAnalysis, December 2025

Carbon sequestration. If/when gas suppliers build out CCS wells and pipelines, Bloom customers might eventually have the option to run their fuel cells on a largely decarbonized basis if they sequester emissions (but not 100% decarbonized since carbon monoxide is burned with its CO_2 vented). The minimum practical scale for a CCS project is at least 300 MW, so most smaller Bloom installations may never capture CO_2. While Bloom fuel cell emissions are not "CCS ready", their higher CO_2 concentration makes it much easier (less energy and capital cost) to produce a pure dehydrated CO_2 stream suitable for CCS than gas plant flue gas.

One example: Crusoe is developing a Wyoming data center using Bloom fuel cells, and stated that its proximity to existing the Tallgrass CO_2 sequestration hub can eventually provide long term carbon capture solutions.

Bloom's rare earth dependency on China. In its 10-Q, Bloom states that *"China as a country supplies multiple components including 70% of rare earth metals used in electronic and electromechanical components that are part of our tier 2 and tier 3 sub-assembly suppliers"*.

Lifetime efficiency. Bloom fuel cell efficiency drops over its lifetime; Bloom cites a stack life of ~5 years but doesn't publicly disclose performance guarantee information except under a non-disclosure agreement (which is unusual). Replacement of fuel cell stacks makes up ~65% of total anticipated service costs.

Waste heat utilization. Hot air from the fuel cell, along with combustion heat from the anode tail gas oxidizer, can be used to provide heat. Assuming no CCS is attempted, the fuel cell and the oxidizer produce steam at 5 bar of pressure with 10-15 degrees of superheat (i.e. low pressure industrial steam) that might be used to drive absorption chillers or to provide district heating, but the steam is of insufficient pressure and superheat to be used for further electricity generation.

Cycling and load following mode. Bloom claims that its fuel cells can be operated in "load following" mode in data center applications (ramping up and down) without an intermediate battery or capacitor storage system often required by other forms of generation such as combined cycle plants. Bloom claims that high heat capacity in the stack materials protects the stack from thermal cycling damage, but no figures are given for the depth of cycling permitted or what impact this would have on performance or durability.

Gas turbine and solid oxide fuel cell manufacturer cumulative total return since January 2022

Company	Product	Return	Benchmark	Return
Bloom Energy	Solid oxide fuel cells	697%	Russell 2000	26%
GE Vernova	Combined cycle turbines	570%	S&P 500	36%
Siemens Energy	Combined cycle turbines	657%	DAX	58%
Mitsubishi Heavy Industries	Combined cycle turbines	1818%	Nikkei 225	120%
Caterpillar	Gas turbines, reciprocating engines	300%	S&P 500	55%
Doosan	H class turbines	408%	MSCI Korea	146%
Rolls Royce	Aeroderivative engines	980%	MSCI UK	-41%
Wartsila	Modified ship engines	237%	Stoxx 600	49%

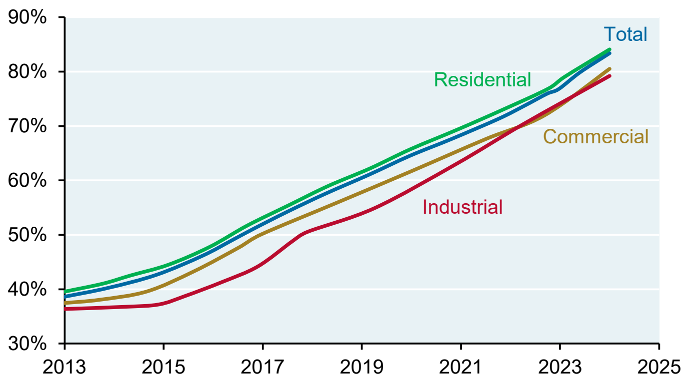
Source: Bloomberg, JPMAM, February 25, 2026. GE Vernova & S&P 500 returns shown since GE Vernova's listing on March 27, 2024

An update on virtual power plants and demand response

I've never liked the phrase "virtual power plant" (VPP) since I think it poorly describes what's going on. Virtual makes it sound like it's digital and not real, like the Metaverse. Virtual power plants are real but they're not power plants at all: they're a combination of (a) stored, distributed reservoirs of power that can be drawn on by utilities with the approval of power owners, and (b) agreements by power consumers to curtail or shift consumption at times of peak demand. In the US, VPPs have long been discussed and are finally being deployed.

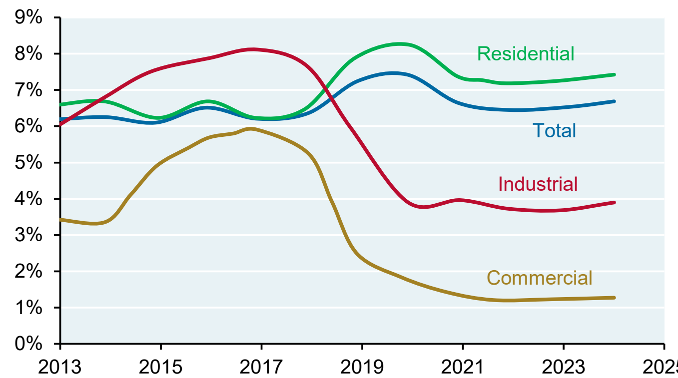
Rob West at Thunder Said Energy pulled together the data below from EIA form 860 filings. As you can see, ~80% of US homes and businesses are now equipped with smart meters, and 40% of customers also have daily digital access to view their electricity consumption, informed by smart meter data. VPP progress is gradual: 7% of electricity customers are enrolled in demand response programs, 11% have dynamic tariffs usually linked to "peak/off-peak" pricing and only 1% have true time-of-use tariffs.

Advanced "smart" meter deployment by segment
Percent



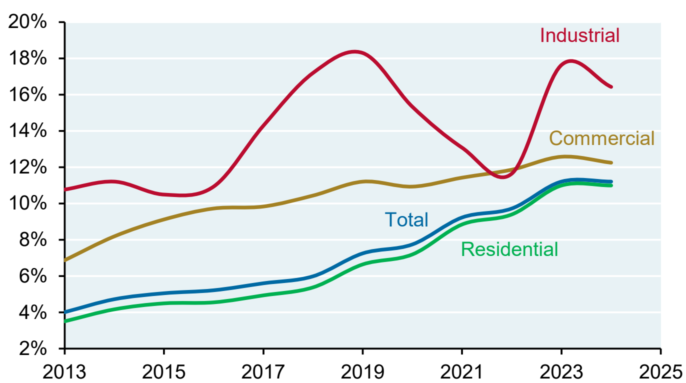
Source: EIA Form 860, Thunder Said Energy, October 2025

Customers enrolled in demand response programs
Percent



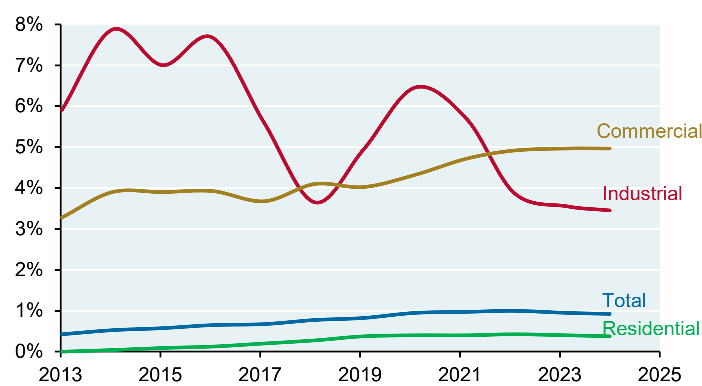
Source: EIA Form 860, Thunder Said Energy, October 2025

Customers enrolled in dynamic pricing tariffs
Percent



Source: EIA Form 860, Thunder Said Energy, October 2025

Customers enrolled in real-time, time-of-use tariffs
Percent



Source: EIA Form 860, Thunder Said Energy, October 2025

VPP activity now appears to be picking up. According to Wood Mackenzie, the number of monetized demand response programs administered by grid operators grew by 35% in 2025, and the number of agreements of VPP aggregators pledging capacity to demand response programs grew by 33%. VPP capacity, measured as the dispatchable electricity from VPP supply-side assets and the amount that demand can be curtailed by VPP demand-side assets, increased by 14% to 37.5 GW (roughly 4%-8% of peak loads). According to the US DoE, increasing VPPs to 80 - 160 GW could address 10%-20% of peak loads and save $10 billion in annual grid costs through avoided generation buildout, delayed power infrastructure investments and reduced operation of natural gas peaker plants.

North America VPP market growth

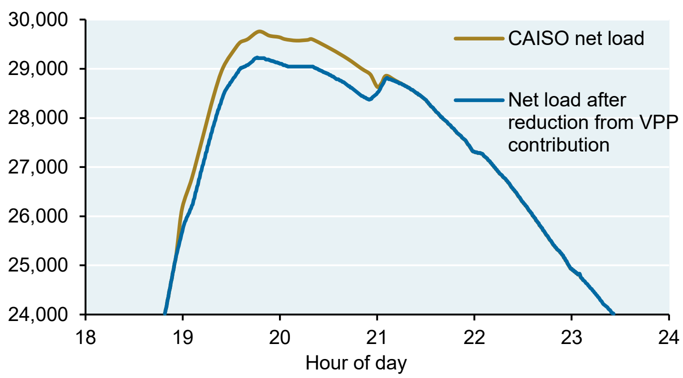
	2024	2025	Growth
Active company deployments	1459	1940	33%
Programs monetized	321	433	35%
Unique offtakers	139	192	38%
VPP capacity	33 GW	37.5 GW	14%

Source: Wood Mackenzie, September 2025

VPPs in action

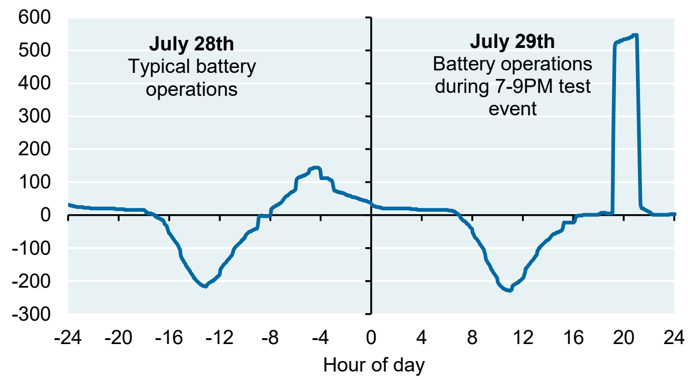
On July 29th 2025, California's Demand Side Grid Support and Emergency Load Reduction programs conducted a test event, collectively producing 535 MW from ~100,000 residential batteries between 7 and 9 PM during CAISO's system peak demand. The demand response shifted CAISO's net load down by 1.7% as shown on the left. On the right: the atypical nighttime discharge of battery capacity during the test period.

Shift in CAISO system net load during VPP test event
Net load, MW



Source: Brattle Group, August 2025

CAISO residential batteries before and during test event
Battery charge (negative) and discharge (positive), MW



Source: Brattle Group, August 2025

More examples. Leap, a VPP aggregator powering demand response programs in New York, Massachusetts and Rhode Island, dispatched 546 MWh from June 23nd to June 25th during a heatwave across the Northeast. Leap drew on 12,125 distributed energy resources including commercial batteries, industrial HVAC systems, residential EV chargers and smart thermostats. On June 24th, Tesla's VPP in California used thousands of Powerwall batteries to dispatch 345 MW of power to the grid for two hours during evening peak demand.

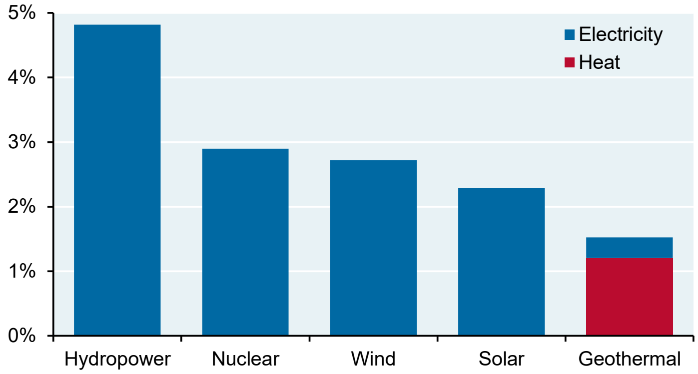
In principle, VPPs should reduce the number of peaker plants in operation and their utilization. That's a topic I plan on examining for next year's paper. Something tells me that data center demand may derail this. One example: NRG Energy was planning on retiring a peaker plant in Chicago but opted against it since the plant is profitable again due to demand from data centers. PJM has reportedly postponed or canceled plans to retire 60% of oil, gas and coal plants, many of them being peakers[74].

[74] "*The AI Boom's Dirty Secret: Reviving Polluting Peaker Plants*", Modern Diplomacy, December 23, 2025

G Forces: an update on geothermal power and geologic hydrogen

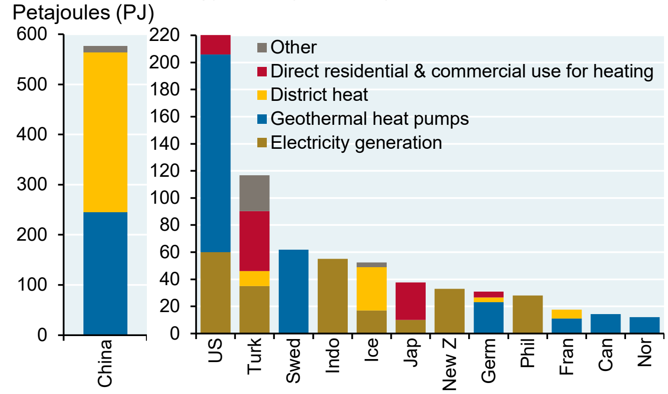
Geothermal energy comes from harvesting the Earth's internal heat and turning it into useful energy, either directly as heat or when converted to electricity. Geothermal energy output is smaller than other low-carbon energy sources; it often doesn't even get its own category in energy databases and is instead lumped in with biomass or "other"[75]. In the first chart we estimate geothermal's share of global useful final energy, while the second chart shows geothermal energy use by country. China, the US and Turkey represent ~65% of global geothermal energy production.

Shares of global useful final energy
Percent



Source: Energy Institute, IEA, JPMAM, 2025

Geothermal energy use by country
Petajoules (PJ)

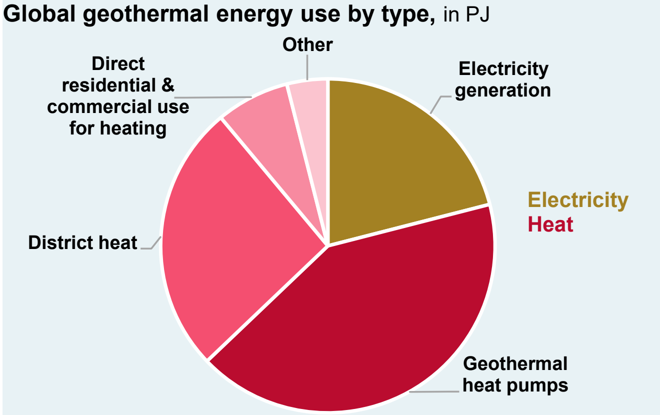


Source: IEA, December 2024

Around 80% of geothermal energy is used as heat rather than power as shown in the pie chart. In most places, temperatures increase by 25° to 30°C per kilometer below 15 meters in depth. At select tectonic hotspots the temperature gradients are higher and where conventional geothermal is often located (Iceland, Indonesia and Nevada), accessing natural reservoirs of hot water or steam. Almost all existing geothermal power production occurs at these conventional reservoir locations.

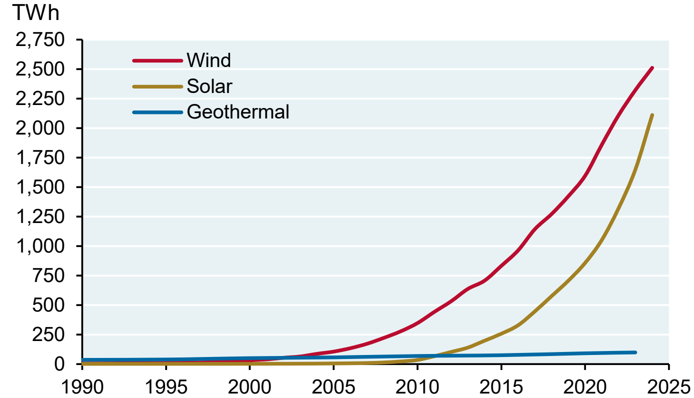
In locations without such hotspots, ground-sourced heat pumps can circulate fluids at depths of 50-200 meters and stable temperatures of 10° to 25°C. This energy can then be used for ambient heating and cooling when surface temperatures are much higher/lower than these levels. At these depths, a mix of heat exchangers, refrigerants and compressors could also be used to generate temperatures of 80°-120°C for low-temperature industrial heat applications such as those shown on the next page. **These unglamorous examples appear to be the most straightforward geothermal use cases from a feasibility, cost and risk management perspective**.

Global geothermal energy use by type, in PJ



Source: IEA, December 2024

Global wind, solar and geothermal electricity generation
TWh

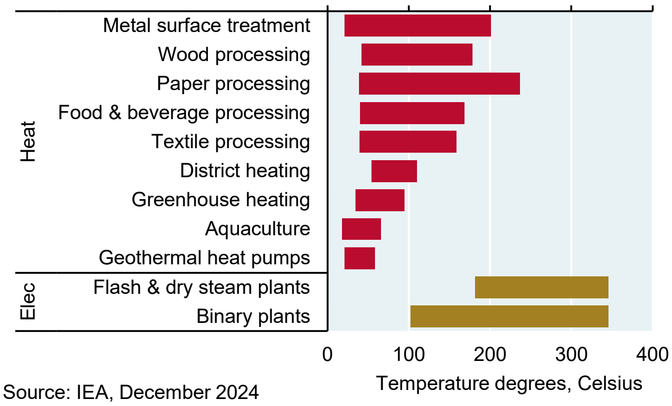


Source: Energy Institute, Geothermal Energy Journal, JPMAM, 2025

75 Some databases such as the Energy Institute only show geothermal power production and exclude geothermal heat, which is unfortunate since heat predominates geothermal applications

Levelized cost estimates for geothermal heat vary substantially. This is not a surprise; the less developed an energy resource, the more uncertainty regarding its real-world cost. The table shows levelized cost of heat estimates for geothermal vs US and European wholesale gas costs. It looks like geothermal power could be cost-competitive in parts of Europe but these would be very location-specific determinations.

Temperature requirements for possible geothermal energy applications



Source: IEA, December 2024

Levelized cost of closed loop geothermal heat

Estimate	Heat (LCOH) $ per MMBtu
Cornell, 2021	$9.30
Stanford, 2022	$15.62
NREL, 2023	$3.7 - $17.5
Energy Journal, 2025	$5.8 - $7.0
US natural gas heat	Wholesale $2-$4
Europe natural gas heat	Wholesale $9-$12

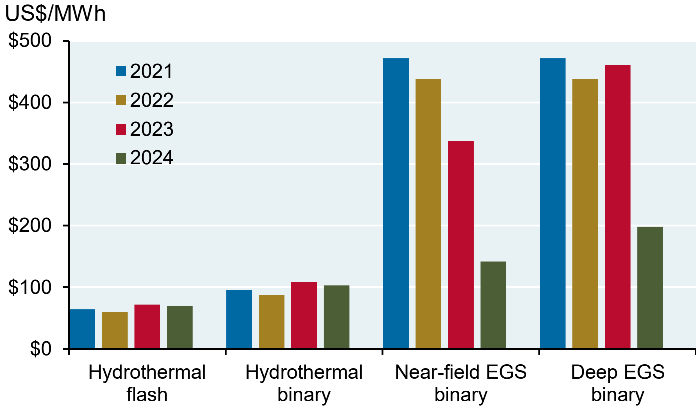
Sources: American Gas Association, EIA, NREL, Eurostat. 2026

As shown on the prior page, ~20% of global geothermal energy entails conversion of heat into constant dispatchable power. For power generation, wells are drilled 0.5 to 2 km deep into zones with temperatures above ~150°C. Like many conversions of thermal heat to electrical energy, efficiencies are low; conversion of geothermal heat to power is just 10%-20% efficient. How much does geothermal power generation cost? The latest estimates come from a 2025 NREL paper (sorry! Now the "National Laboratory of the Rockies" based on its Trump era rebranding). A couple of things to note about the chart below:

- There's a big difference between conventional flash/binary geothermal and Enhanced Geothermal Energy (EGS), although the cost of the latter declined sharply in 2024 according to NREL estimates
- NREL flash and binary geothermal cost estimates of $70 and $103 per MWh are higher than LCOE for wind ($62) and solar ($58), but geothermal provides baseload power while wind and solar don't (2024 geothermal power plant capacity factors were 88%)
- Take all geothermal cost estimates with a giant grain of salt given the scarcity of real world applications

Levelized cost of energy for geothermal power

US$/MWh



Source: National Laboratory of the Rockies, January 2026

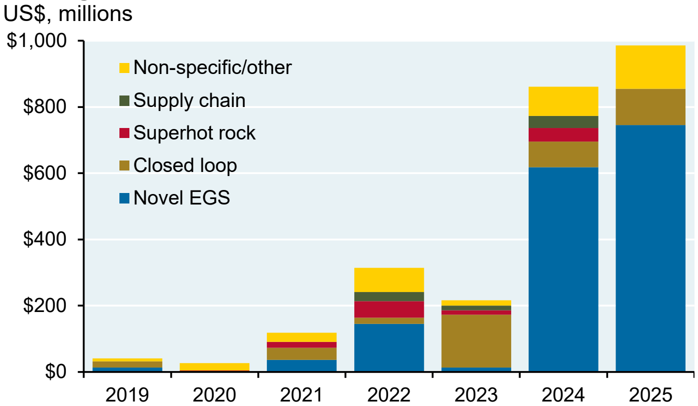
- **Hydrothermal Flash:** Hot geothermal water is extracted and converted to steam to spin a turbine. Water is converted to steam through a process called flashing; as its pressure drops near the surface, the water converts to steam. The leftover water is re-injected to maintain reservoir pressure
- **Hydrothermal Binary:** Hot geothermal water heats a secondary liquid with a low boiling point which turns to steam and drives a turbine. The secondary liquid is typically an organic fluid such as a hydrocarbon (isobutane or pentane) or a refrigerant

At the end of the day, power markets are competitive and there's ample opportunity for geothermal to gain share if its real-world costs are attractive to utilities and independent power producers. As shown earlier, this is happening very slowly compared to more rapid uptake of other renewable energy sources. Recent PPA data highlight why. For 2024, NREL cites a few conventional geothermal PPAs at $60-$75 per MWh compared to $50 - $60 for solar PPAs and $60 - $65 for wind PPAs signed during the same year. For 2025, Ormat cites geothermal PPAs of $100-$110 per MWh compared to wind and solar PPAs of $75 and $60 (Level Ten). Recent high profile geothermal agreements include Microsoft's 51 MW in New Zealand with Contract Energy, Google's 115 MW in the US with Fervo, Meta's two 150 MW projects with Sage and XGS and Panasonic's PPA with Mirai in Japan. This is consistent with an LBNL analysis from 2023 concluding that there's a large cost gap between geothermal and wind/solar power even after adjusting for intermittency[76].

Getting into the details on Enhanced Geothermal Energy (EGS)

Since hot rock exists almost everywhere but is often too impermeable for standard fluid flow, EGS uses injection to create pathways, fracturing rock to form underground heat exchangers so that fluid can circulate, pick up heat and return it to the surface. Fluid can be degraded water (contaminated groundwater, treated municipal water, industrial process water or wastewater, irrigation return water, storm water runoff or brackish water) or freshwater, with chemicals added to improve the fluid's ability to expand and crack rocks. As shown in the next chart, EGS received the lion's share of geothermal investment in 2024 and 2025.

Novel geothermal investment
US$, millions



Source: Sightline Climate, January 2026

Fervo's EGS progress is worth watching as a bellwether on temperature and cost. Fervo's Sugarloaf EGS appraisal well reached ~16,000 feet with expected bottomhole temperatures of ~270°C and was completed in just 16 drilling days, 80% faster than typical ultradeep geothermal DoE benchmarks. The company achieved similar results at another Utah site in February of this year. Fervo cites thermal recovery rates of 50% - 60%, around 3x the efficiency of conventional geothermal (see next page for details).

While Fervo's progress is impressive, like all energy sources we will eventually need a better understanding of fully loaded levelized costs. With geothermal energy, there are also risks with certain approaches that wells lose pressure or temperature over time, something that could substantially affect levelized cost (similar to the concept of solar or battery degradation).

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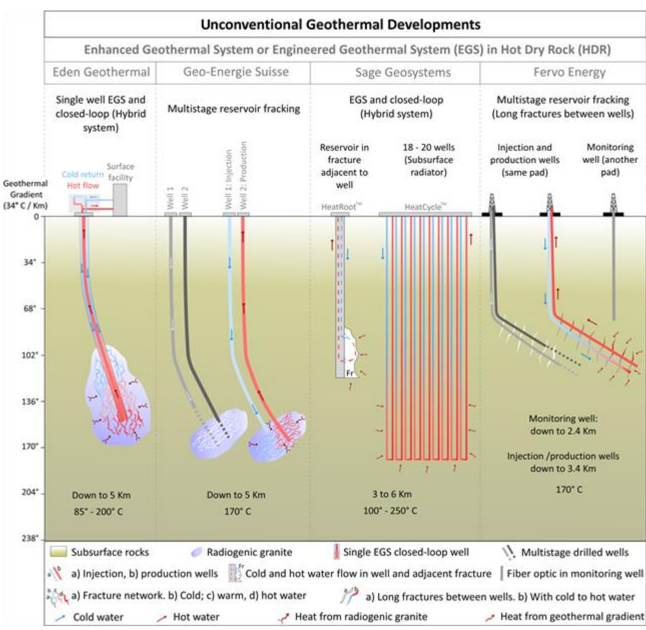
[76] "*Mind the gap: Comparing the net value of geothermal, wind, solar, and solar+storage in the Western United States*", Bolinger et al (LBNL), Renewable Energy Journal, 2023. LBNL conclusions: high capacity factor resources like geothermal should become more important as complements to variable, weather-dependent resources like wind and solar. However, while wind, solar and storage have seen significant growth, deployment of new geothermal plants has barely budged over the same period. Continued growth in wind, solar and storage should improve geothermal's relative market value, "**yet likely not by enough to overcome the persistent cost gap between geothermal and these other, lower-cost resources"**

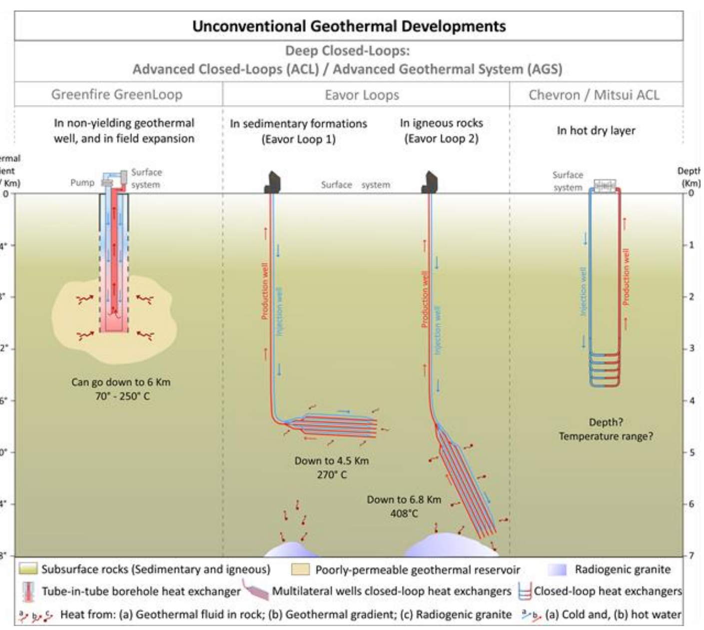
Understanding EGS thermal recovery rates

Thermal recovery factors reflect how efficiently geothermal designs recover heat from a given geothermal operating zone, heat which can be used as is or converted to electricity. The operating zone is essentially the rectangular area whose boundaries reflect the horizontal wellbore, the hydraulic fracture height and the wellbore spacing between the injector well and the producer well (which recovers the heat). Useful thermal energy is based on differences between the initial reservoir temperature and that of the reinjected fluid. If a system ran optimally for long enough throughout an entire reservoir, eventually the injected fluid temperature would equilibrate to reservoir temperature and result in 100% thermal recovery.

Real world recovery thermal recovery rates are well below 100% and represent the technically and economically recoverable energy over a project's lifetime. These recovery rates depend on the efficiency of the reservoir stimulation process, and on the rate at which heat is depleted since geothermal heat recovery is typically engineered to occur faster than the earth replenishes it. Things that lower recovery factors include stages that don't initiate new fractures near the wellbore, fracture pathways that do not connect effectively within the operating zone or highly conductive fractures that move flow outside the zone. Fervo believes that its EGS process mitigates these issues given the use of cased and cemented wellbores and limited-entry designs. While Fervo cites higher thermal heat recovery rates than conventional geothermal, its projected thermal-to-electric conversion efficiency for Project Cape is still 19% since these processes are governed by the normal efficiencies for converting heat to mechanical or electric energy based on Rankine cycle mechanics

Compared to conventional vertical geothermal wells, unconventional wells can provide access to a larger reservoir volume with more consistent and predictable temperatures. Well fracking creates hundreds of individual flow pathways that distribute flow evenly throughout the reservoir, increasing the surface area to volume ratio of the system. The images below are excellent depictions of unconventional geothermal wells. On the left: fracking-based systems in hot dry rock. On the right: closed-loop systems. You will need to zoom in to see them. The big EGS question: at what cost? Within 2-3 years, we should have a much better idea.



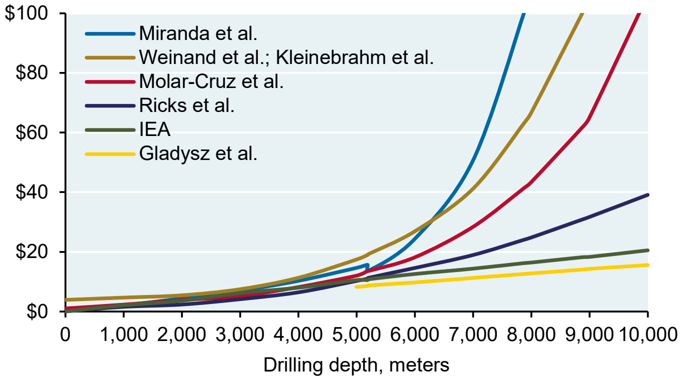


Source: "*Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview*", Open Journal of Geology, Khodayar and Bjornsson, February 2024

Drilling. Growth in EGS will require improved efficiencies in drilling costs. As shown in the first chart, drilling costs tend to increase on a non-linear basis with depth, although studies differ on the degree of non-linearity. The good news is that drilling costs and efficiencies appear to be improving. The second chart shows the time required to reach certain geothermal depths at the FORGE site in Utah. FORGE is a dedicated site where scientists and engineers develop and test breakthroughs in EGS techniques. The third chart also shows substantial progress, measuring Fervo's declining drilling costs and timelines at its Nevada and Utah sites. The US Department of Energy is supportive of geothermal development[77]; we will have to see how/if this translates into reduced permitting times, cost-sharing or expanded subsidies.

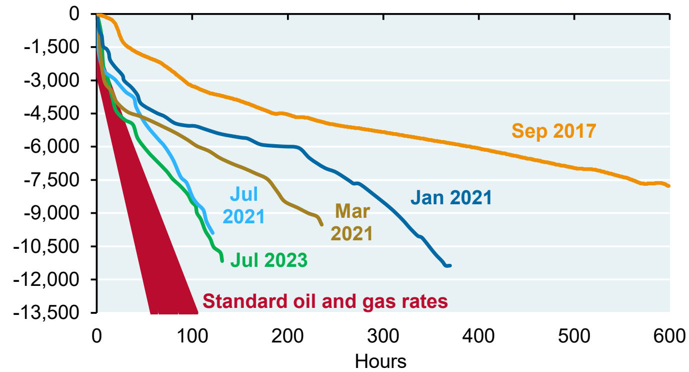
There are other deep-drilling techniques being investigated (using lasers, plasma torches or microwaves to melt rocks instead of grinding them) but their all-in costs, durability and scalability are still unknown. Until then, shallower ground-sourced heat pumps for heating and cooling homes, universities, offices, data centers and low temperature industrial heat appear to be the geothermal paths of least resistance.

Drilling costs by depth in different geothermal energy system optimization models, US$, millions



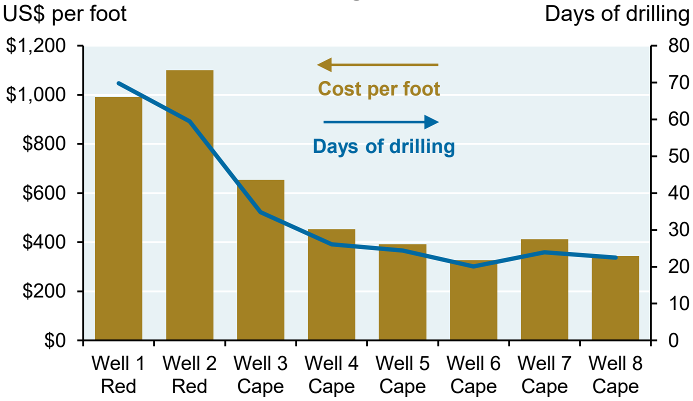
Source: Nexus Journal, December 16, 2025

Utah FORGE well drilling rates
Measured depth, feet



Source: National Laboratory of the Rockies, January 2026

Fervo Nevada and Utah drilling costs and timeline
US$ per foot
Days of drilling



Source: National Laboratory of the Rockies, January 2026

Permitting. Permitting for geothermal projects on public BLM-managed land takes 7 to 10 years, a process which can include several reviews under the National Environmental Policy Act. In contrast, oil & gas projects benefit from existing categorical exclusions (CXs) and established permitting offices. The average oil & gas well on public lands is typically approved in less than a year.

On private lands, gas drilling permits are often processed by the Railroad Commission of Texas in an average of just two days, and Pennsylvania's Oil & Gas Act requires permit processing in 45 to 60 days

Sources: NREL, Oil & Gas Watch, RRC

[77] The OBBBA extended the eligibility period for full and partial clean energy credits for geothermal power along with hydro, nuclear and batteries. The Dep't of the Interior and Bureau of Land Management also announced measures to expedite permitting and increase frequency of geothermal lease sales. Permitting times were cut from one year to 14 days for environmental assessments and from two years to 28 days for environmental impact statements. Utah and California have also streamlined geothermal permitting

What about repurposing old oil and gas wells into geothermal? It sounds interesting but most depleted wells are located far from energy demand centers, many locations are not thermally conductive, well remediation costs can be high and temperatures may only be suitable for district heating.

Emissions. Geothermal can release naturally occurring CO_2 and methane trapped in rock formations. When used for electricity, conventional flash and steam geothermal plants emit an average of 45 grams of CO_2 per kWh (IEA). That's roughly the same as solar and higher than nuclear and wind, but still 20x lower than coal and 10x-11x lower than combined cycle natural gas plants.

Geologic hydrogen sounds great on paper: if just 2% of the probable in-place geologic hydrogen could be recovered, that would amount to ~100,000 million tons of hydrogen which in turn contains 1.4×10^{16} joules of energy. That would be 1.7x the amount of energy in all proven natural gas reserves on earth[78].

But like everything in the world of energy, the devil is in the details:

- One of the few documented geologic hydrogen-producing wells is in Mali, producing almost pure hydrogen from a shallow reservoir at the rate of 5 to 50 tonnes per year; that's the equivalent of 3 barrels of oil per day, or less than one tenth of a single medium-sized wind turbine. Another reported site in Albania produces 200 tonnes per year, which is just 1/350th of the energy a typical steel plant consumes in a year
- Plenty of hydrogen seeps from the earth each year, with some estimates at 23 mm tonnes (global hydrogen consumption is around 100 mm tonnes). But seeps are by their nature very diffuse and low-pressure which makes them difficult to capture
- Geologic hydrogen is often found 40%-60% mixed with other gases (methane, CO_2 and nitrogen) that would have to be removed and separated, which would be energetically costly
- Even assuming a 75% hydrogen/25% other gases mixture, emissions of 1.5 kg of CO_2 per kg of geologic hydrogen would be 50% higher than the Hydrogen Science Coalition definition of clean hydrogen
- Geologic hydrogen is unlikely to be where it's needed. Currently, almost all hydrogen is produced at the same site where it's consumed given difficulties with storage and transmission

Hydrogen reservoirs suitable for continuous, commercial-scale collection near hydrogen consumption hubs would be a welcome development. At the current time, the existence of such reservoirs exists only on paper. More details if you're interested[79]:

- There are three kinds of hydrogen reservoirs, each with its own dynamics
- Focused seepage plays: predominance of aqueous rather than gaseous hydrogen leads to lower hydrogen density, a low recovery factor and low hydrogen production rates per well. Production rates may be difficult to increase in fields where the hydrogen resource is spread across multiple reservoir zones
- Coal-seam plays: resource density can be substantial due to the gas-adsorption capacity of coal, and gas recovery potential can be higher than in focused seepage plays if wells are closely-spaced. However, well productivity may be low due to low permeability of coal, especially at larger depths. Also; to depressurize coal, large quantities of water must be lifted from the wells and managed at the surface. Finally, the hydrogen fraction in the adsorbed gas may be low due to higher adsorption capacity of CO_2 and methane
- Reservoir-trap-seal plays can have high hydrogen resource density, a high recovery factor and high well productivity. An industrial scale offtake might be achieved with 10-50 wells. However, to commit long-duration supply to a large industrial facility like an ammonia plant, an area from 10 to 60 square km might be required. And if hydrogen occurs mixed with other gases or mixed in water, achieving industrial supply-rates becomes challenging since large volumes of gas need to be produced for a modest hydrogen yield

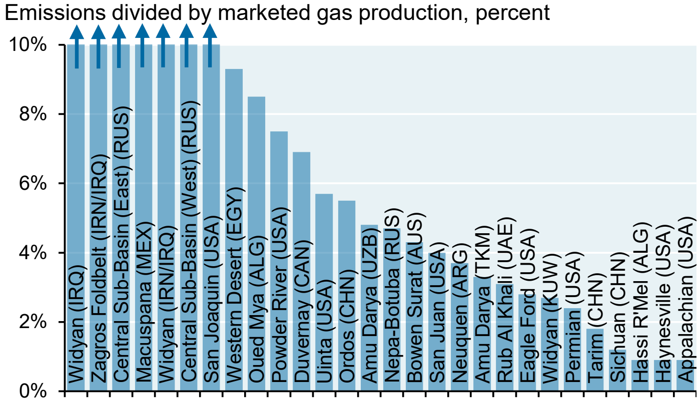
[78] "*Model predictions of geologic hydrogen resources*", Ellis (USGS) and Gelman, Science Advances, Dec 2024

[79] "*Natural hydrogen development: potential and challenges*", Arnout Everts (AEGeo), International Journal of Hydrogen Energy, 2025

Emissions footprints: MethaneSAT, LNG supply chains and xAI's mobile natural gas plants

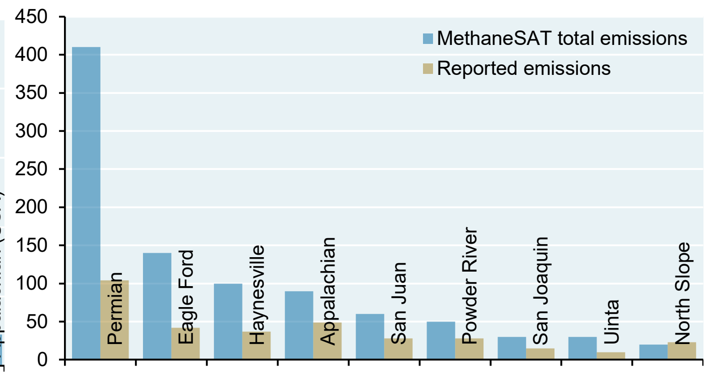
Before MethaneSAT lost contact with earth after suffering a power failure, it gathered important data on GHG emissions from oil and gas basins that account for half of global onshore production. The overall findings show that GHG emissions from these basins generally exceed commonly cited inventories such as EDGAR and the EPA GHG inventory by ~50%. While methane intensity tends to be higher in oil basins than gas basins, the latter were identified as having GHG emissions that were 3x higher than reported levels. While gas basins vary in GHG intensity (i.e., emissions divided by marketed gas production), **none was below the 0.2% target agreed to under the UN Oil & Gas Decarbonization Charter** (OGDC). The second chart shows MethaneSAT vs Reported emissions for major US oil & gas basins; remember, reported emissions figures are often based on emissions factors and engineering estimates rather than empirical measurements.

Gas-normalized methane intensity vs 0.2% OGDC target
Emissions divided by marketed gas production, percent



Source: MethaneSAT, observations from May 2024 to June 2025

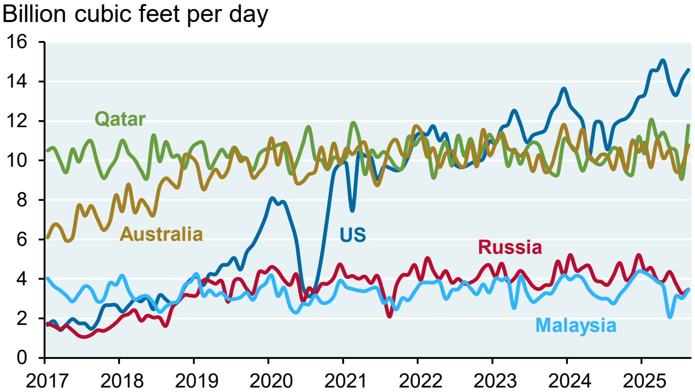
US basins: MethaneSAT vs reported oil and gas emissions
Tonnes of GHG emissions per hour



Source: MethaneSAT, observations from May 2024 to June 2025

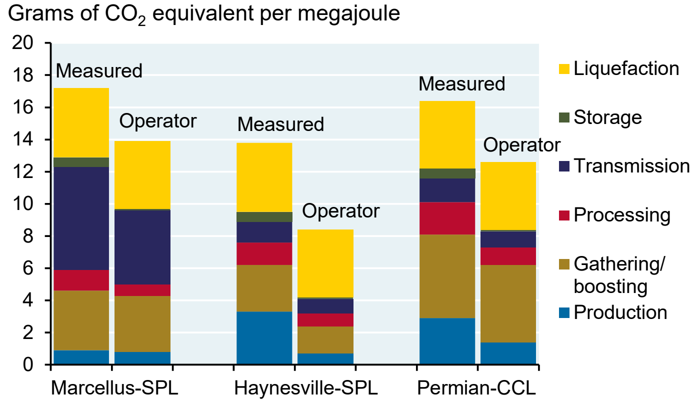
LNG supply chains. The US is now the world leader in LNG exports as shown in the next chart. Using aerial LIDAR surveys, scientists at UT Austin aggregated results from a three-year measurement campaign across six stages of LNG supply chains[80]. Their aerial GHG measurements were 20%-40% higher than activity-based inventory assessments by what they describe as "operators", which include stack tests, ground-based leak detection, fuel gas flow rates and other information. Another example of aerial surveys painting a very different picture of real world emissions.

LNG exports from select countries
Billion cubic feet per day



Source: EIA, China Customs, Bloomberg, JPM Commodities Research, Aug 25

Life cycle GHG emissions of three gas supply chains
Grams of CO_2 equivalent per megajoule



Source: Zhu et al (UT Austin), July 2025

80 "*Tracking US Liquefied Natural Gas Supply Chain GHG Emissions Intensity through Direct Measurements*", UT Austin Energy Emissions Modeling and Data Lab/Dep't of Petroleum and Geosystems Engineering, July 2025

Nitrogen Oxide (NOx) emissions and xAI data centers. In 2024 when Elon Musk announced that xAI's Memphis Colossus supercomputer project was powered by mobile gas plants, he was lauded in some corners for nimbleness and creativity at side-stepping pollution control regulations that normally apply to stationary gas plants but not mobile ones, allowing xAI to complete the project in 122 days. Not everyone agrees:

- In 2024 the EPA proposed new regulations to strengthen limits on NOx emissions from most new, modified and reconstructed combustion turbines. But xAI mobile turbines were not equipped with pollution controls after being given a waiver by the Tennessee Department of Environment and Conservation. This led to xAI reportedly becoming one of the largest industrial NOx emitters in the county[81]
- xAI mobile turbines were meant to be temporary until the county can meet xAI power needs via the grid or until xAI substitutes mobile turbines with its own permanent behind the meter generation
- xAI received permits in 2025 to make 15 of the 35 turbines permanent and stated that it intends to install pollution controls that would reduce NOx emissions to 2 parts per million compared to current uncontrolled rates of 9-25 parts per million. But until such controls are in place, xAI turbine NOx emissions continue with associated risks to human health (see box)
- In January 2026, the EPA weakened restrictions on NOx emissions and denied a proposal to require turbines to be equipped with state-of-the-art pollution controls. That said, the EPA appeared to side with environmental groups pushing for controls at xAI's Memphis facility, with the EPA concluding that portable turbines do in fact require permits even if they are on trailers and can be moved[82]. Whether the EPA or state officials will enforce this ruling is a separate matter entirely
- xAI is also relying on mobile natural gas turbines without pollution controls in Mississippi to support its Colossus II project, with plans to add more[83]. State regulators in Mississippi maintain that since the turbines are parked on tractor trailers, they don't require permits

Is mobility the new regulatory workaround? Tennessee and Mississippi have among the highest concentrations of "dry" (alcohol-free) counties in the US, and both states are working on legislation to ban sweepstakes casinos. **I guess liquor stores and casinos in those states could just mount them on tractor trailers instead and do business as usual.**

Power plants, NOx emissions and human health

1. A 2022 review of multiple studies found that elevated levels of NOx were strongly associated with heart and lung harm, affected pregnancy and birth outcomes, and were likely associated with increased risk of kidney and neurological harm, autoimmune disorders and cancer
2. After four Louisville (KY) coal-fired power plants retired coal as their energy source or installed stricter emissions controls on NOx, local residents' asthma symptoms and asthma-related hospitalizations and emergency room visits dropped dramatically
3. After adjusting for age, sex, race, median income, there were significant 11%, 15%, and 17% increases in estimated rates of hospitalization for asthma, ARI and COPD among individuals > 10 years of age living in a ZIP code containing a fuel-fired power plant compared with one that had no power plant

Sources: American Lung Association (1), Nature Energy (2), Environmental Health Perspectives (3)

81 "*Musk's data company draws a backlash in Memphis*", Politico, May 6, 2025

82 "*EPA pokes Musk over using unpermitted turbines for AI*", Politico, January 22, 2026; "*EPA rules that xAI's natural gas generators were illegally used*", Tech Crunch, January 16, 2026

83 "*Elon Musk gambles billions in Memphis to catch up on AI*", WSJ, October 5, 2025

My Jeep Wrangler hybrid, part IV: assessing the cost of local gasoline and electricity options

I own a Jeep Wrangler 4xe which I've written about before due to its many recalls and repairs[84]. Despite the aggravation, I like the car since I can load my fishing kayak into the back, keeping the tailgate door open while keeping the lift gate closed. Now that it's finally fixed (fingers crossed), I want to focus on fuel costs.

Hybrids like mine make up 10%-50% of the EV fleet in major car markets[85]. The Wrangler 4xe is rated at 22 miles of electric-only range from its 17 kWh battery, resulting in 1.29 miles per kWh. When the battery is depleted, it can travel 20 miles per gallon of gasoline. I assumed that charging would be cheaper than gasoline given everything I've read about EVs, but this turned out to be highly dependent on which power plan I sign up for and how religious I am about charging at night. Let's get into the details.

PSEG Long Island offers two rate plans, each with a rate per kWh reflecting the cost of power and delivery. There's also a fixed charge of 56 cents per day that's the same under both plans.

- **Standard Plan**: Peak rates of 47.5 cents/kWh (3PM-7PM) and off-peak rates of 21.5 cents/kWh (7PM-3PM)
- **Optional Plan**: This plan is intended for customers willing to shift electricity usage to when demand is at its lowest overnight. Super off-peak rates of 13.3 cents/kWh (10PM-6AM); off-peak rates of 24.0 cents/kWh (6AM-3PM) and (7PM-10PM); peak rates of 50.0 cents/kWh (3PM-7PM)

I now need to make assumptions as to when I charge the Jeep each day. It takes around 2 hours to fully charge its 17 kWh battery with my Level 2 charger, so it would not be difficult to condense 90% of my charging into Standard Plan off-peak hours and charge only 10% during the 4-hour peak window. If I sign up for the Optional Plan and were only mildly focused on its benefits, I might charge 50% during super off-peak, 40% during off-peak and 10% during peak (Scenario 1). If I only charged during super off-peak hours, that might be inconvenient but would maximize economic benefits (Scenario 2).

Jeep charging options on Long Island (PSEG)

		Super Off Peak	Off Peak	Peak
Standard Plan	Time	N/A	7PM-3PM	3PM-7PM
	Delivery charge, ¢/kWh	N/A	9.3	18.9
	Power supply, ¢/kWh	N/A	12.2	28.7
	Total rate, ¢/kWh	N/A	21.5	47.5
	Assumed share of day	N/A	90%	10%
Optional Plan, Scenario 1	Time	10PM-6AM	6AM-3PM, 7PM-10PM	3PM-7PM
	Delivery charge, ¢/kWh	4.5	9.3	24.4
	Power supply, ¢/kWh	8.8	14.7	25.6
	Total rate, ¢/kWh	13.3	24.0	50.0
	Assumed share of day	50%	40%	10%
Optional Plan, Scenario 2	Time	10PM-6AM	6AM-3PM, 7PM-10PM	3PM-7PM
	Delivery charge, ¢/kWh	4.5	9.3	24.4
	Power supply, ¢/kWh	8.8	14.7	25.6
	Total rate, ¢/kWh	13.3	24.0	50.0
	Assumed share of day	100%	0%	0%

Source: "Common Residential Electric Rates 2026", PSEG, JPMAM, February 2026

Getting ready to hunt for striped bass on Peconic Bay in early May

[84] First recall: loss of motor power. Second recall: thermostat gasket failure leading to coolant leakage and electric battery heater failure. Third recall: "The high voltage battery may fail internally. The defect has not been identified and the root cause is still being investigated. An internally failed battery **could lead to a vehicle fire with the ignition on or off**…customers are advised to refrain from recharging these vehicles, and **not to park inside buildings or structures** or near other vehicles until the vehicle has the final repair completed"

[85] Plug-in hybrid share of EV fleet for top 10 countries with largest EV fleets: China 28%, US 24%, Germany 40%, UK 34%, France 35%, Canada 28%, South Korea 10%, Japan 51%, Italy 47%, Australia 17%

Results. Unless I choose the Optional Plan AND only charge at night, gasoline is actually cheaper than electricity as shown in the table. This is mostly a reflection of the very high cost of electricity on Long Island.

Jeep Wrangler 4xe fueling cost comparison, 100 miles of driving
ICE fuel mileage: 20 mpg; EV miles per kWh: 1.29

	Gas cost	EV cost	Gas-Elec
Standard Plan	$15.50	$20.68	-$5.18
Optional Plan, Scenario 1	$15.50	$18.25	-$2.75
Optional Plan, Scenario 2	$15.50	$11.43	$4.07

Source: EVAdoption, Fuel Economy, PSEG, JPMAM, 2026. Assuming roundtrip efficiency of 90%

In areas where electricity costs are lower and gas prices are higher, the benefits of electric charging increase. Paul Martin, an industrial/chemical engineer who consults for us on energy topics, lives in Ontario where his electricity rates are ~4 cents per kWh during super off-peak overnight hours due to plentiful hydroelectric and nuclear power; his gasoline costs are also higher at $3.45 per gallon. If PSEG offered that kind of pricing, there would be a large benefit for Jeep charging: $13.82 compared to $4.07 in my Optional PSEG Plan, Scenario 2.

What about other PHEVs? Rachel owns a Lexus which I generally don't drive since she does not like live bait or dead caught fish in the car. In the second grid I compute Rachel's Lexus charging tradeoffs which are similar to the Jeep for the Standard Plan and even worse for Optional Plans. Why? The benefit of better Lexus EV mileage of 2.06 miles per kWh is offset by the Lexus having even better ICE mileage of 36 mpg. So, she has even less incentive to charge her PHEV than I do.

What kind of PHEV has a consistently positive incentive for EV charging on Long Island? Something like the BMW x5 45e since its EV mileage is high at 1.82 miles per kWh relative to low ICE fuel mileage of 20 mpg. **What would be the worst?** The Volvo XC90 since its EV mileage of 0.95 miles per kWh is terrible compared to its 27 ICE mpg. In other words: you cannot make blanket statements on PHEV electricity vs fuel costs for places like Long Island given its high electricity prices and substantial differences in PHEV electricity vs gasoline mileage.

Lexus NX 450h+ fueling cost comparison, 100 miles of driving
ICE fuel mileage: 36 mpg; EV miles per kWh: 2.06

	Gas cost	EV cost	Gas-Elec
Standard Plan	$8.61	$13.02	-$4.41
Optional Plan, Scenario 1	$8.61	$11.49	-$2.88
Optional Plan, Scenario 2	$8.61	$7.20	$1.41

BMW X5 xDrive 45e fueling cost comparison, 100 miles of driving
ICE fuel mileage: 20 mpg; EV miles per kWh: 1.82

	Gas cost	EV cost	Gas-Elec
Standard Plan	$15.50	$14.68	$0.82
Optional Plan, Scenario 1	$15.50	$12.95	$2.55
Optional Plan, Scenario 2	$15.50	$8.11	$7.39

Volvo XC90 T8 fueling cost comparison, 100 miles of driving
ICE fuel mileage: 27 mpg; EV miles per kWh: 0.95

	Gas cost	EV cost	Gas-Elec
Standard Plan	$11.48	$28.25	-$16.77
Optional Plan, Scenario 1	$11.48	$24.93	-$13.44
Optional Plan, Scenario 2	$11.48	$15.62	-$4.14

Source: EVAdoption, Fuel Economy, PSEG, JPMAM, 2026

Bluefish tastes best as ceviche or smoked into fish jerky or pâté

It's tough to make money in the EV business

Four Chinese EV companies and Tesla have positive operating margins selling EVs. The rest of the universe below is still in the red on an operating margin basis. It's unclear if this will change in the US given the expiration of the $7,500 tax subsidy, the weakening of OEM environmental compliance rules (Zero Emission Vehicle, EPA and CAFE mileage standards) and tariffs on battery parts from China. Stellantis announced a $26 billion writeoff related to EVs, announcing that the charges "reflect a strategic shift to put freedom of choice". In other words, producing what customers want rather than what government regulatory mandates demand. The Stellantis writeoff follows on a $6 bn EV writeoff from GM and a $19.5 bn writeoff from Ford. Bottom chart: EV investing has been a money-loser vs traditional autos since April 2023, although EVs made up some lost ground last year.

EV operating margins

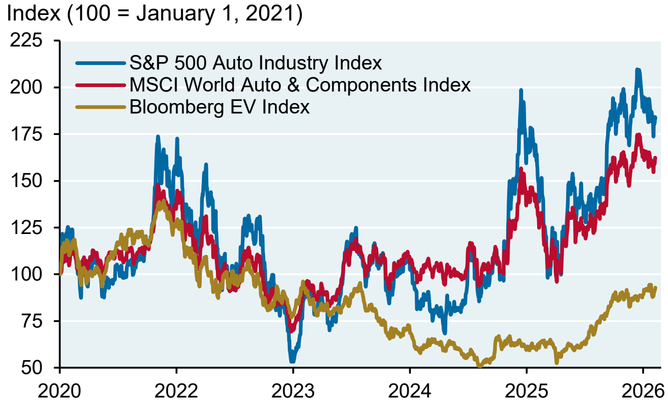
Brand	Country	Public or private	EVs sold in 2024	EV operating margins 2023	2024	2025	Latest EV op margin	Type	Trailing 2 yr price return
Xiaomi	China	Public	136,854			11%	11%	DV	170%
BYD	China	Public	4,272,145	6%	6%		6%	PP	63%
Li Auto	China	Public	500,508	6%	5%		5%	PP	-46%
Tesla	United States	Public	1,789,226	9%	7%	5%	5%	PP	113%
Seres	China	Public	497,008	-16%	3%		3%	DV	N/A
Kia	South Korea	Public	638,000			-3%	-3%	DV	36%
Hyundai	South Korea	Public	757,191			-5%	-5%	DV	99%
Zeekr	China	Private	222,123	-16%	-9%		-9%	PP	N/A
Leapmotor	China	Public	293,724	-26%	-10%		-10%	PP	85%
BMW	Germany	Public	593,150			-10%	-10%	DV	-9%
Mercedes	Germany	Public	387,126			-10%	-10%	DV	-11%
Volvo	Sweden	Public	352,787			-10%	-10%	DV	44%
Stellantis	Netherlands	Public	314,500			-15%	-15%	DV	-71%
VW	Germany	Public	1,014,456			-15%	-15%	DV	-21%
Xpeng	China	Public	190,068	-35%	-16%		-16%	PP	117%
NIO	China	Public	221,970	-41%	-33%		-33%	PP	-2%
GM	United States	Public	114,432			-43%	-43%	DV	105%
Toyota	Japan	Public	4,304,400			-60%	-60%	DV	2%
Rivian	United States	Public	51,579	-129%	-94%	-67%	-67%	PP	50%
Ford	United States	Public	105,000	-80%	-132%	-72%	-72%	DV	17%
Honda	Japan	Public	932,709			-74%	-74%	DV	-16%
Polestar	Sweden	Public	44,458	-62%	-89%		-89%	PP	-51%
Vinfast	Vietnam	Public	178,653	-141%	-126%		-126%	PP	-35%
Lucid	United States	Public	10,241	-521%	-374%	-259%	-259%	PP	-67%
MSCI China Consumer Discretionary Index									36%
S&P 500 Consumer Discretionary Index									27%

Type: PP = pure play EV only, DV = diversified ICE and EV segments

Source: Bloomberg, EV.com, Motor Illustrated, Argus Media, Autoblog, JPMAM estimates, 2026

Auto and EV equity indices total returns

Index (100 = January 1, 2021)



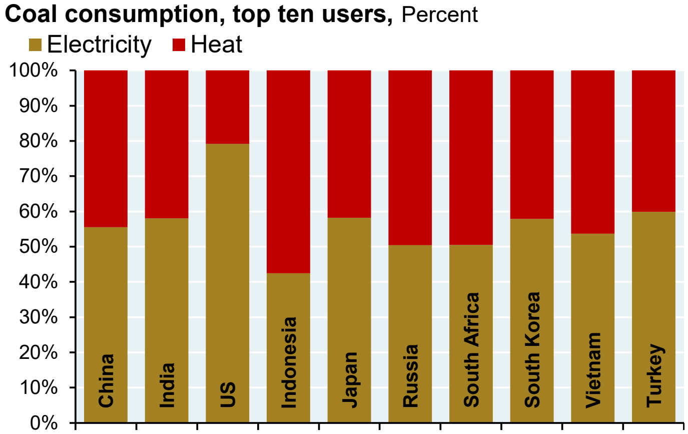
Source: Bloomberg, JPMAM, February 11, 2026

Essential charts: on renewables, electrification, fossil fuels, nuclear, CCS, hydrogen and sustainable fuels

A lot of energy analysis is exclusively focused on power generation. As discussed earlier, while electrification of energy use is rising (currently ~33% on a global basis), energy consumption is still dominated by non-electric uses. Another way to think about it: the charts below show the shares of coal and gas used for power, thermal heat and transport. A lot of countries are reducing coal used for power generation, but for most large coal users power represents only around half of their total coal consumption. For most large gas users, power generation represents an even smaller share of total gas consumption; the rest is harder-to-decarbonize thermal heat. **So: don't overestimate the impact of grid decarbonization on total fossil fuel consumption.**

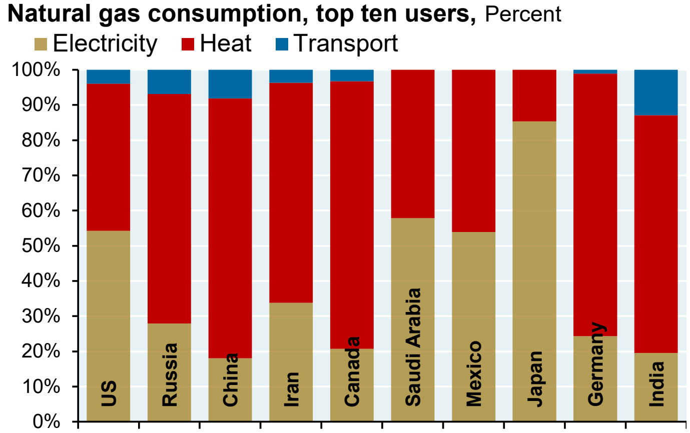
Our essential charts section starts with country-specific statistics and then focuses on renewables and electricity #2 - #7, fossil fuels #8 - #11, nuclear #12 and concludes with CCS, hydrogen and sustainable fuels #13 - #15.

Coal consumption, top ten users, Percent



Source: Energy Institute, JPMAM, 2024

Natural gas consumption, top ten users, Percent



Source: Energy Institute, JPMAM, 2024

[1] Useful final energy, electrification and related statistics by country

The table shows useful final energy and related statistics on UFE, electricity and other variables. These 33 countries represent 86% of global useful final energy consumption. See Appendix I for our UFE methodology.

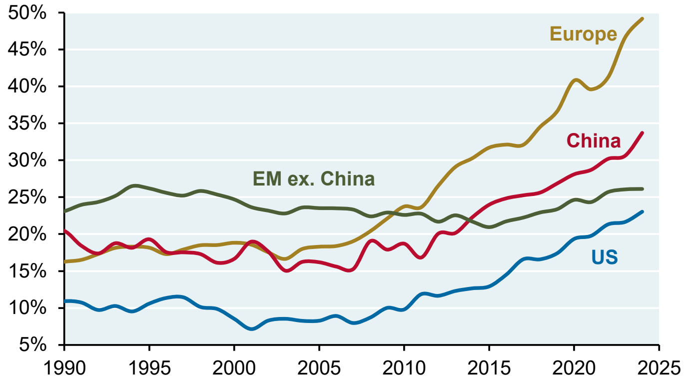
		Useful final energy								Electricity								BioF	Import reliance		
	Country	Useful final energy (EJ)	Nuclear Share Of Useful Final Energy	Renewable Share Of Useful Final Energy	Wind And Solar Share Of Useful Final Energy	Fossil Fuel Share Of Useful Final Energy	Oil Share Of Useful Final Energy	Gas Share Of Useful Final Energy	Coal Share Of Useful Final Energy	Electricity Share Of Useful Final Energy	Renewable Share Of Elgen	Wind+Solar Share Of Elgen	Hydro Share Of Elgen	Nuclear Share Of Elgen	Biomass/Geothermal Share Of Elgen	Fossil Fuel Share Of Elgen	Coal Share Of Elgen	Biofuel Share Of Transport Energy	Oil import reliance	Gas import reliance	Coal import reliance
1	China	87.7	2%	13%	7%	85%	18%	12%	54%	39%	34%	18%	13%	4%	2%	61%	58%	0%	72%	43%	-3%
2	US	44.5	6%	9%	6%	85%	30%	47%	8%	35%	23%	16%	5%	18%	1%	59%	15%	5%	0%	-14%	-34%
3	India	20.0	1%	7%	4%	92%	27%	8%	56%	35%	20%	11%	8%	3%	1%	78%	75%	0%	87%	54%	21%
4	Russian Federa	17.1	4%	4%	0%	91%	20%	60%	12%	24%	18%	1%	17%	18%	0%	64%	18%	0%	-188%	-32%	-143%
5	Japan	8.5	3%	9%	4%	85%	35%	23%	27%	40%	23%	11%	8%	8%	4%	63%	30%	0%	100%	100%	100%
6	Iran	7.5	0%	1%	0%	99%	20%	78%	1%	17%	5%	1%	5%	2%	0%	93%	0%	0%	-161%	-7%	100%
7	Canada	7.1	4%	20%	3%	76%	28%	46%	2%	30%	64%	9%	54%	13%	2%	22%	4%	0%	-179%	-51%	-291%
8	South Korea	6.6	9%	3%	2%	87%	45%	22%	21%	32%	10%	6%	1%	30%	3%	59%	30%	0%	100%	100%	100%
9	Saudi Arabia	6.1	0%	1%	1%	99%	57%	43%	0%	16%	2%	2%	0%	0%	0%	98%	0%	0%	-190%	0%	100%
10	Brazil	5.7	1%	43%	11%	56%	37%	13%	6%	44%	87%	24%	55%	2%	8%	10%	2%	0%	-48%	27%	80%
11	Germany	5.7	0%	17%	13%	81%	33%	34%	13%	30%	57%	43%	4%	0%	10%	38%	21%	3%	100%	95%	48%
12	Indonesia	5.2	0%	7%	0%	93%	23%	22%	48%	24%	19%	0%	7%	0%	12%	80%	61%	11%	60%	-51%	-259%
13	Mexico	4.0	1%	6%	4%	93%	34%	56%	3%	27%	21%	13%	7%	3%	2%	75%	3%	0%	-12%	64%	54%
14	France	3.9	32%	14%	6%	53%	29%	21%	3%	48%	27%	13%	13%	68%	2%	4%	0%	4%	100%	100%	100%
15	Turkey	3.7	0%	15%	6%	85%	26%	35%	25%	33%	46%	19%	21%	0%	6%	54%	35%	0%	100%	100%	58%
16	United Kingdon	3.3	4%	16%	10%	79%	29%	47%	3%	30%	51%	35%	2%	14%	14%	31%	1%	3%	52%	50%	98%
17	Italy	2.9	0%	16%	7%	84%	34%	48%	2%	30%	49%	21%	20%	0%	7%	50%	5%	2%	93%	95%	100%
18	Australia	2.9	0%	12%	10%	88%	32%	32%	25%	33%	35%	29%	5%	0%	1%	64%	45%	0%	72%	-306%	-676%
19	Thailand	2.6	0%	5%	1%	95%	43%	40%	13%	26%	15%	4%	3%	0%	7%	85%	17%	4%	78%	41%	78%
20	Spain	2.5	7%	23%	16%	69%	40%	27%	2%	38%	56%	42%	12%	19%	2%	22%	1%	3%	100%	100%	99%
21	South Africa	2.5	1%	3%	2%	96%	16%	5%	75%	32%	8%	8%	0%	3%	0%	87%	86%	0%	100%	100%	-58%
22	Vietnam	2.4	0%	18%	6%	82%	23%	5%	53%	43%	42%	13%	29%	0%	0%	58%	50%	0%	75%	0%	59%
23	Malaysia	2.4	0%	6%	1%	94%	27%	48%	19%	30%	18%	2%	16%	0%	1%	82%	46%	0%	44%	-74%	100%
24	Taiwan	2.3	2%	5%	4%	93%	36%	26%	30%	42%	11%	9%	1%	4%	1%	83%	39%	0%	100%	100%	100%
25	Poland	1.9	0%	10%	7%	90%	28%	28%	34%	30%	30%	24%	1%	0%	5%	69%	56%	4%	100%	83%	-5%
26	Argentina	1.8	2%	11%	4%	87%	28%	58%	1%	27%	34%	13%	19%	7%	2%	58%	1%	4%	-101%	3%	100%
27	Netherlands	1.6	1%	13%	11%	85%	41%	39%	6%	25%	51%	45%	0%	3%	6%	45%	8%	2%	100%	69%	100%
28	Pakistan	1.6	5%	9%	1%	86%	16%	56%	14%	26%	34%	4%	29%	17%	1%	49%	18%	0%	100%	30%	13%
29	Belgium	1.1	9%	8%	7%	82%	46%	30%	6%	21%	34%	29%	1%	41%	4%	25%	3%	3%	100%	100%	100%
30	Sweden	0.9	19%	47%	17%	34%	26%	3%	5%	66%	69%	26%	37%	29%	6%	1%	1%	3%	100%	100%	100%
31	Norway	0.8	0%	64%	6%	36%	22%	11%	3%	65%	98%	10%	88%	0%	0%	2%	0%	0%	-828%	-3261%	100%
32	Switzerland	0.5	15%	36%	4%	49%	30%	19%	0%	52%	65%	8%	56%	29%	2%	6%	0%	0%	100%	100%	100%
33	Denmark	0.3	0%	37%	30%	63%	45%	15%	3%	40%	85%	69%	0%	0%	16%	15%	5%	0%	62%	-13%	100%

Source: Energy Institute, IEA, JPMAM, 2025

[2] Renewable and clean electricity generation

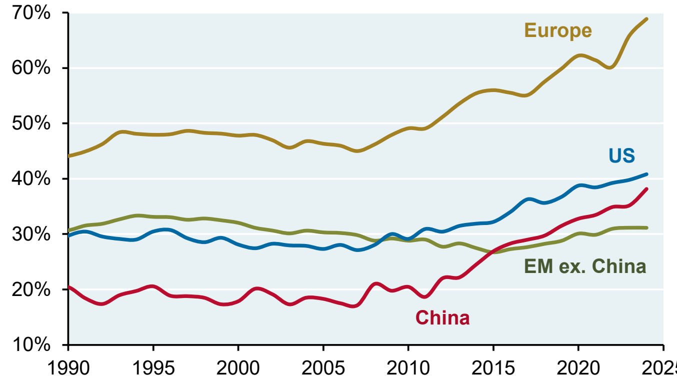
The charts below show various cuts on renewable and clean (i.e., including nuclear) shares of power generation. Europe is the leader here by a wide margin. Using the clean energy metric: Sweden 99%, Switzerland 94%, France 95%, Denmark 85%, Spain 75%, Germany 57%, Netherlands 53% and Italy 49%. Note that the 70% clean energy share in Europe is comprised of wind/solar at 25%, nuclear 20%, hydro 18% and biomass 6%.

Renewable share of electricity consumption
Percent



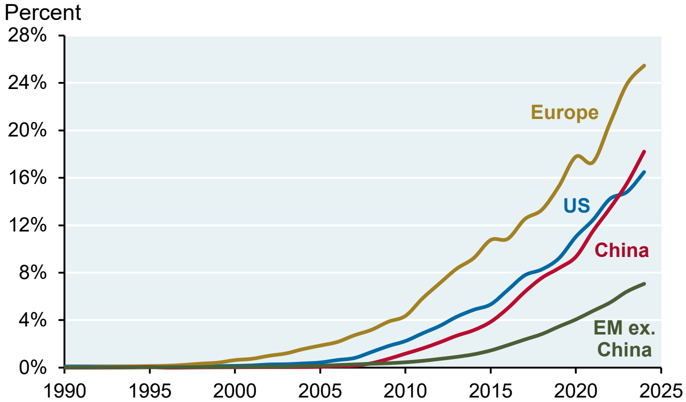
Source: Energy Institute, JPMAM, 2025

Renewable + nuclear share of electricity consumption
Percent



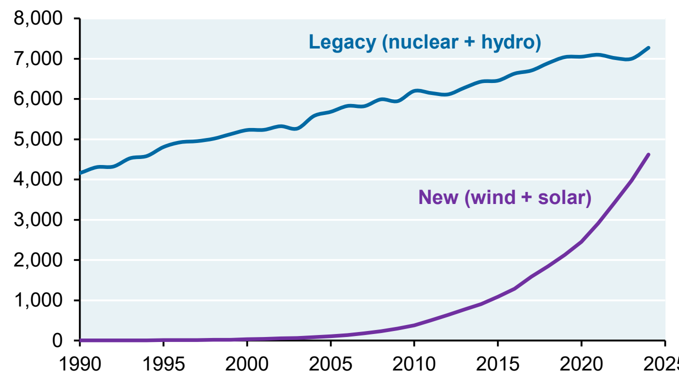
Source: Energy Institute, JPMAM, 2025

Wind and solar share of electricity consumption
Percent



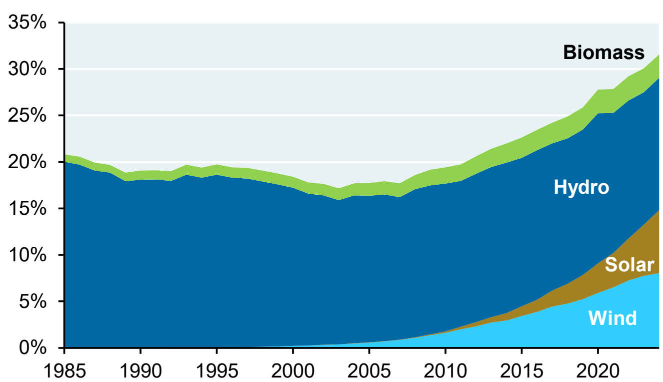
Source: Energy Institute, JPMAM, 2025

Legacy vs new low carbon electricity generation, global
Terawatt-hours



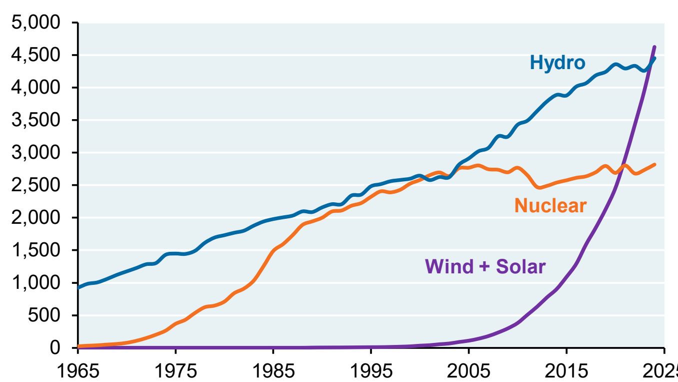
Source: Energy Institute, JPMAM, 2025

Renewable share of global electricity generation
Percent



Source: Energy Institute, JPMAM, 2025

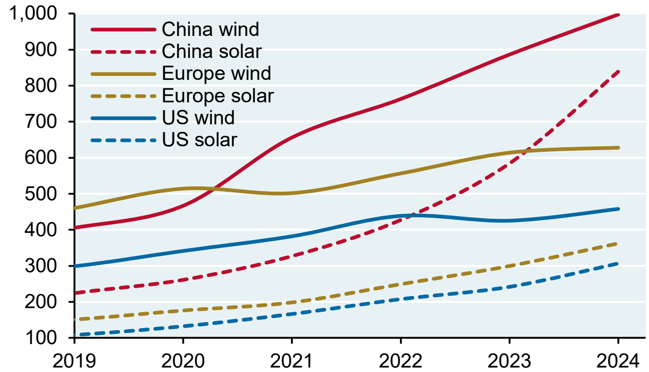
Global electricity generation
Terawatt-hours



Source: Energy Institute, JPMAM, 2025

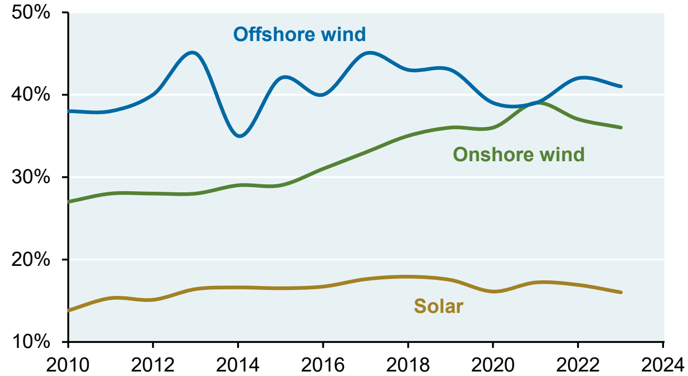
Solar is converging with wind generation in China, the US and Europe. Capacity factors remain stable for solar, onshore wind and offshore wind. Hydro capacity factors rebounded last year after a three year decline. China and the rest of the emerging world continue to add new hydropower while OECD hydro capacity has been flat for the last decade.

Solar generation converging with wind
TWh



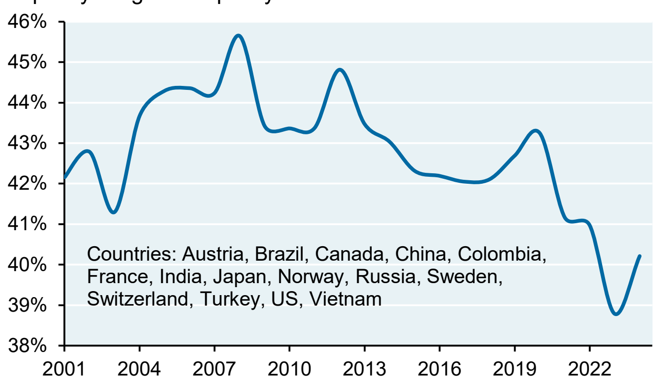
Source: Energy Institute, JPMAM, 2025

Global capacity factors
Capacity weighted percentage



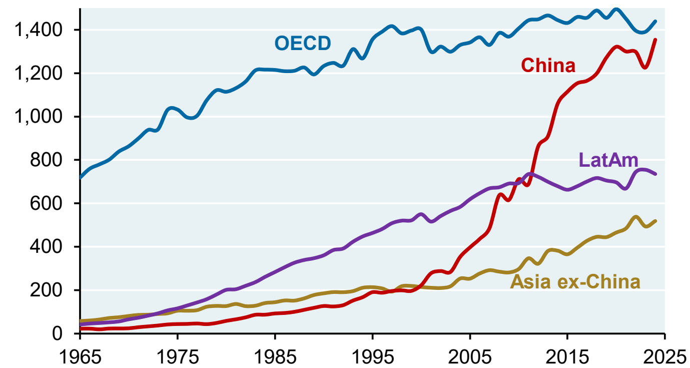
Source: International Renewable Energy Agency, 2024

Top 15 hydropower countries
Capacity-weighted capacity factor



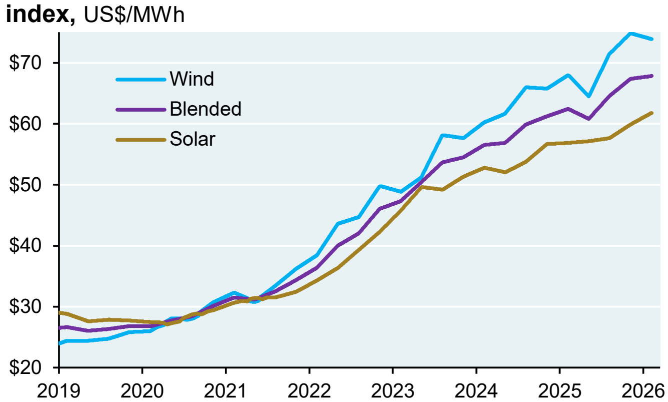
Source: EMBER, JPMAM, 2025

China accounts for 60% of global hydropower growth since 1995 while OECD is flat, Terawatt hours



Source: Energy Institute, JPMAM, 2025

North America PPA price market-averaged continental index, US$/MWh



Source: LevelTen Energy, Q4 2025

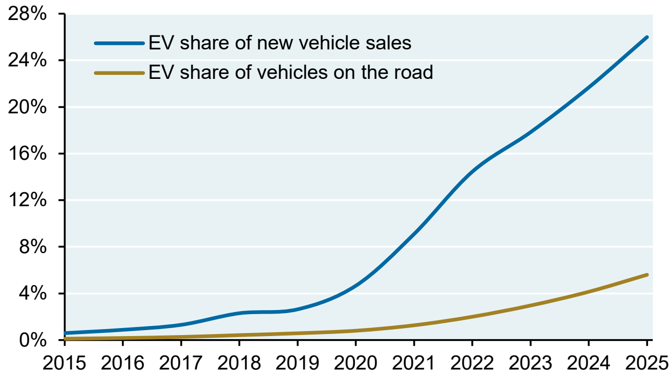
Why are US wind and solar PPA prices rising?
According to Level Ten Energy, the OBBBA spurred a frenzy of development and procurement activity in 2025 as developers rushed to comply with milestones to qualify for expiring tax credits. Other reasons for rising PPA prices include Section 232 50% tariffs on aluminum, steel and copper; tougher review and permitting processes from federal entities; pending Foreign Entity of Concern rules; and a new AD/CVD investigation into solar component producers. PPA increases from 2021 to 2023 also reflect global inflation which rose during that period

[3] Electric vehicles: steady adoption progress

Globally, EVs represent ~25% of passenger car[86] sales and ~6% of the passenger car fleet. The fastest transition is in China where over 50% of sales are EVs. In charts on EV adoption, we include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and extended-range electric vehicles (EREVs). EREVs are powered by an electric motor with a small gasoline engine used only as a backup generator to recharge the battery, whereas PHEVs can also use their gasoline engine to power the wheels directly. We exclude hybrids that cannot be plugged in (HEVs) since they typically have very small batteries that store energy from regenerative braking and rely primarily on gasoline for propulsion.

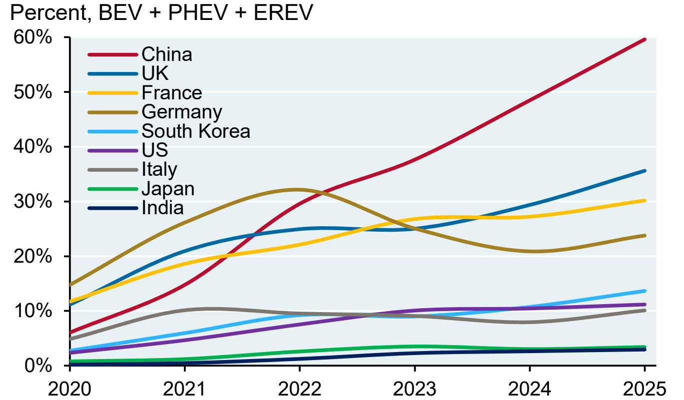
In the US, the September 2025 expiration of the EV tax subsidy for new and used vehicles led to a spike in EV purchases before the expiration, and a subsequent decline in Q4 2025. Tesla's US market share dropped in 2025 by ~10% before rebounding in Q4, when Tesla picked up share of a more slowly growing EV market.

EV share of global passenger vehicles
Percent, BEV + PHEV + EREV



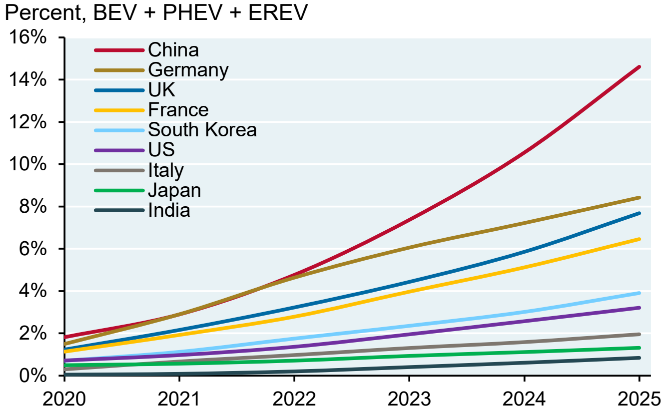
Source: BloombergNEF, June 2025

EV share of passenger vehicle SALES, largest car markets
Percent, BEV + PHEV + EREV



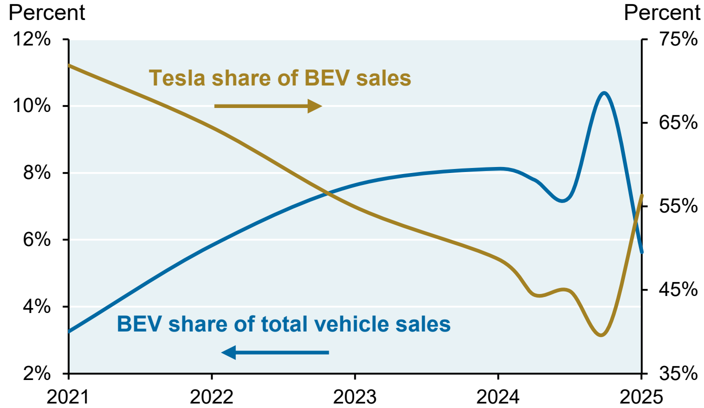
Source: BloombergNEF, JPMAM, June 2025

EV share of passenger vehicle FLEET, largest car markets
Percent, BEV + PHEV + EREV



Source: BloombergNEF, JPMAM, June 2025

US EV & Tesla market shares
Percent



Source: JPMAM, Q4 2025

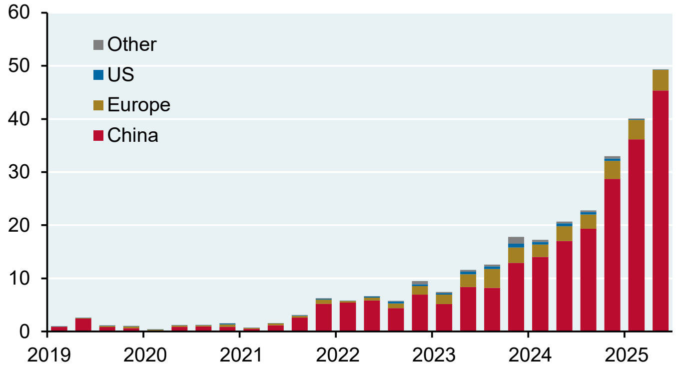
While costs for all battery types declined from 2022 levels, US EV manufacturers are starting to use cheaper LFP batteries to lower costs. LFP cells are cheaper, more durable and safer but have lower energy density and thus lower ranges. This tradeoff is considered worthwhile since average distances travelled per day in the US are 33 miles. The LFP impact on range is fairly modest. Using the Tesla Model 3 as an example, the difference between the LFP standard range (270-300 miles) and NMC long range (340-400 miles) at the midpoint is ~30%. However, LFP batteries are generally charged to 100% while NMC batteries are recommended to be charged 80% - 90%. If we assume an 85% charging limit this decreases the effective NMC range to 315 miles. At the midpoint this would represent 285 miles for LFP vs 315 miles for NMC, so an effective decrease of just 10%.

[86] BNEF passenger vehicles include station wagons, sedans, SUVs, pickups and non-commercial vans

[4] EVs: commercial vehicles: mostly a China story for now

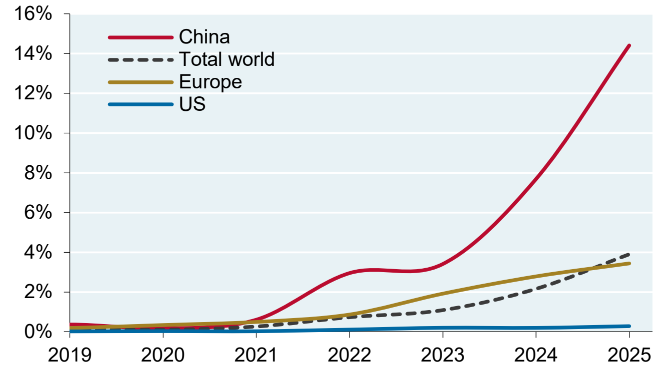
This is mostly a China story for now, although in Scandinavian countries the EV share of commercial vehicle sales is similar to China at ~15%. The lower unit cost for EV batteries in China is a key driver of the adoption gap.

Global sales of zero emission medium & heavy duty trucks
Thousand units sold per quarter



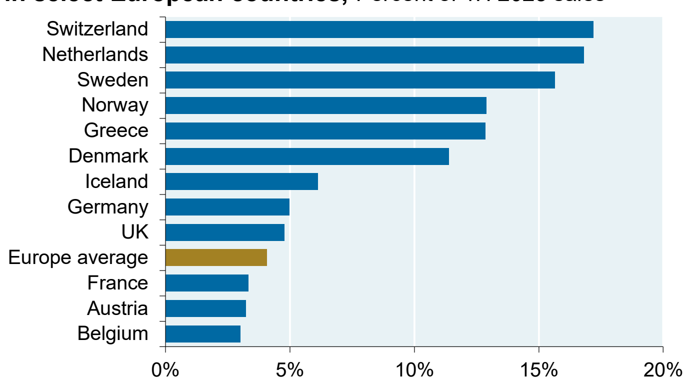
Source: BloombergNEF, September 2025

Sales share of zero emission medium & heavy duty trucks
Percent of total sales



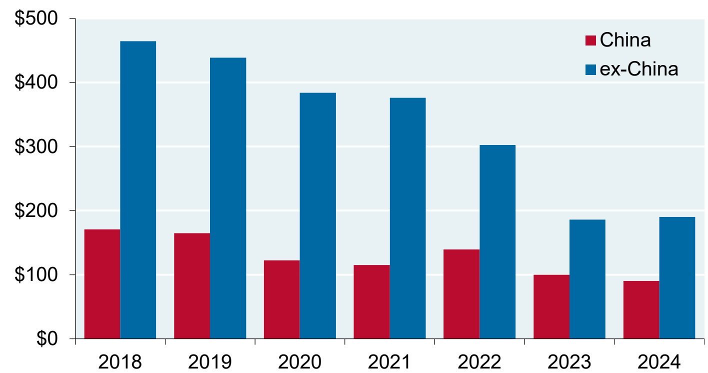
Source: BloombergNEF, September 2025

Sales share of zero emission medium & heavy duty trucks in select European countries, Percent of 1H 2025 sales



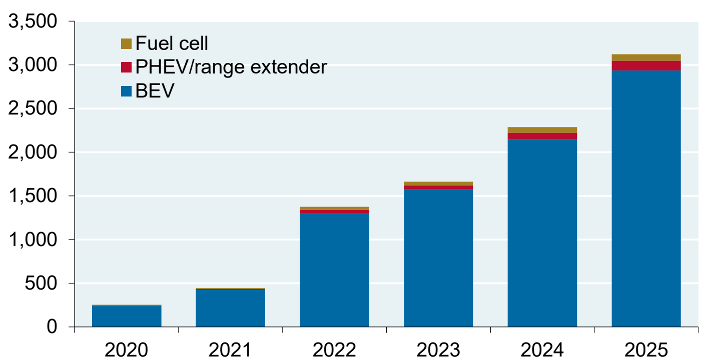
Source: BloombergNEF, September 2025

Average lithium ion battery pack prices for commercial vehicles & buses, 2024 US$ per kilowatt-hour



Source: BloombergNEF, September 2025

Zero emission commercial vehicle models available
Number of models

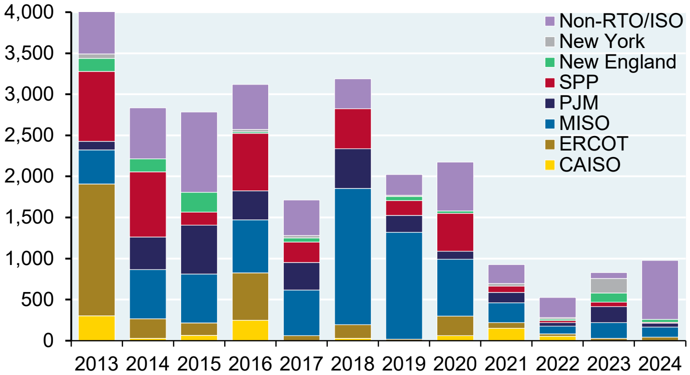


Source: BloombergNEF, September 2025. PHEV/REX are zero emission for the part of their operation relying on battery power alone

[5] US electricity grid: a small rebound in line growth, falling capacity buffers and Canada-New England

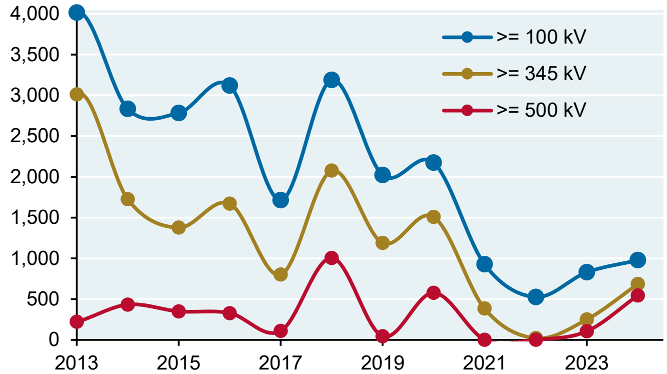
Transmission line growth in 2024 matched 2023 levels and remains close to the lowest levels of the last decade, with little progress on development of higher voltage lines > 345 kV. Anticipated reserve margins are projected to decline in many regions due to retirement of thermal capacity, particularly in MISO and PJM. Around 45% of the US power distribution network is estimated to be near or at the end of its useful life.

US transmission line growth by ISO
Miles added per year, total grid size = ~200,000 GW-miles



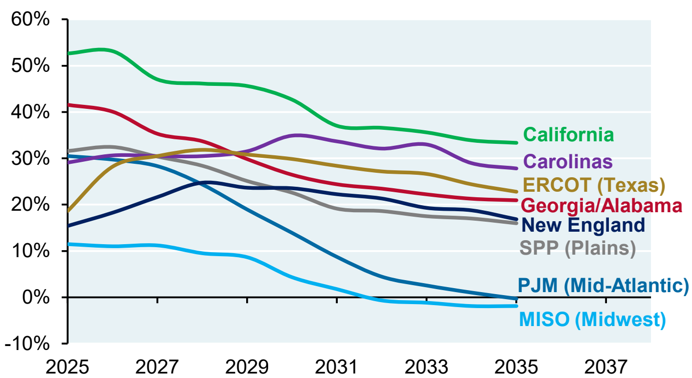
Source: S&P Global, JPMAM, 2025. Note: Transmission lines >= 100 kV.

US transmission line growth by voltage
Miles added per year



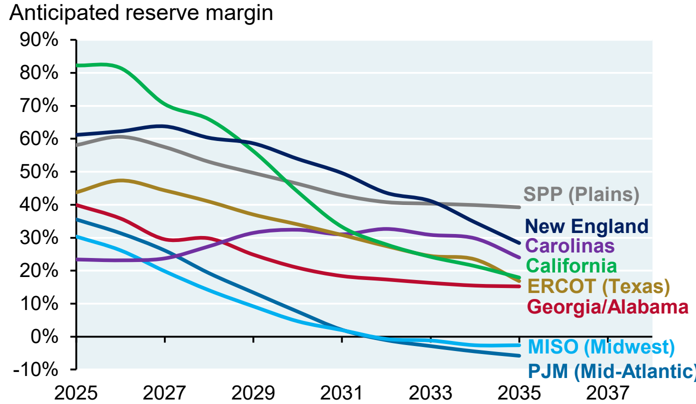
Source: S&P Global, JPMAM, 2025

Generation capacity buffer during peak summer demand
Anticipated reserve margin



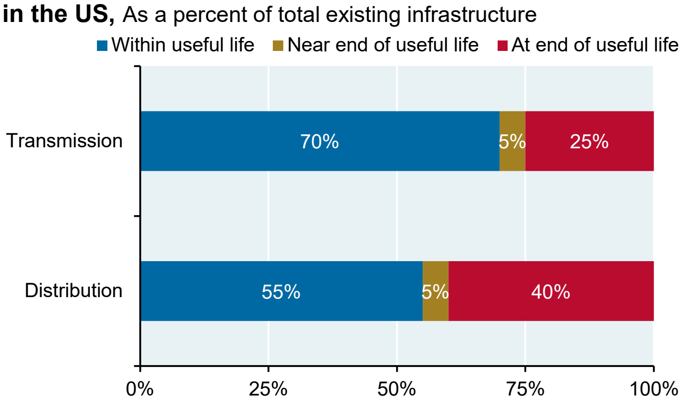
Source: NERC, JPMAM, January 2026

Generation capacity buffer during peak winter demand
Anticipated reserve margin



Source: NERC, JPMAM, January 2026

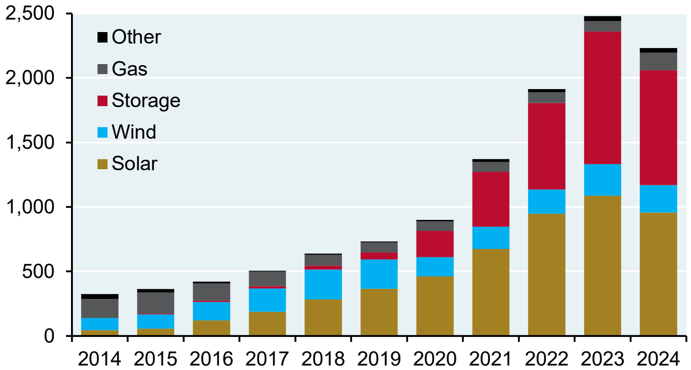
Existing transmission and distribution infrastructure age in the US, As a percent of total existing infrastructure



Source: Solomon Partners, Q1 2025

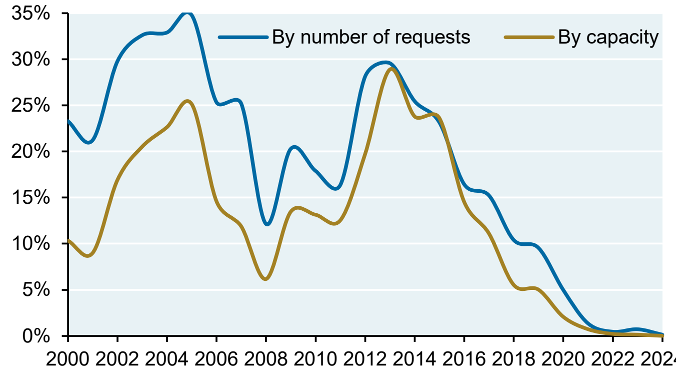
There's a massive amount of capacity in the US grid queue, almost all of which is wind, solar and storage. The 2,300 GW in the queue is actually greater than US installed generation capacity of 1,300 GW. But only 19% of queue requests made from 2000-2019 were ever connected and became operational (13% based on capacity of requests), **so the queue is not a good proxy for future operational capacity**. Even projects with signed interconnection agreements only have 40%-60% completion rates. The median time from interconnection request to commercial operation has risen from 22 to 54 months.

US capacity in the queue by type
GW



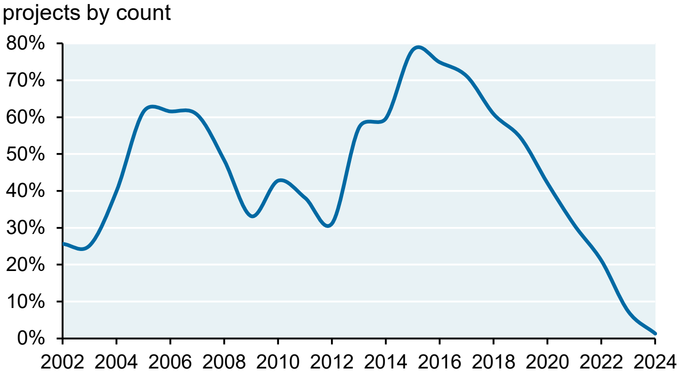
Source: LBNL, 2025

Generation completion rates by interconnection request year, Percent of total capacity or number of requests



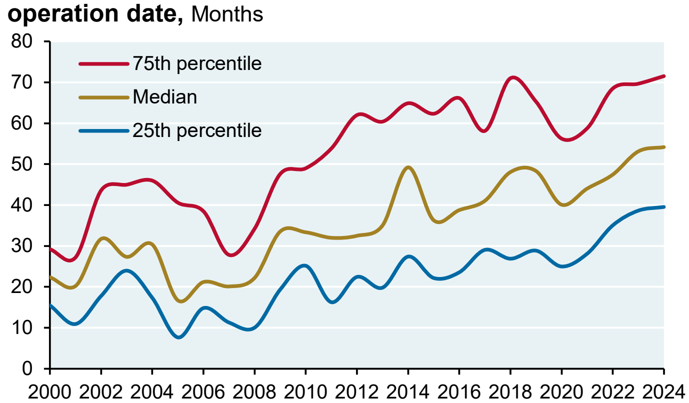
Source: LBNL, 2025

Completion rates for projects with signed interconnection agreements by interconnection request year, Percent of projects by count



Source: LBNL, 2025

Time elapsed from interconnection request to commercial operation date, Months

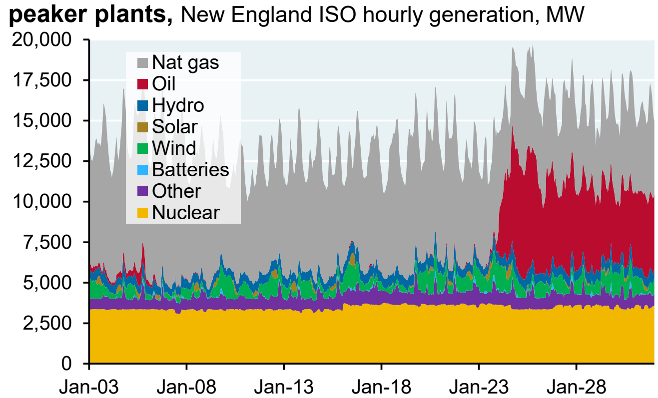


Source: LBNL, 2025

Oh Canada! Storm-related hydropower export issues

For many years I used the example of the aborted Northern Pass project as an example of US dysfunction since the progressive Northeast could not figure out a way to build a HVDC line to import Canadian hydropower at 5 cents/kWh. The $1.6 bn New England Clean Energy Connect power line was finally built from Quebec to Massachusetts and became operational this year. A winter storm caused temperatures to plummet in January 2026, driving up power demand in Quebec for winter electric heat. Imported electricity carried on the line stopped during the storm, leading New England to rely on a fuel mix of 33% fuel oil, 30% natural gas, 18% nuclear, 6% wind/solar and 6% hydro. Fuel oil peaker plants were activated subject to an Emergency Order from the DoE allowing the grid operator to tap into them. Electricity imports from Canada eventually resumed within 72 hours.

Winter storm cuts off Canadian hydropower, requires oil peaker plants, New England ISO hourly generation, MW

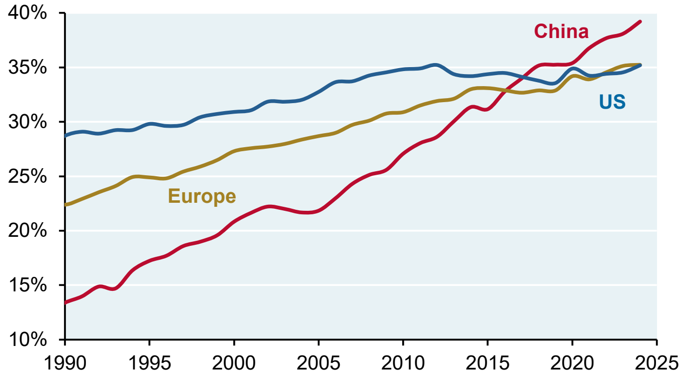


Source: EIA, JPMAM, February 1, 2026

[6] US electrification: the primary impediment is cost

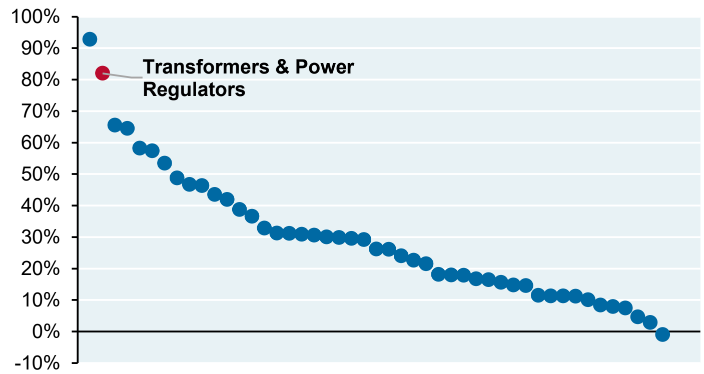
The pace of electrification in the US is impeded by (a) the high cost of transformers, power regulators and other related equipment, (b) the high cost of electricity per MJ compared to natural gas for residential and industrial users and (c) challenges in electrifying industrial energy use, particularly as it relates to high temperature applications. For (b), if the electricity to gas price ratio were 3.0, the higher cost of power would roughly offset the benefits of a heat pump with a COP of 3.0 which consume 3x less energy. While lower temperature industrial applications can be electrified, progress has been very slow so far as shown in the 5th chart. While US heat pump sales have surpassed new gas furnaces, the impact on the stock of winter heating devices is gradual given the long useful lives of existing furnaces and boilers, and the slow pace of annual new home construction as a share of the existing housing stock (~1% in both the US and Europe).

Electricity share of useful final energy
Percent



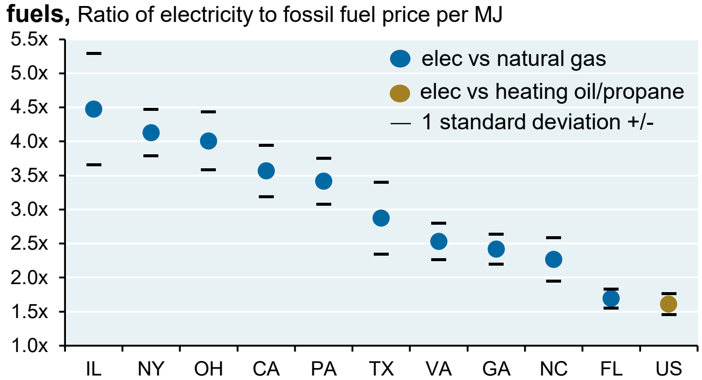
Source: Energy Institute, IEA, JPMAM, 2025

Producer price inflation: core goods
% increase vs 2018 for each of the 47 core goods categories



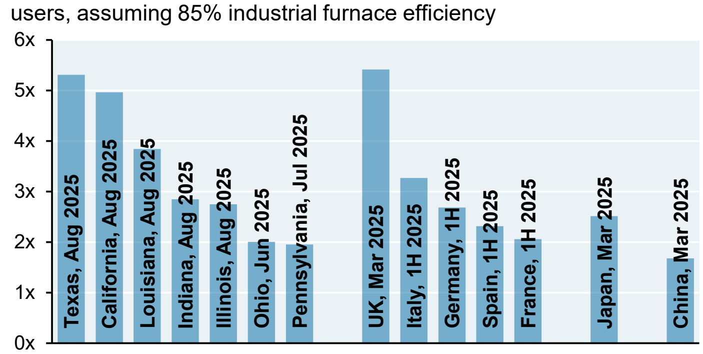
Source: Bloomberg, BLS, JPMAM, December 31, 2025

Residential winter heating options: electricity vs fossil fuels, Ratio of electricity to fossil fuel price per MJ



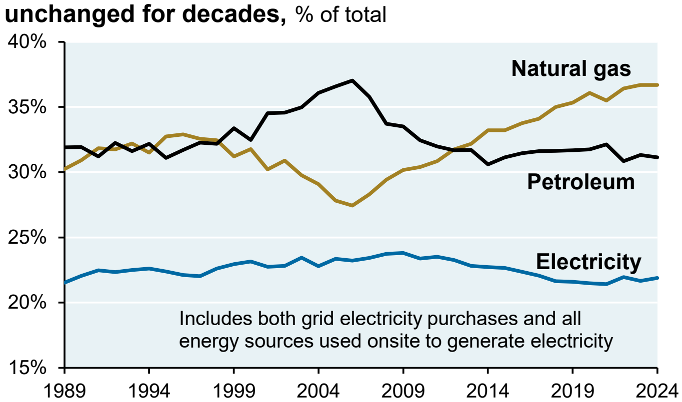
Source: EIA, JPMAM, 2025. Top 10 states by electricity consumption; assuming 90% gas furnace efficiency. Residential pricing, 2019-2025 average

Electricity: 2x-5.5x more costly than gas for industrial heat
Electricity cost per MJ divided by natural gas cost per MJ, industrial users, assuming 85% industrial furnace efficiency



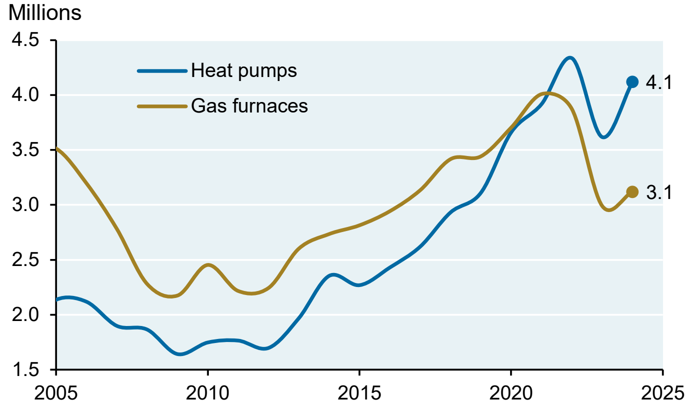
Source: EIA, Eurostat, CEIC, JPMAM, 2025. States shown are largest industrial users of US primary energy

Electricity share of US industrial final energy consumption unchanged for decades, % of total



Source: EIA, JPMAM, 2024

Air-source heat pumps and gas furnaces sales
Millions

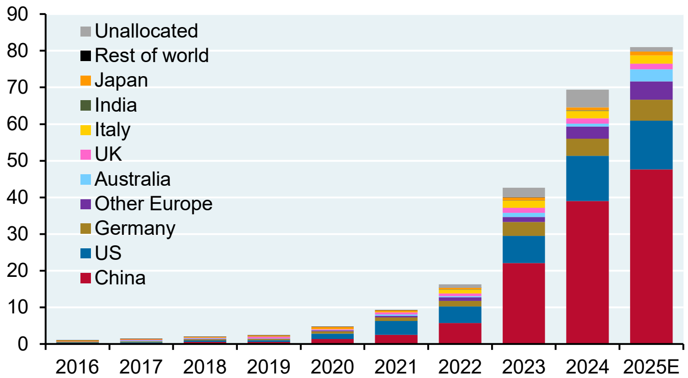


Source: AHRI, Monthly Shipments Report, September 2025

[7] Energy storage: costs keep falling, adoption rising globally

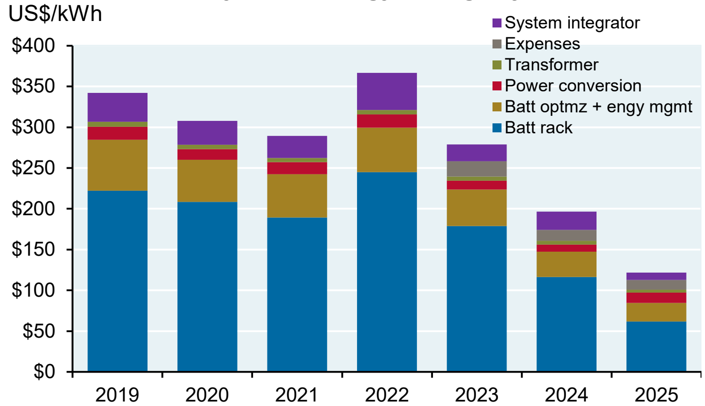
Battery storage capacity is rising around the world, aided by falling prices per kWh. The fourth chart compares the wide range of capital cost estimates. The NREL figure includes li-ion battery cabinets, bidirectional inverters, EBOS/SBOS components, labor, permitting, installation, sales taxes, contingencies, EPC overhead and profit. Despite lower energy density, LFP batteries dominate stationary energy storage in the US with a 90% share, up from 25% in 2020. China of course dominates manufacturing of almost every battery component.

Global gross energy storage additions by market
GW



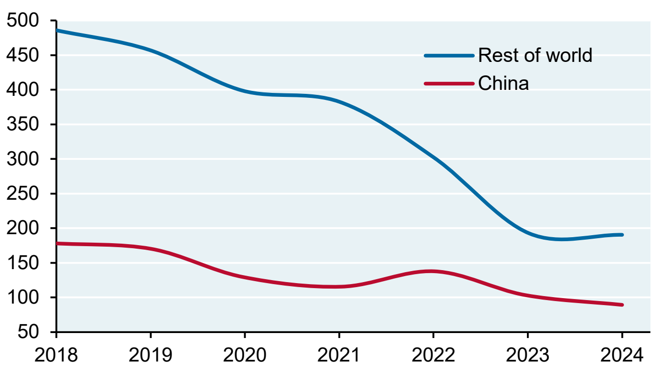
Source: BloombergNEF, JPMAM, October 2025

Price of a 4hr utility-scale energy storage system
US$/kWh



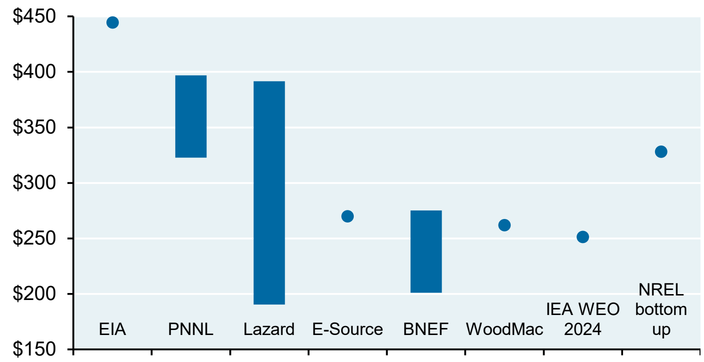
Source: BloombergNEF, JPMAM, December 2025

E-bus and commercial lithium-ion battery pack prices
Real 2024 US$ per kWh, volume-weighted average



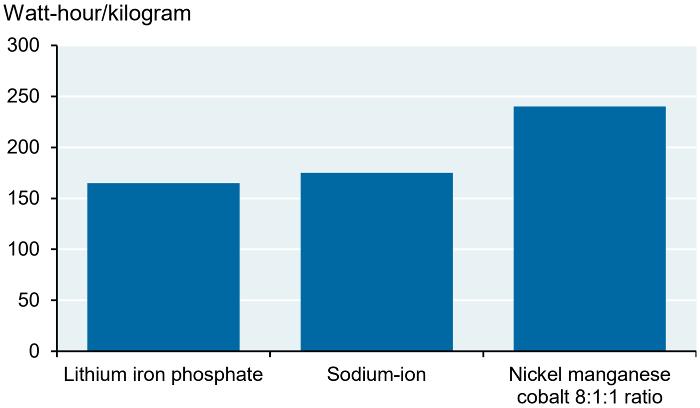
Source: BloombergNEF, JPMAM, 2025

Comparison of li-ion utility scale battery costs
Current 4hr battery cost, 2024 US$ per kilowatt-hour



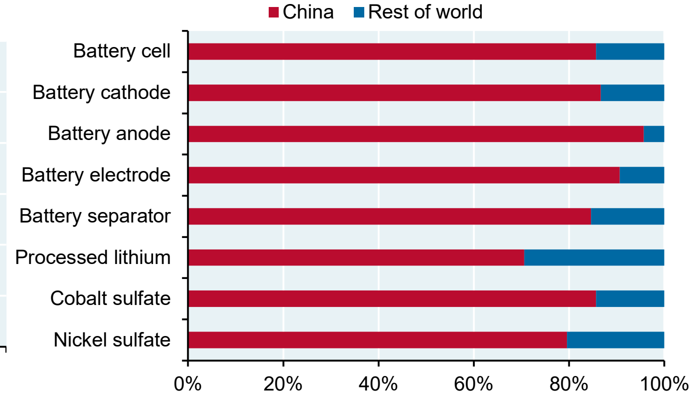
Source: "Cost Projections for Utility-Scale Battery Storage", NREL, 2025

Battery-pack energy density, 2025
Watt-hour/kilogram



Source: BloombergNEF, JPMAM, 2025

Global manufacturing capacity for batteries



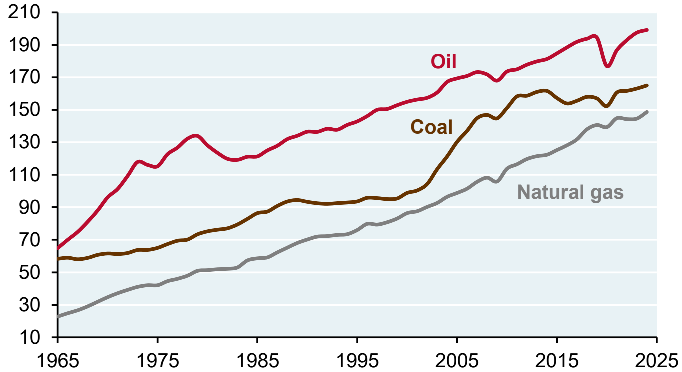
Source: BloombergNEF, December 2025

[8] Fossil fuels, Global: consumption and emissions still rising; a pending LNG glut and coal zombies

While we focus on useful final energy to track the transition, fossil fuel primary energy is more relevant for tracking why GHG emissions are still rising on a global basis. This is not just a China story; since 2010, China only represents ~50% of the increase in GHG emissions with remaining increases coming from other emerging countries. Oil, coal and gas consumption continue to rise at a slightly slower pace than 2018-2019.

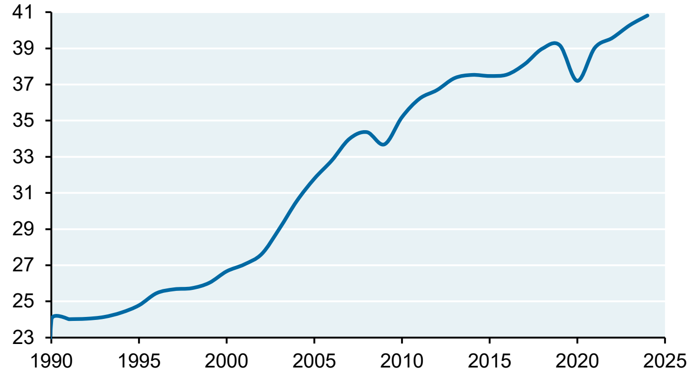
New LNG capacity is projected to drive LNG capacity utilization figures below 90% for the first time on record. Coal represents a falling share of China power generation, dropping below 60% for the first time in 2024. But in absolute terms coal consumption is still rising in China, for power and for heat.

Global fossil fuel primary energy consumption
Exajoules



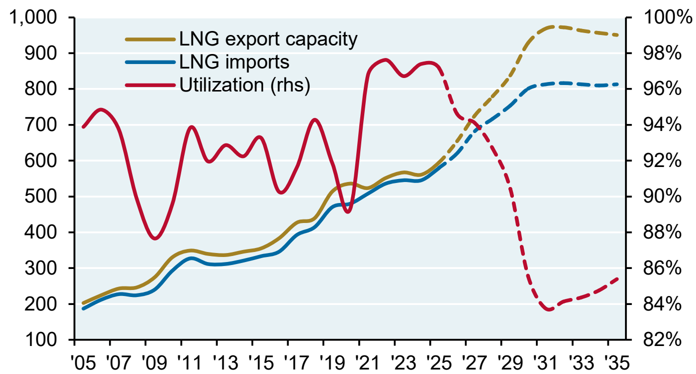
Source: Energy Institute, JPMAM, 2025

Global CO_2 equivalent emissions from energy, process emissions, methane & flaring, Billion tons



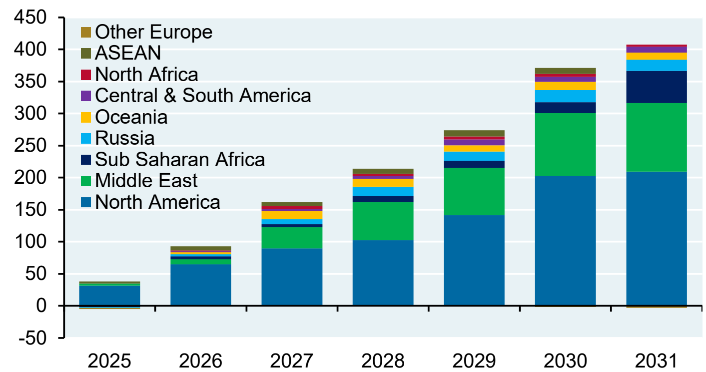
Source: Energy Institute, JPMAM, 2025

Global LNG capacity utilization
Billion cubic meters | Percent



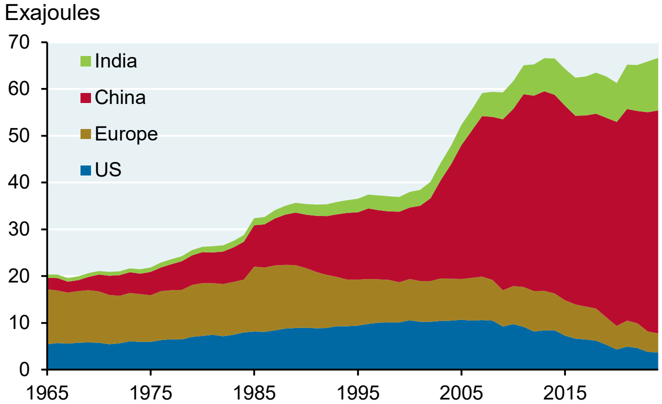
Source: Oxford Institute for Energy Studies, October 2025

Cumulative change in LNG export capacity
Billion cubic meters



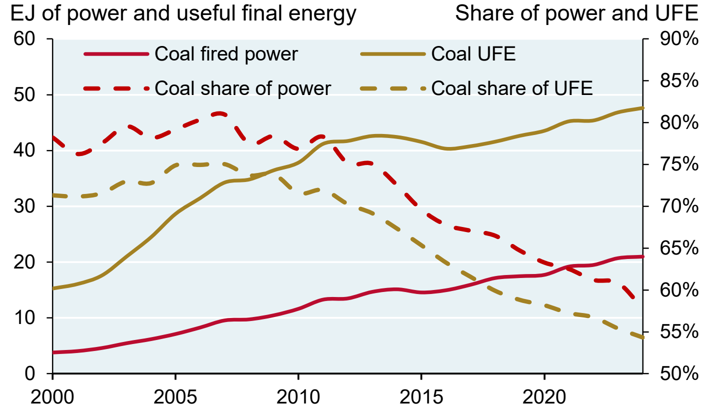
Source: Oxford Institute for Energy Studies, October 2025

Coal useful final energy by country
Exajoules



Source: Energy Institute, IEA, JPMAM, 2025

China coal tracker
EJ of power and useful final energy | Share of power and UFE

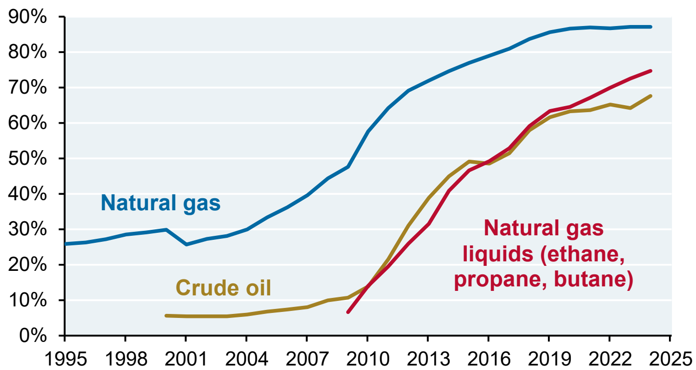


Source: Energy Institute, Global Energy Monitor, JPMAM, 2025

[9] Fossil fuels, US: all about natural gas and contributions from hydraulic fracturing

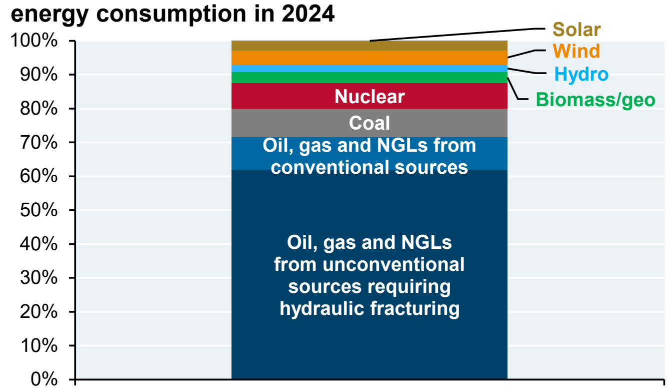
As shown in the first two charts, 68%-87% of crude oil, NGLs and natural gas were derived from fracking in 2024, and these fracked fuels accounted for 62% of all US primary energy consumption. Estimates of potential US gas reserves have been rising due to potential supply found in the Haynesville/Deep Bossier Shale in the Gulf Coast area, a new assessment of Alaskan gas (the first in 10 years) and the addition of offshore resources in Alaska and Atlantic East Coast. While many analysts project an imminent peak in US oil consumption, it was stable through the end of 2025. LNG exports have now hit 10% of total US production.

Percentage of US oil and gas production derived from hydraulic fracturing through year-end 2024



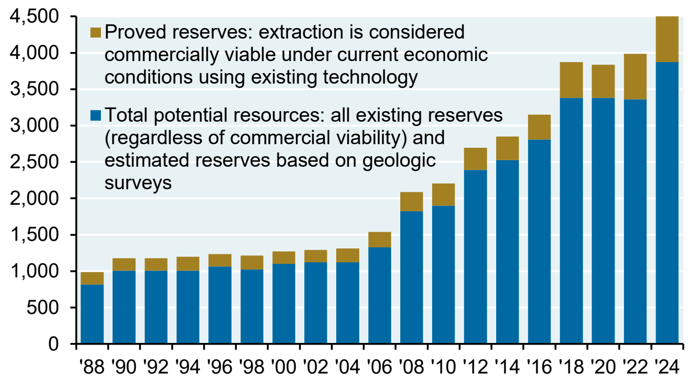
Source: EIA, US Department of Energy, JPMAM, 2024

Hydraulic fracturing accounted for 62% of all US primary energy consumption in 2024



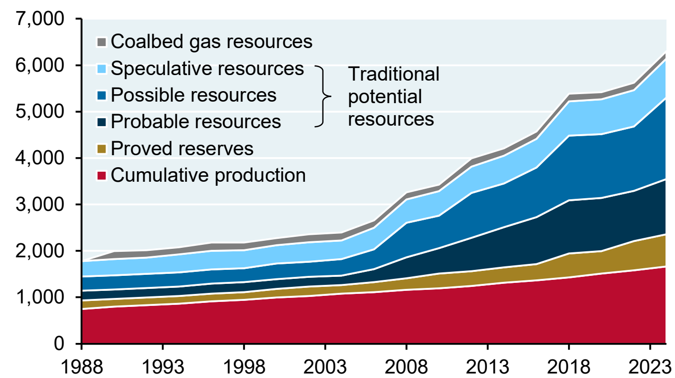
Source: EIA, BP, Society of Petroleum Engineers, S&P Platts, JPMAM, 2024

Estimates of US natural gas supply
Trillion cubic feet



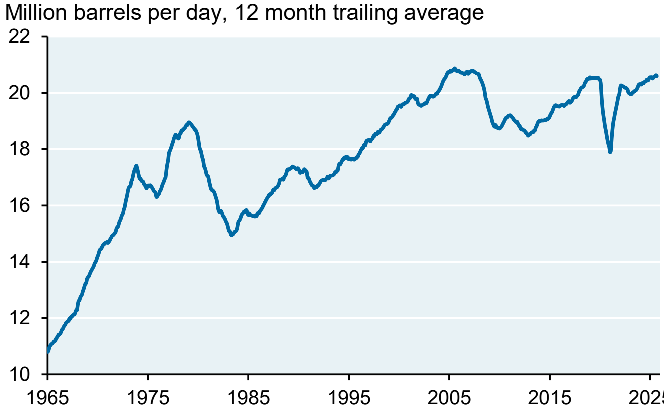
Source: Potential Gas Committee, 2025

US natural gas resources by component
Trillion cubic feet



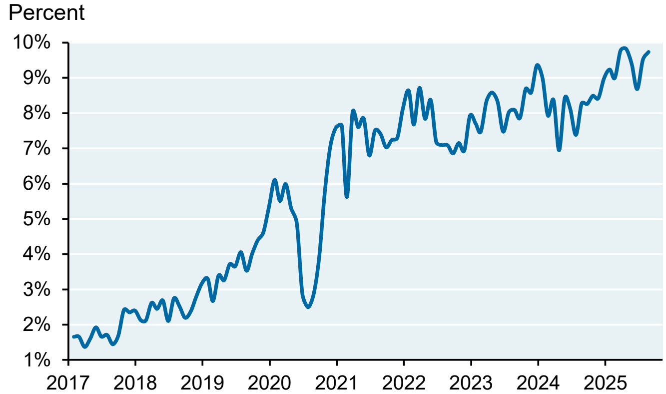
Source: Potential Gas Cmte. (Colorado School of Mines), September 2025

US demand for crude oil and petroleum products
Million barrels per day, 12 month trailing average



Source: EIA, JPMAM, October 2025

US monthly LNG exports as a share of gas production
Percent

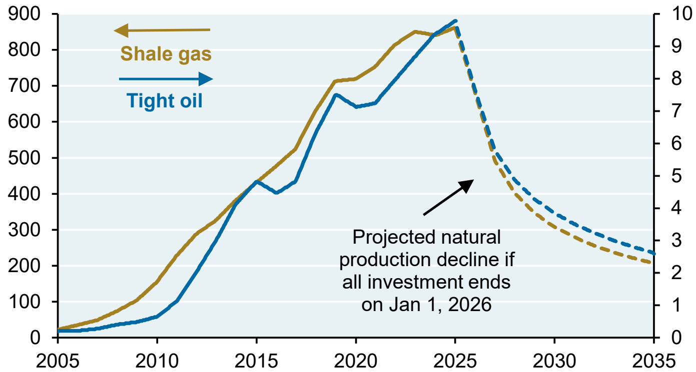


Source: EIA, JPMAM, August 2025

Without continued investment in US tight oil and shale gas, production would rapidly decline due to the short production lives of most wells. The US hydro, coal, oil and nuclear fleets are very old. US LNG export capacity utilization is projected to decline by the end of the decade due to a glut in global LNG capacity.

US shale gas and tight oil production

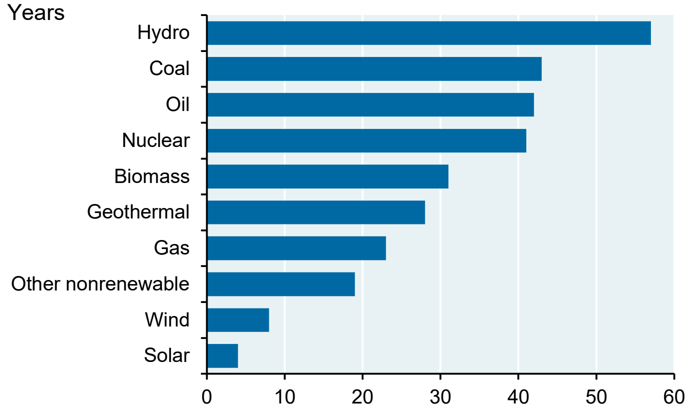
Billion cubic meters / Million barrels per day



Source: IEA, JPMAM, September 2025

US capacity weighted average fleet age

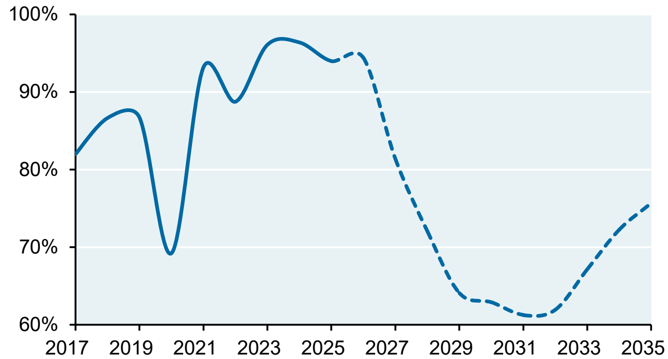
Years



Source: S&P Global, September 2022

US LNG export capacity utilization

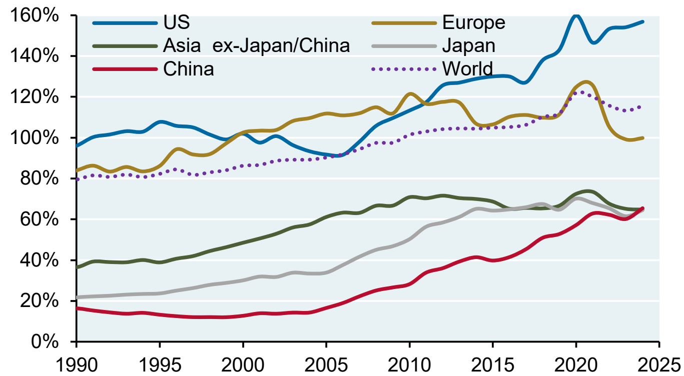
Percent



Source: Woodmac, Bloomberg Finance L.P., EIA, China Customs, J.P. Morgan Commodities Research, January 2026

The rise of natural gas

Nat gas consumption divided by oil consumption, UFE basis

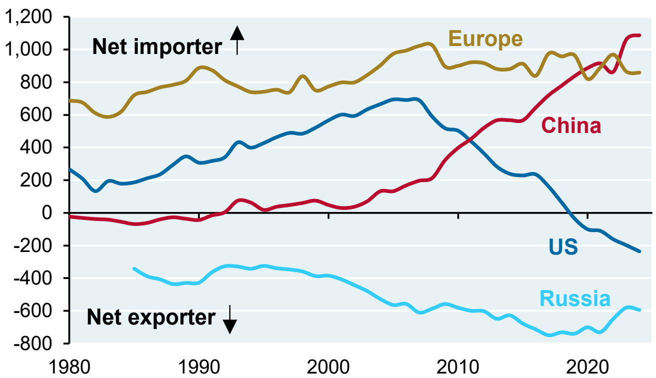


Source: Energy Institute, IEA, JPMAM, 2025

[10] Energy independence: China and Europe compete for resources as the US remains a net exporter

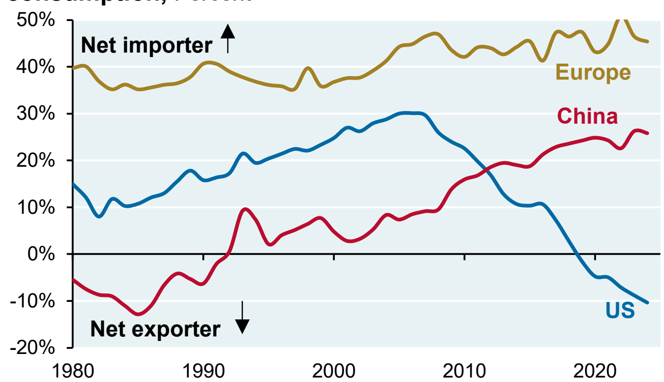
The US has achieved US energy independence for the first time in 40 years while Europe and China compete for global energy resources. China's imports are similar to Europe in energy terms but half as much as a share of energy consumption. Energy intensive manufacturing has shifted to the developing world since the mid 1990's. The fourth chart shows the countries with the highest degree of import dependence of fossil fuels, measured as a share of primary energy consumption. Last chart: Europe proposes to cut off Russian gas by 2028.

Energy dependence and independence
Net imports of oil, natural gas and coal in million tonnes of oil equiv.



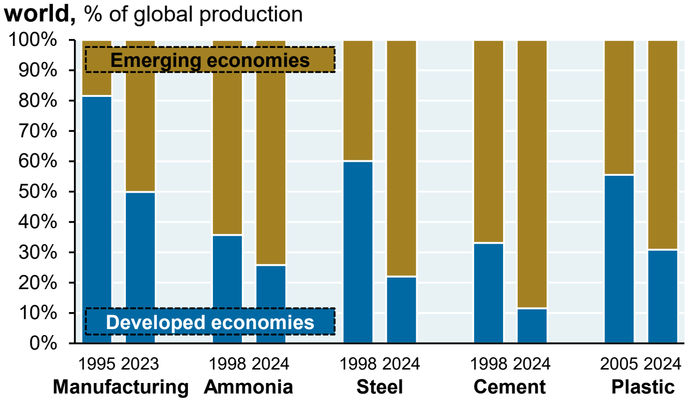
Source: Energy Institute, JPMAM, 2025

Net imports of fossil fuels as a percent of primary energy consumption, Percent



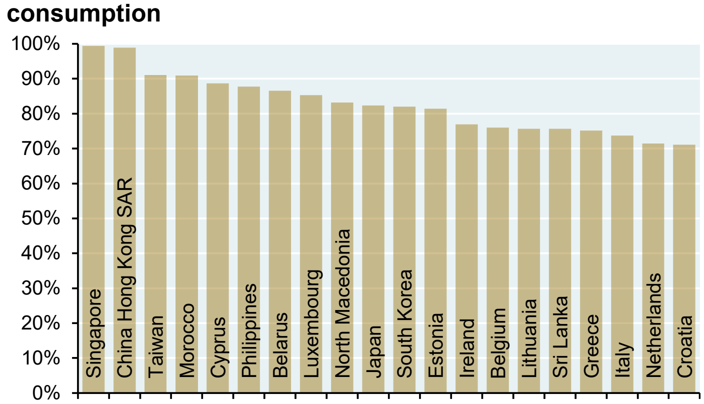
Source: Energy Institute, JPMAM, 2025

A shift in energy intensive manufacturing to the emerging world, % of global production



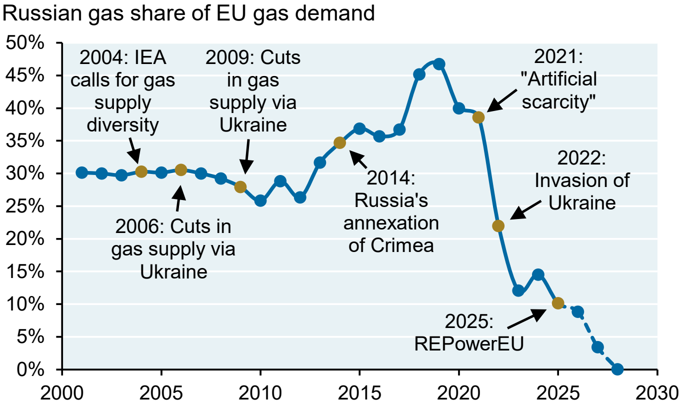
Source: UN DESA, Worldsteel, Plastics Europe, USGS, JPMAM, 2025

Net imports of fossil fuels as a share of primary energy consumption



Source: Energy Institute, JPMAM, 2025

Europe proposes to phase out Russian gas by 2028…
Russian gas share of EU gas demand



Source: European Gas Hub, December 3, 2025

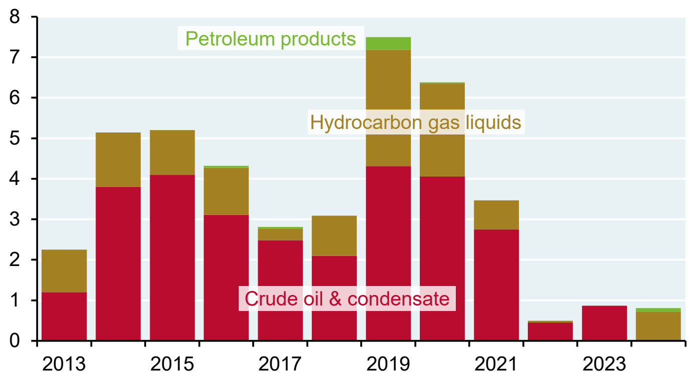
…**but an equally likely outcome** is that Russia ties a resumption of European purchases of Russian gas to the end of the Ukraine War and no future hostilities elsewhere in Eastern Europe. All the gas pipelines that Russia is building to China will still represent half the volume Europe imported in 2019, so Russia has incentives to eventually find a solution that resumes gas flows to Europe

[11] New US liquids and gas pipeline projects: some progress off a low base

The construction of US liquids and gas pipelines slowed markedly starting in 2022. While liquids pipeline growth remains low, natural gas pipeline completions rose in 2024. Some of the largest additions include the completion of the Matterhorn Express Pipeline which carries 2.5 bcf per day of Permian Basin natural gas to the Houston area, the Mountain Valley Pipeline which moves 2.0 bcf per day of Appalachian Basin production from West Virginia to Virginia, and the ADCC Pipeline which moves 1.7 bcf per day of natural gas to the Corpus Christi Stage 3 LNG export facility.

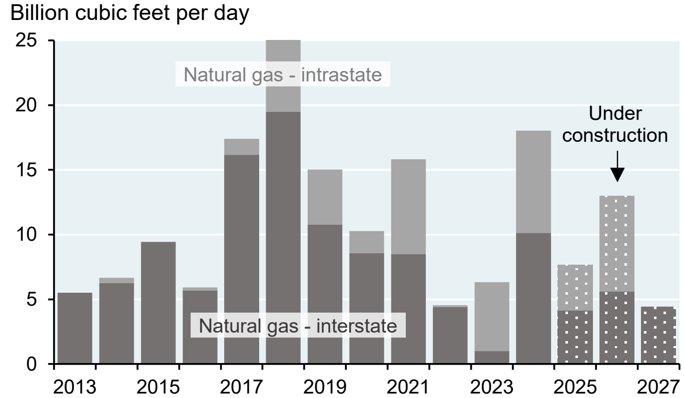
According to EIA data, pending natural gas pipeline projects entail the addition of 29 bcf per day, which is a ~15% increase on the 188 bcf per day capacity of natural gas pipelines in existence at the end of 2024. Twelve projects in Texas, Oklahoma and Louisiana on pace to be completed in 2026 represent the largest buildout in nearly 20 years and are linked to growing demand for US LNG. Some of the largest include the Rio Bravo Pipeline that will feed NextDecade's Rio Grande LNG project in Texas, and the Blackcomb Pipeline out of the Permian Basin. In the Permian Basin, much of the gas flows from wells drilled primarily for oil. On dozens of occasions in 2025, gas prices in the region plunged below zero as sellers had to pay customers to take the gas off their hands. Some new projects should ease that issue, including Energy Transfer's Hugh Brinson Pipeline which will transport gas from West Texas to Dallas-Fort Worth, from where it can flow to multiple destinations in Texas and Louisiana including LNG export facilities and data centers.

Annual US liquid pipeline capacity added
Million barrels per day



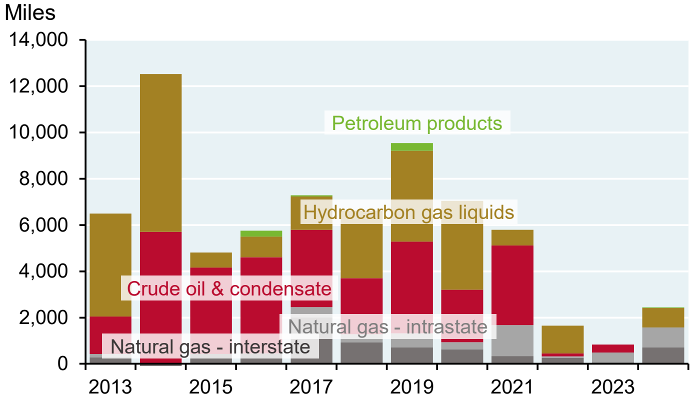
Source: EIA, JPMAM, 2024

Annual US natural gas pipeline capacity added
Billion cubic feet per day



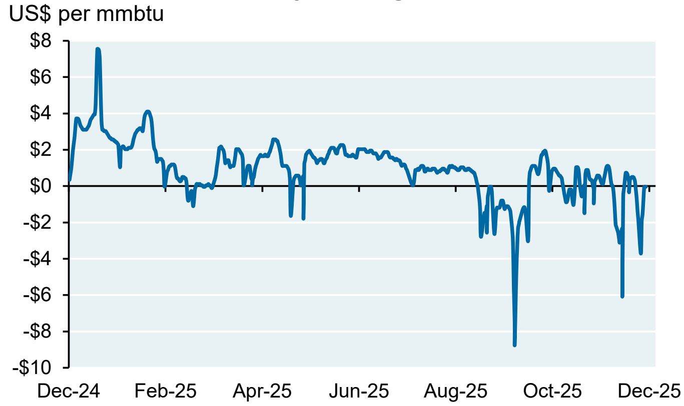
Source: EIA, JPMAM, 2024

Annual US miles of pipeline added
Miles



Source: EIA, JPMAM, 2024

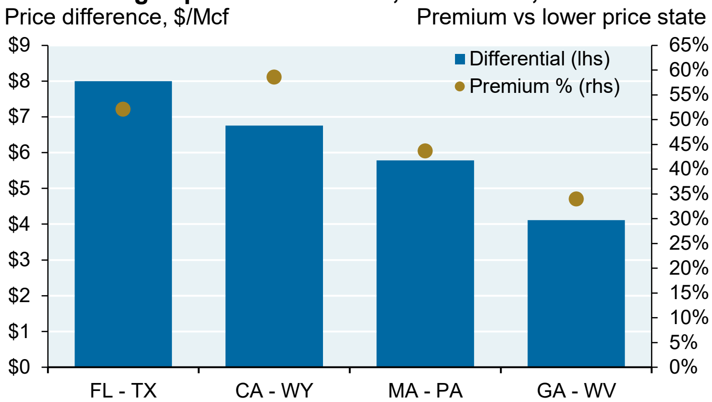
Waha Hub/ Pecos County Texas gas prices
US$ per mmbtu



Source: NGI's Daily Gas Price Index, December 30, 2025

The next chart is a rough estimate of potential benefits from building new pipelines. The bars on the left axis show residential natural gas price gaps between each pair of states, while the right axis shows the price gap premium. For example: residential gas prices have been ~$6 higher per mcf in Massachusetts vs Pennsylvania in winter months, which has resulted in a 40%-45% gas premium paid by Massachusetts residents.

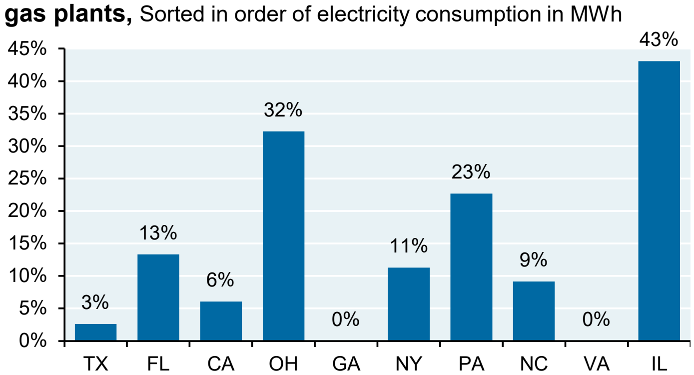
Winter nat gas price differentials, residential, since 2020



Source: EIA, JPMAM, February 2025

The last chart shows the MW of gas turbines installed since 2019 as a share of gas capacity in ten US states with the most electricity consumption. Texas for example only installed 3% of its gas capacity in the last 6 years; in California, 6%.

Gas plants added since Jan 2019 as a share of operating gas plants, Sorted in order of electricity consumption in MWh

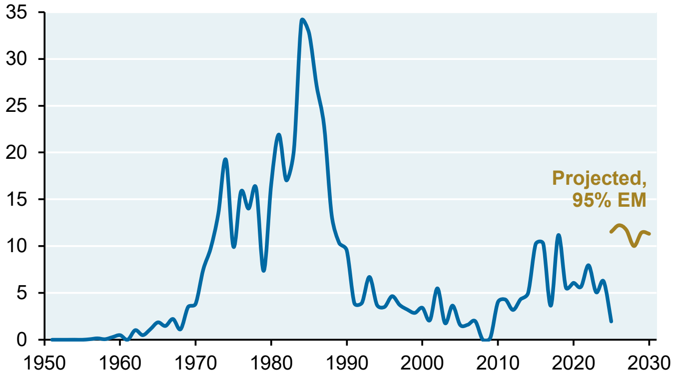


Source: EIA Form 860, JPMAM. Includes gas-powered combined cycle combustion/steam turbines, 2024

[12] Nuclear: China leads the way as the West tries to figure out how they're doing it

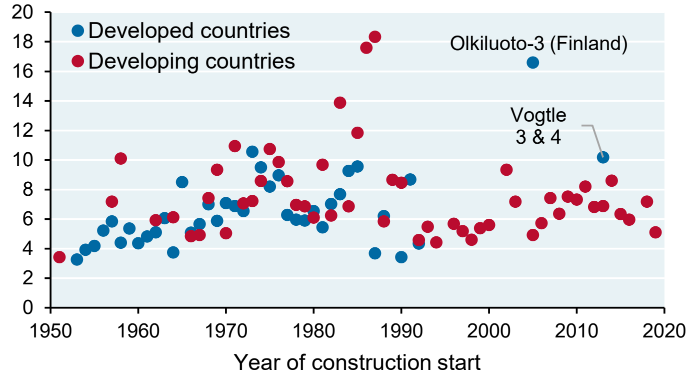
The story of nuclear is all about its transition from the West to China and the developing world.

Global nuclear power plants by year of completion
Gross GW



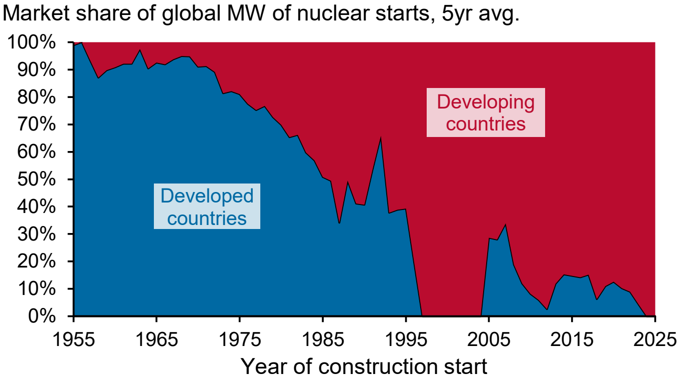
Source: Power Reactor System Database, JPMAM, September 2025

Average nuclear plant completion time by year and region
Years



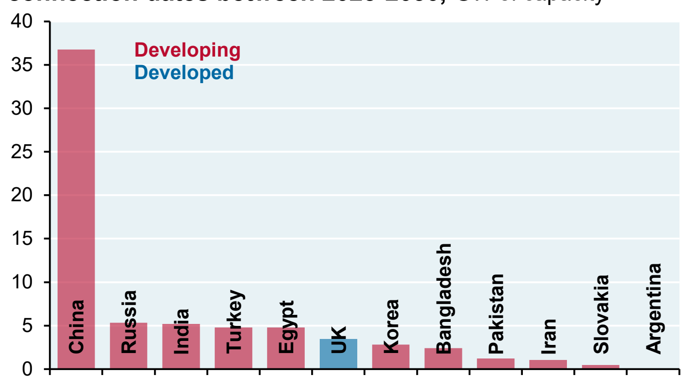
Source: Power Reactor System Database, JPMAM, September 2025

During the 1980's, nuclear development shifted from developed to developing countries
Market share of global MW of nuclear starts, 5yr avg.



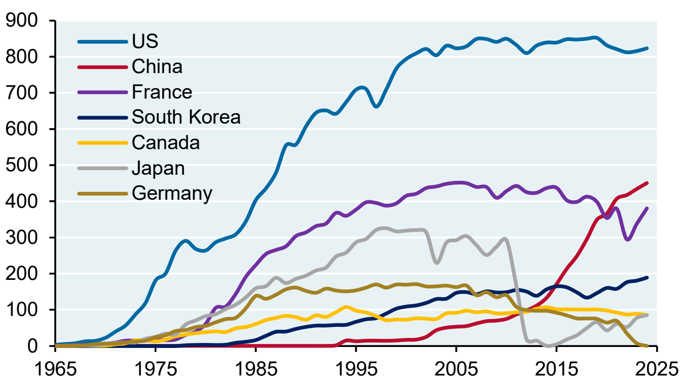
Source: Power Reactor System Database, JPMAM, September 2025

Nuclear plants under development with estimated grid connection dates between 2025-2030, GW of capacity



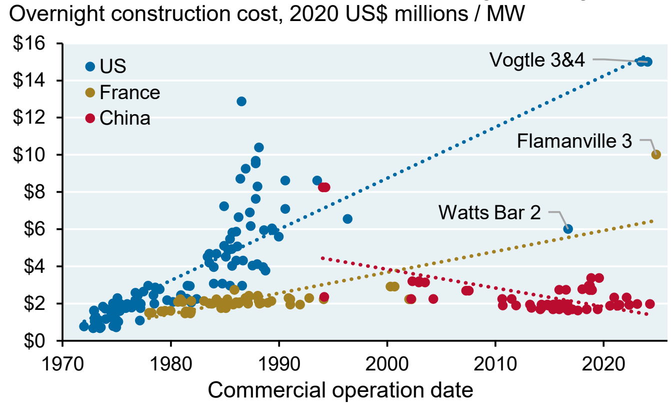
Source: World Nuclear Association, JPMAM, 2025

Nuclear generation by country
Terawatt-hours



Source: Energy Institute, JPMAM, 2025

Construction costs of nuclear reactors by country
Overnight construction cost, 2020 US$ millions / MW

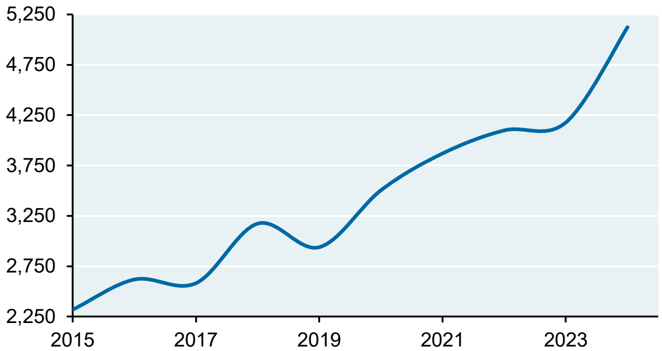


Source: Liu et al (Harvard), July 2025. Excludes plants under construction

[13] Carbon capture and storage: the definition of progress at a snail's pace

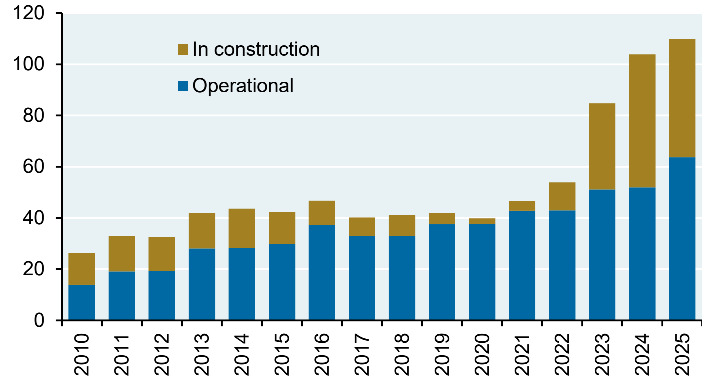
The academic citation-to-actual deployment ratio for CCS is still the highest ratio in the history of science. The fundamental challenge: while coal and gas-powered electricity generation account for the bulk of industrial CO_2 emissions, they have among the lowest flue gas concentrations of CO_2 which increases the cost and complexity of CCS. From 2024 to 2025, global CCS capacity grew from 51 million tons per annum to 64 million tons per annum. **So, from 0.135% of global emissions from fossil fuels to 0.168%. Wake me if this figure ever gets to 3%.**

The highest ratio in the history of science
Carbon capture research citations per year divided by million tons of annual global operational CCS capacity



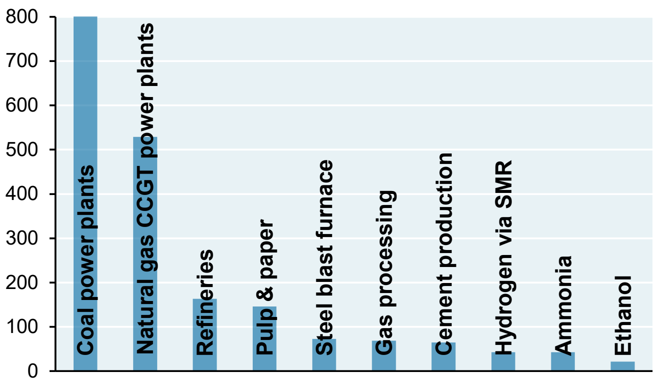
Source: Dimensions.AI, Global CCS Institute, 2024

Global CO_2 capture capacity commercial facility pipeline
Million tons per annum



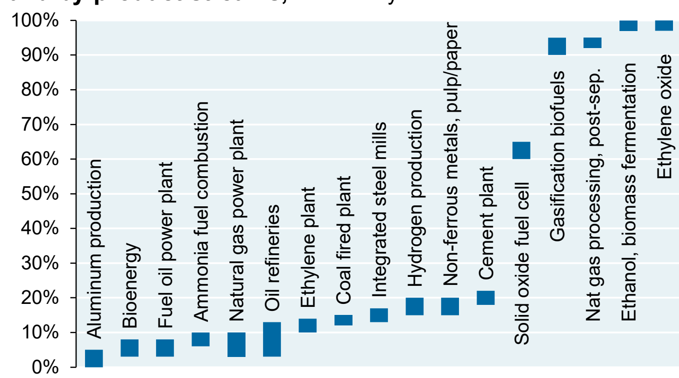
Source: Global CSS Institute, 2025

Annual US GHG emissions from industrial sector
Million tonnes of CO_2 equivalent



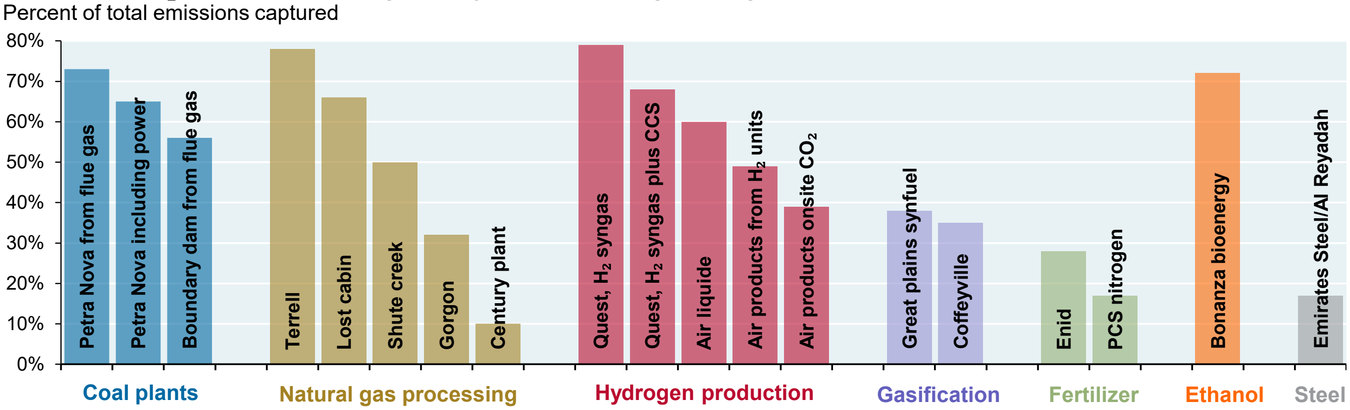
Source: Energy Futures Initiative. February 2023.

CO_2 concentration in flue gas streams, reject streams and by-product streams, Percent by volume



Source: IPCC, Swedish Env. Research Institute, Penn State, JPMAM. 2022.

Real-world CO_2 capture rates are generally well below original targets
Percent of total emissions captured



Source: Institute for Energy Economics and Financial Analysis, Schlissel and Juhn, December 2023

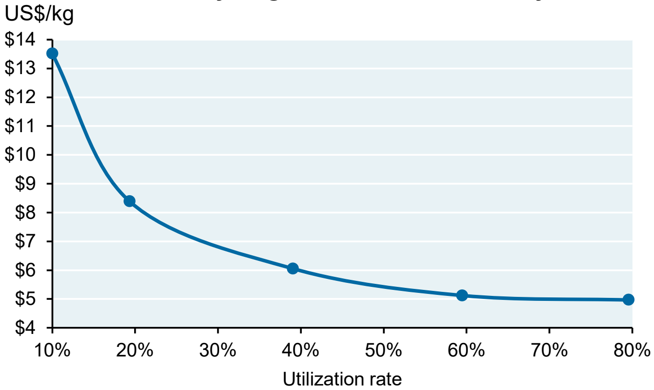
[14] Whydrogen? More like "Bye-drogen!"

I have been bashing the prospects for widespread green hydrogen production for years. It looks like investors and project engineers increasingly agree. According to Wood Mackenzie, the capacity of green hydrogen project cancellations since 2020 are 4x higher than existing clean hydrogen capacity of 1 mm tons per year. The hydrogen sector that got clobbered the most in 2025: transportation dreams[87]:

- French hydrogen taxi firm Hype pivoted to battery electric…fuel cell car sales fell near zero outside of the subsidy regime in Korea…hydrogen refueling stations closed in Europe, North America and China…Shell exited the refueling business and BP shut down its hydrogen fuels division… Daimler, Stellantis, GM, Honda and MAN withdrew from hydrogen truck programs…Nikola, Hyzon and Quantron went bankrupt... Cummins began a strategic assessment of its hydrogen business as losses mounted…cities such as Dijon abandoned hydrogen buses…hydrogen train projects were reduced or dropped in Germany as electrification and battery assisted rail proved cheaper and more reliable…hydrogen ferries remain stuck in pilots with higher costs…Fortescue abandoned hydrogen and ordered billions of dollars of battery electric equipment…Airbus shelved hydrogen aircraft programs and ZeroAvia shed staff and did not hit any of its targets

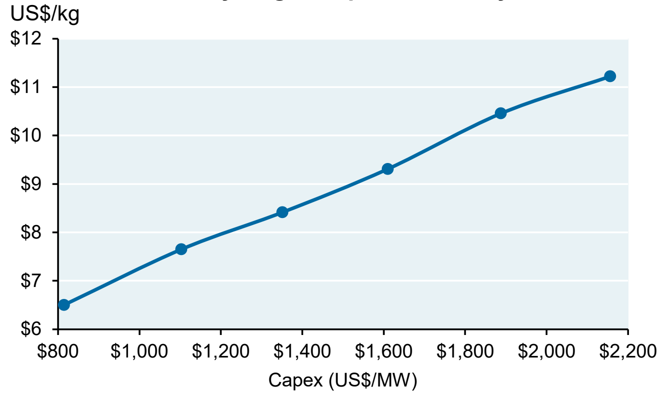
"*The Green Hydrogen Reset*" in the December 2025 issue of *The Chemical Engineer* included the charts below. Key conclusions: intermittent electrolyzer utilization via wind/solar power that would otherwise be curtailed is terrible for green hydrogen economics; reduced capital costs and higher electrolyzer efficiency don't reduce green hydrogen costs that much since electricity comprises 60%-70% of total levelized costs; and even if electricity were free, green hydrogen costs would still be 3x-4x higher than the cost of hydrogen made from steam methane reforming or coal gasification. If hydrogen capital equipment and power for electrolyzers were completely free, then hydrogen would be pretty competitive economically.

Levelized cost of hydrogen utilization sensitivity
US$/kg



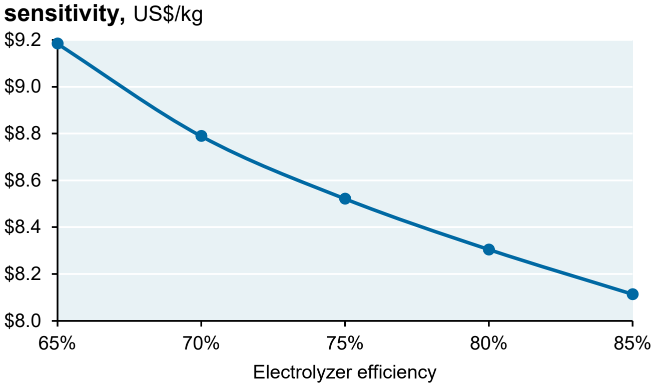
Source: The Chemical Engineer, December 11, 2025

Levelized cost of hydrogen capex sensitivity
US$/kg



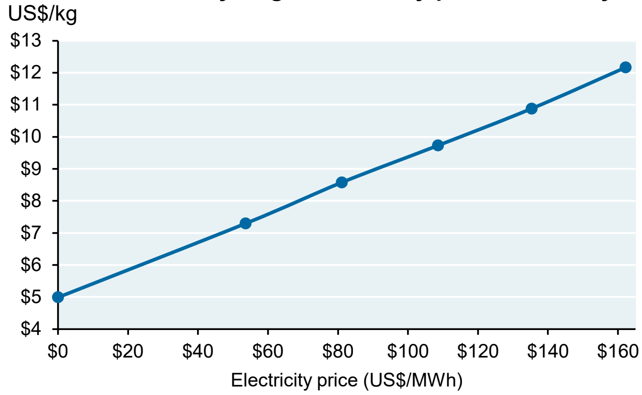
Source: The Chemical Engineer, December 11, 2025

Levelized cost of hydrogen electrolyzer efficiency sensitivity, US$/kg



Source: The Chemical Engineer, December 11, 2025

Levelized cost of hydrogen electricity price sensitivity
US$/kg



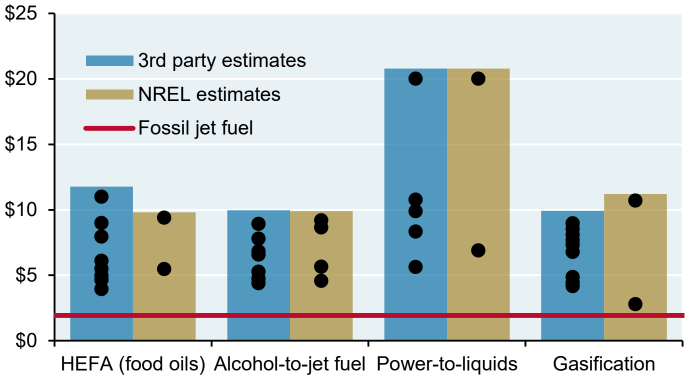
Source: The Chemical Engineer, December 11, 2025

[87] "*Hydrogen for Transportation Didn't Fail Just Once in 2025. It Failed Everywhere*", Clean Technica, Michael Barnard, December 22, 2025

[15] Sustainable aviation, motor and shipping fuels stuck in neutral; the electric shipping density problem

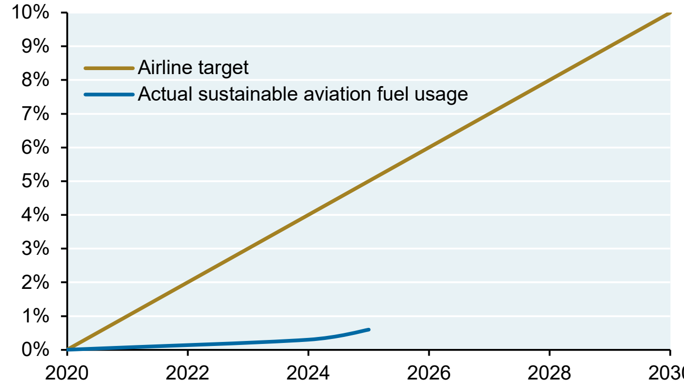
We included a deep dive on sustainable aviation fuels (SAF) last year along with the following charts showing much higher SAF costs than traditional jet fuel irrespective of the SAF pathway chosen, along with a chart on limited SAF adoption rates compared to prior targets.

Renewable jet fuel cost estimates
US$ per gallon



Source: "Sustainable Aviation Fuel", DoE, JPMAM, 2024

Global sustainable aviation fuel usage
Sustainable fuel as a % of commercial aviation fuel consumption

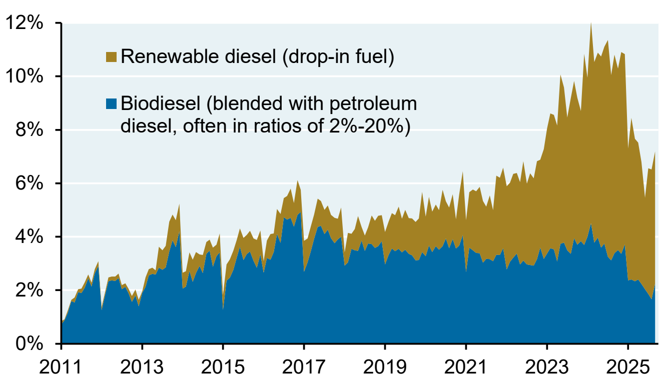


Source: International Air Transport Association, Bloomberg, December 2025

On sustainable motor fuels. Renewable diesel is chemically equivalent to traditional diesel and is used as a drop-in fuel. In contrast, biodiesel dissolves other materials and gels more easily so it's typically blended with petroleum diesel in ratios of 2%-20%.[88] Renewable diesel and biodiesel are made from the same feedstocks: cooking oil and animal fats. Renewable diesel is produced via hydrotreating, similar to cracking crude oil (feedstocks react with hydrogen at a high temperature and pressure, byproducts are separated and distilled). Biodiesel is created through transesterification, in which feedstocks react with alcohols and catalysts to produce fatty acid alkyl esters, a process with lower capital costs than hydrotreating. Roughly 8 lbs of feedstock are needed per gallon of renewable diesel, while ~7.5 lbs of feedstock are needed per gallon of biodiesel[89].

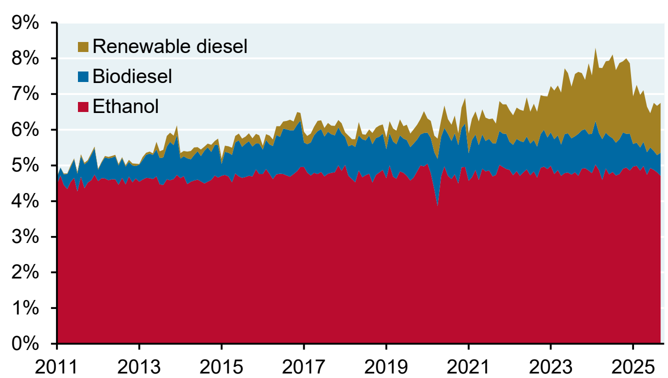
How are things going? Sustainable motor fuels are stuck in neutral in the US. As shown on the left, the sustainable share of diesel consumption is back at ~6% since tax credits are now only available for domestically produced sustainable diesel and not for imports[90]. Within gasoline supplies, ethanol shares have been steady at ~7%. On a blended basis, the sustainable share of all motor fuels is still 6%-7% as shown on the right.

Sustainable share of US diesel consumption
Percent



Source: EIA, JPMAM, September 2025

Sustainable share of US motor fuel consumption
Percent



Source: EIA, JPMAM, September 2025

88 *"Biofuels explained"*, EIA, February 2024

89 *"Biodiesel and Renewable Diesel: What's the Difference?"*, Gerveni et al (University of Illinois), February 2023

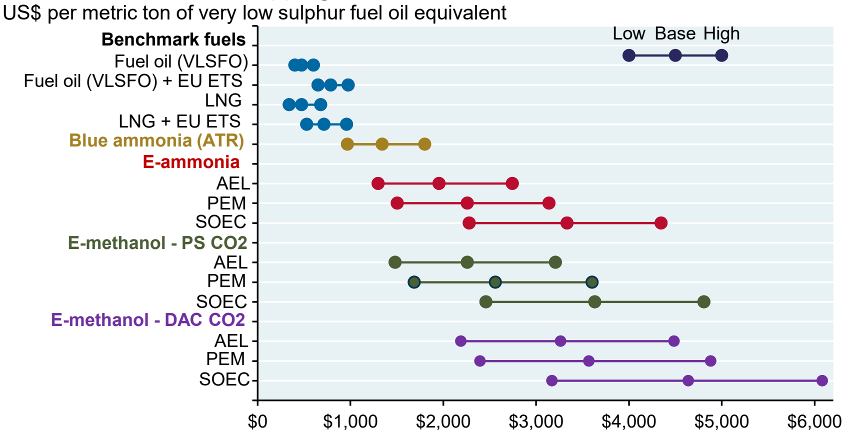
90 *"US biodiesel and renewable diesel imports fall sharply in 2025 after tax credit change"*, EIA, September 2025

Sustainable shipping fuels are also stuck in neutral. By most estimates, sustainable/renewable shipping fuels represent less than 1% of all maritime fuel consumption[91]. While some ships are now built with flexible engines that handle different fuels, I'm more interested in how companies ***are*** using these flexible engines rather than how they ***could*** use them.

The first chart shows the high cost of ammonia and E-methanol fuels vs traditional low sulfur fuel oil[92]. Blue ammonia is the cheapest alternative and involves carbon capture of CO_2 emissions resulting from reforming of methane. After that, costs skyrocket for all of the reasons discussed in #14 on the high cost of electrolysis as a means of hydrogen production, and become absurd when using direct air carbon capture to source the CO_2. The second chart is another take on why learning curves may not be enough: for most approaches the capital equipment cost is less than 50% of the levelized cost; and when it's higher, the overall cost is so high that even learning curve capex declines may be insufficient. It's hard to see carbon taxes bridging these gaps.

Ammonia is also a controversial choice for a shipping fuel: "ammonia is a toxic and corrosive gas, and using it as a fuel aboard ships fails the 1st principle of safety in design"[93]. There's a big difference between (a) carrying a cargo of a poisonous, corrosive gas like ammonia *aboard* a cargo ship and (b) *using* ammonia in any open system use such as feeding it to engines. The safety risk of the latter may be orders of magnitude higher.

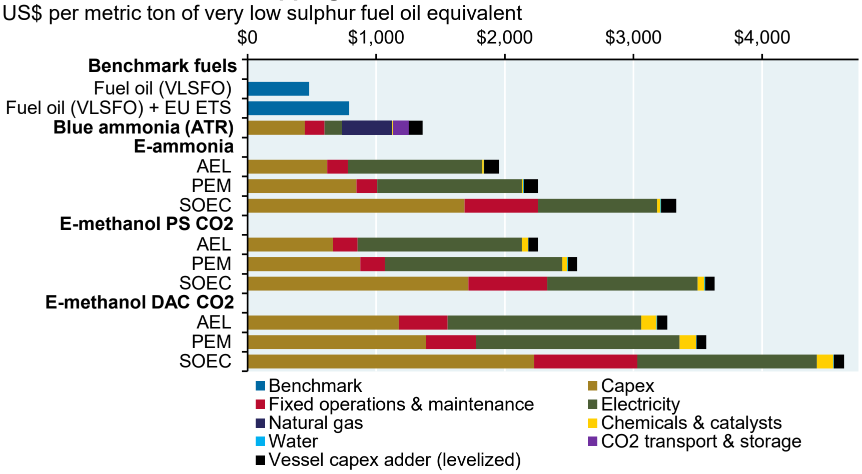
2026 levelized cost of shipping fuels
US$ per metric ton of very low sulphur fuel oil equivalent



Source: CovalentIQ LCOF Model v1.0, JPMAM, January 2026

- VLSFO: very low sulfur fuel oil
- EU ETS: European Union Emissions Trading System
- LNG: liquefied natural gas
- ATR: auto-thermal reforming
- AEL: alkaline electrolysis
- PEM: proton exchange membrane electrolysis
- SOEC: solid oxide electrolyzer cell
- PS: point source (CO_2 origin)
- DAC: direct air capture (CO_2 origin)

2026 levelized cost of shipping fuels breakdown, base case
US$ per metric ton of very low sulphur fuel oil equivalent



Source: CovalentIQ LCOF Model v1.0, JPMAM, January 2026

[91] Renewable Fuels Association, October 2025 and the IEA, October 2025

[92] "*How big is the gap to green parity in marine shipping fuels in 2026?*", Covalent-IQ, 2026

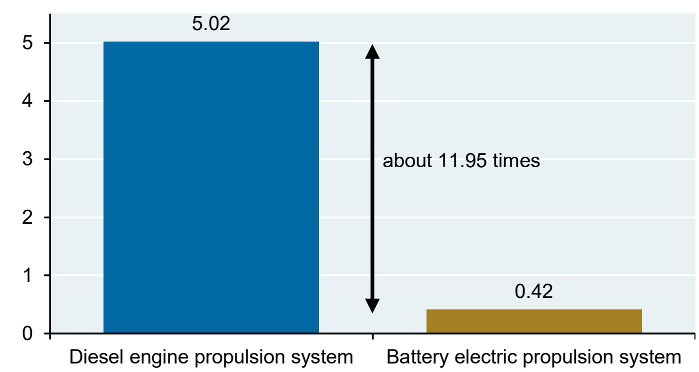
[93] "*Ammonia - Ship of Fuels or Fuel of Fools?*", Paul Martin, Spitfire Research, August 2, 2024

What about electrified shipping?

Like their land-based counterparts, battery electric motors in ships are more efficient than combustion engines burning heavy fuel oil, light fuel oil, diesel or liquefied natural gas. But since the energy density of battery electric motors is so much lower than the energy density of shipping fuels, electric propulsion for shipping is still too energy inefficient to compete for most maritime routes.

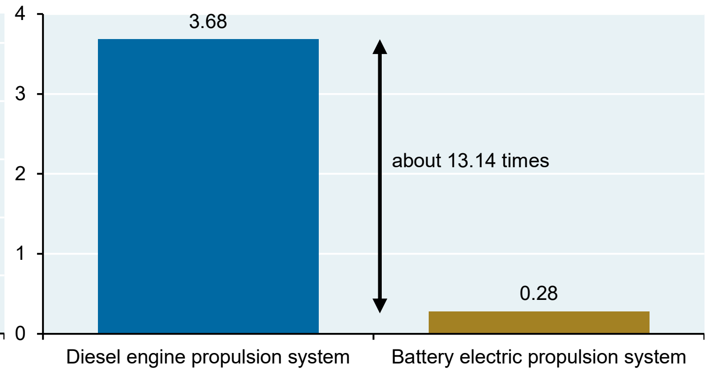
A recent article in the International Journal of Naval Architecture and Ocean Engineering compared diesel vs electric engines in the context of a 10-gross tonnage fishing vessel (30 - 40 feet long) on a one-week voyage, assuming a variety of variables related to distances traveled, speeds, fuel efficiency, voltage converters etc[94]. The charts compare gravimetric energy density (energy per unit of mass) and volumetric energy density of both propulsion systems. **Both energy densities for diesel engines were 12x-13x higher than battery propulsion even after accounting for higher efficiency of the electric motor.** As the weight and volume of a diesel propulsion system increases with larger vessels and longer trips for traditional commerce, the diesel density advantage vs electric gets even bigger, approaching 26x-36x at practical maximums according to this study.

Effective gravimetric energy density
MJ/kg



Source: Int. J. Nav. Archit. Ocean Eng., Zhang et al, August 7, 2025

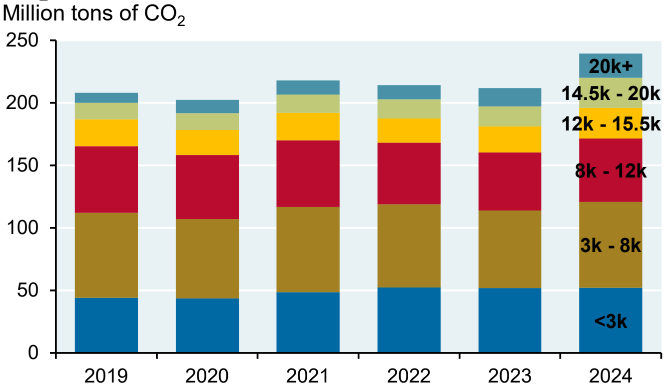
Effective volumetric energy density
MJ/L



Source: Int. J. Nav. Archit. Ocean Eng., Zhang et al, August 7, 2025

The authors did find that in some edge cases, battery propulsion systems can be more efficient than diesel: very low speed, lighter cargo, short distance voyages. In that regard, China just launched sea trials for a small electric containership capable of carrying 740 TEUs (twenty foot equivalent units). But while containerships of < 3,000 TEUs represent 50% of all containership *vessels*, they only represent 22% of all containership *emissions*. So, even if there is some uptake of electrification for short duration maritime trips, the impact on diesel fuel demand and shipping emissions looks pretty modest, at least for now.

CO_2 emissions by containership size
Million tons of CO_2



Source: Xeneta, Marine Benchmark, April 2025. Ship sizes measured in twenty-foot equivalent units (TEUs)

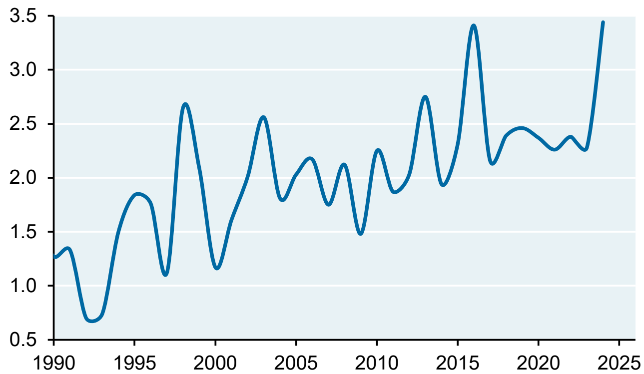
94 "*Effective energy density in small vessels: a comparative study of diesel and battery electric propulsion systems*", International Journal of Naval Architecture and Ocean Engineering, Zhang et al, August 2025

Essential charts: Vaclav Smil on the limits and constraints on green electrification

Vaclav Smil has been working on a new piece entitled "*Global energy 2000-2025: status and outlook*". I asked Vaclav if I could create some charts that correspond to some of his findings on topics that I haven't covered elsewhere this year; these charts and Vaclav's associated commentary appear below.

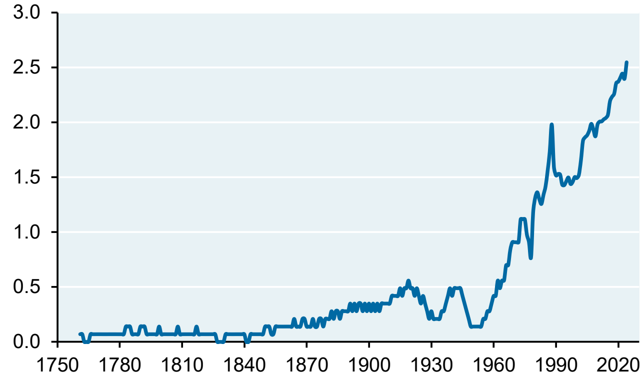
[1] **CO_2 emissions are now rising faster than at any time in modern history**. Because of complex interactions of carbon reservoirs in the atmosphere, oceans and the biosphere, rare annual emission dips have not affected the steadily rising atmospheric concentrations of CO_2. Their average annual increase accelerated from 1.5 ppm (parts per million, that is 0.0125%) during the 1990s to 2.4 ppm between 2010 and 2020 and to 3.5 ppm in 2024.

Atmospheric CO_2 concentration annual increase
Parts per million, since 1990



Source: NOAA, JPMAM, 2024

Atmospheric CO_2 concentration annual increase
Parts per million, ten year trailing average, since 1760



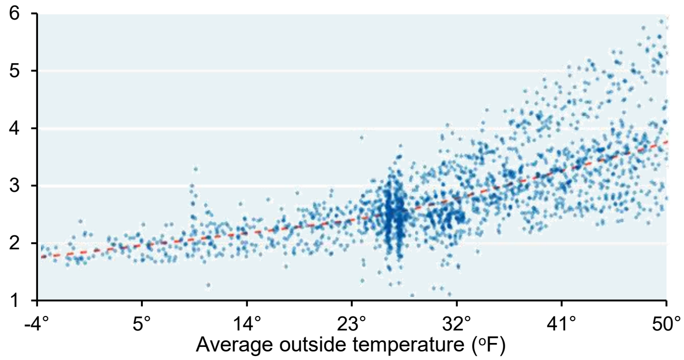
Source: NOAA, JPMAM, 2024

[2] **Efficiency gains from electric vehicles and heat pumps are real and they are most welcome**, but it would be a mistake to conclude that a renewably electrified world of 2050 could function with only a small fraction of today's primary energy supply. The first reason is the difference between typical long-term conversion efficiencies and the claimed maxima; the second is the impracticability and high cost of some rapid substitutions of fuels by electricity; and the third is the impossibility of electrifying several fundamental industrial and transportation tasks that are now energized by fossil fuels.

[3] Electrification of transportation faces combined challenges of longer ownership, higher first costs and the absence of readily available alternatives. Fifty years ago Americans changed their cars every 3-5 years, now it is every 12-14 years, and new US EVs are $6,000-10,000 more expensive while heavy-duty long-haul (Class 8) electric trucks cost twice as much (up to $500,000) as diesel versions. Global trade depends on large container ships (carrying 10,000-24,000 steel boxes), global passenger travel relies on jetliners and harvests of cereal and leguminous grains need large combines. The first and the third activities are now powered by large diesel engines, the second one by gas turbines. As of 2025 there are no commercially available large container ships, jetliners or large combines running on electricity and there are no imminent prospects for their early introduction followed by rapid mass-scale adoption.

[4] **As with any performance claims, there are gaps between the best possible ratings and standard long-term performances**. Space heating offers an excellent example. New natural gas furnaces are now at least 90% efficient and the best heat pumps claim coefficient of performance (COF) at 4.0 (400% efficient). But many measurements of actual heat pump efficiency show the seasonal COF in climates like New England to be most commonly about 2.0 and less in colder regions that need most heating. Prudent conversion would just see completely electrified heating requiring about half of today's energy input to provide the same service. Similarly, the difference of overall efficiency between increasingly popular hybrid and plug-in hybrid vehicles and EVs is only twofold (30-35% vs. 60-70%).

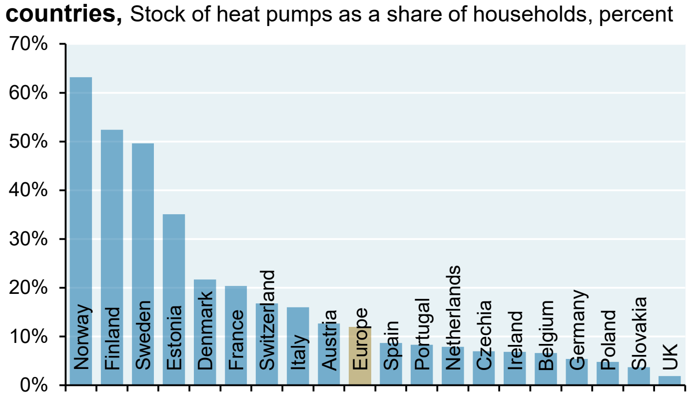
Air-source heat pump COP vs ambient temperature
Avg coefficient of peformance



Source: "*Coming in from the cold: heat pump efficiency at low temperatures*", Gibb et al (Joule), September 20, 2023

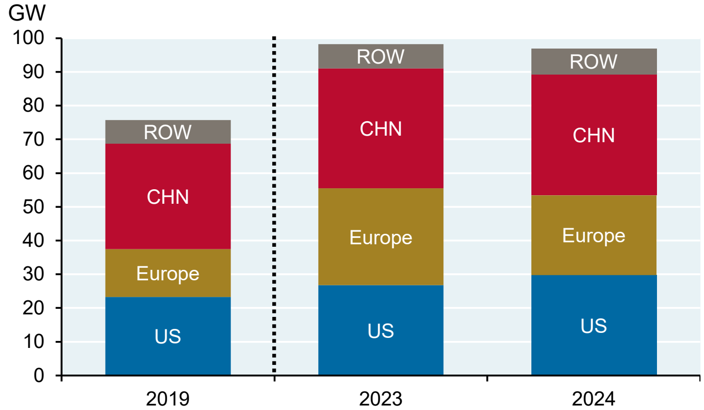
[5] **Initial cost is a serious barrier to universal adoption of some efficient alternatives.** Europe leads in the adoption of heat pumps but new air-source pumps cost €12,000-18,000 and new ground source pumps cost €16,000-30,000. That compares to the EU's annual average disposable income of €20,000 per capita and a cost of €2,000-5,000 for installing a natural gas furnace. Heat pump life-cycle costs will be lower but only a small share of its population could make the switch without substantial subsidies. In 2024 only 5% of households had a heat pump even in rich Germany, and high Nordic adoption rates lifted the European mean to just 12%.

Residential heat pump penetration for select European countries, Stock of heat pumps as a share of households, percent



Source: European Heat Pump Association, 2024

Heat pump sales by region
GW



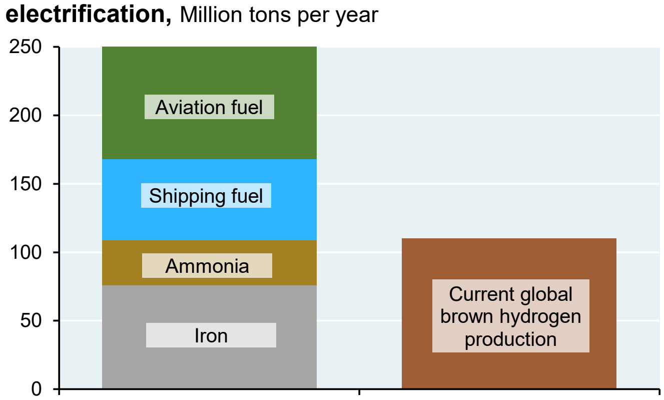
Source: IEA, JPMAM, 2025

[6] **While some indispensable mass-scale industrial processes can in principle be electrified via electrolytic green hydrogen, the related power requirements are immense.**

- Ironmaking (8%), ammonia (1.3%), shipping (2.9%) and aviation (2.5%) account collectively for roughly 15% of global CO_2 emissions. On paper, they can all be decarbonized via electrolytic green hydrogen
- **Ironmaking** can be electrified by reducing iron ores by hydrogen ($Fe_2O_3+3H_2 \rightarrow 2Fe+3H_2O$). Around 76 million tons of green hydrogen would be needed each year to produce current global primary iron consumption
- Synthesis of 185 million tons of **ammonia** produced in 2024 by the Haber-Bosch process ($N_2+3H_2 \rightarrow 2NH_3$) would need around 33 million tons of green hydrogen now derived mostly from natural gas
- **Aviation and shipping fuels**. The Fischer-Tropsch reaction converts CO and hydrogen to liquid hydrocarbons. Stoichiometric calculations (using the equation for dodecane as the molecule representing 280 million tons of aviation kerosene, $25H_2+12CO \rightarrow C_{12}H_{26}+12H_2O$ and hexadecane to represent 200 million tons of marine diesel fuel, $33H_2+16CO \rightarrow C_{16}H_{34}+16H_2O$) result, respectively, in 83 and 59 million tons of green hydrogen needed annually to synthesize both fuels
- **Electricity**. Electrolysis of water to produce green hydrogen with 100% efficiency requires 39.4 MWh/t

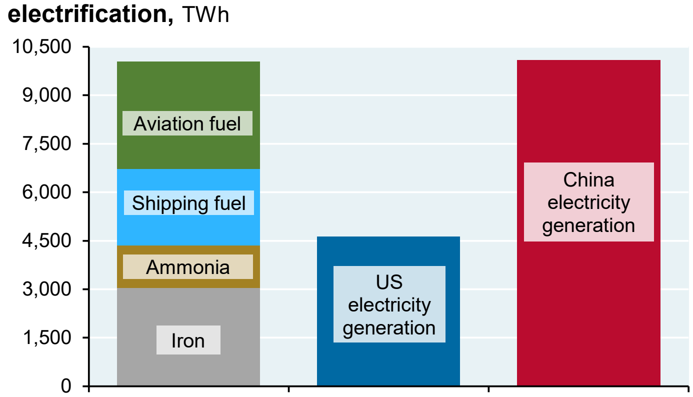
So to conclude…the 109 million tons of green hydrogen required to decarbonize iron and ammonia would be roughly equal to current global brown hydrogen production and also require 4,360 TWh of electricity, almost the same amount as total US electricity generation in 2024. If we add 142 million tons additional of green hydrogen required to produce clean shipping and aviation fuels, the combined 251 million tons would require 10,040 TWh of electricity, roughly equivalent to China's 2024 electricity generation. Producing 251 million tons of green hydrogen would be a 500x increase compared to today's 0.5 million tons of green hydrogen per year.

Green hydrogen requirements for industrial product electrification, Million tons per year



Source: Vaclav Smil, 2024

Generation requirements for industrial product electrification, TWh



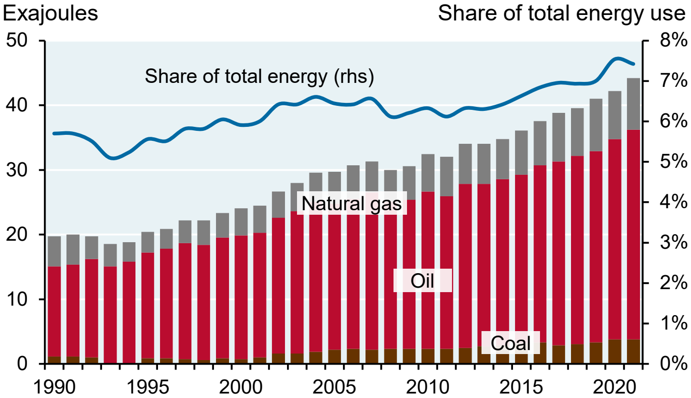
Source: Vaclav Smil, Energy Institute, 2024

What about cement? Production of cement (by mass the world's largest industrial output) surpasses 4 billion tons a year and accounts for ~8% of global CO2 emissions. Cement production is the most difficult to electrify since heating of lime and clay in rotary kilns requires temperatures of 1,400–1,500°C that are beyond the capabilities of electric heaters. As a result, decarbonization of cement is excluded from the analysis above.

[7] **How much might it cost?** In 2024 the average cost of adding 1 MW of generating capacity was $1-$1.5 mm for wind and $0.8-$1.2 mm for solar. Assuming an average load factor of 25% means that each MW would generate 2.19 GWh/year. It would cost ~$5 trillion to pay for the 4.6 TW of wind and solar capacity to produce 10,040 TWh each year for decarbonized iron, ammonia, shipping fuel and aviation fuel via green hydrogen, and reduce global CO_2 emissions by ~15%

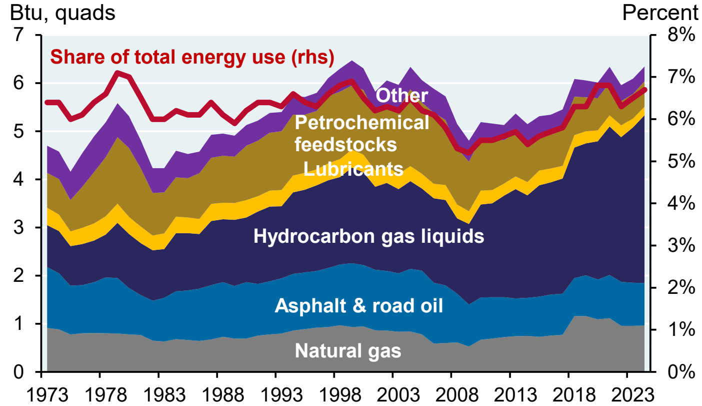
[8] **Don't forget the often overlooked but not easily replaced non-energy use of fossil fuels.** On a global basis, this demand is now equivalent to more than 700 million tons of crude oil. Two-thirds are used as feedstocks to produce primary chemicals (from ammonia for nitrogen fertilizers to ethylene for plastics), the rest is asphalt for paving (about 100 million tons a year), lubricants (essential to reduce friction in myriads of moving parts) and carbon black (indispensable for tires). Some future feedstocks could come from biomass but replacing asphalt would be far more challenging. Globally and in the US, non-energy fossil fuel use is around 7%-8% of fossil fuel used for energy (combustion).

Global non-energy use of fossil fuels, 1990-2021



Source: Boston University Institute for Global Sustainability, March 2025

US non-combustion fossil fuel use



Source: EIA September 2025 Monthly Energy Review

Industrial use of fossil fuels as raw materials

Metallurgical coke	Pig (cast) iron smelting (carbon source), which eventually becomes steel
Methane	Synthesis of ammonia (hydrogen source), mostly used for fertilizing crops
Methane, naphtha and ethane	Synthesis of plastics (sources of monomers)
Heavy petroleum products	Production of carbon black (rubber filler), used in tires & other industrial products

It's tempting to believe that since these fossil fuels are embedded into physical products (i.e., plastic in soda bottles or the rubber in car tires), they would not contribute to increased GHG emissions. But none of these products lasts forever, and many end up in waste incineration plants, in decomposing landfills or in the ocean. The DoE and EIA made detailed permanent carbon storage assumptions by product in a 260-page document in 2008 which is still in use today. Carbon in asphalt is considered 100% stored while for lubricants storage is assumed to be 50%. The IPCC assumes 80% carbon storage in plastics, but actual storage rates may be lower due to incineration or decomposition in landfills.

[9] **Declines in energy use due to efficiency savings and electrification may be substantially reduced or negated by growth of new demand, while some hard-to-electrify sectors might see the doubling of their energy use.** Even before the rise of AI-related demands, global electricity generation was expected grow by 70% by 2050. In mid-2025 there were 30,300 jetliners in service but Boeing expects a need for 43,600 new planes by 2044. Global steel demand could be up by a third by 2050, with most of the iron still coming from blast furnaces: China, the world's largest producer, has added 25 new blast furnaces in 2023, 22 in 2024 and 20 in 2025.

Appendix I: our useful final energy methodology

Many of you may be familiar with Sankey diagrams on energy flows, but they generally only adjust for heat loss in combustion for power generation. Our useful final energy measure goes further and attempts to measure to final energy actually consumed by industrial, transport, commercial and residential end users. The table shows the most important assumptions. The goal is to account for waste heat lost in conversion of energy to electricity, transport and thermal heat, and energy lost in the extraction, refining and distribution process of all forms of energy before its use in final applications. There are many peer-reviewed and industry sources that cite efficiency of vehicles, turbines and furnaces. In the footnote we show the ones we use; your mileage may vary.

Internal combustion engines

[a] Tank to wheel efficiency	Share of FF transport[1]	Efficiency	#	Comments
Passenger cars	45%	18%	2	Assumes 100% gasoline fleet
Trucks	28%	43%	3	
Aviation	12%	33%	4	The product of thermal and propulsive efficiencies
Maritime	10%	47%	5	
Buses	4%	14%	6	
Rail	1%	35%	7	
Weighted average transport tank to wheel efficiency		**30%**		

[b] Oil well to pump efficiency	**82%**	8	Net of energy used in extraction, refining and distribution
[c] Well to wheel efficiency	**24%**		Product of tank-to-wheel and well-to-tank efficiencies

Electricity generation via combustion turbines

Description	Share of gas plants	Efficiency	#	Comments
Coal plants		**40%**	9	Reflects the average of coal plants by age
Oil plants		**30%**	10	
Gas plants				
Combined cycle share, US	*60%*		11	
Simple cycle share, US	*40%*		11	
Combined cycle efficiency		*60%*	12	
Simple cycle efficiency		*38%*	12	
Blended gas plant		**51%**		

Furnaces and boilers for industrial, commercial and residential heat

Description	Efficiency	#	Comments
Gas furnace efficiency	90%	9	
Oil furnace efficiency	85%	12	
Coal furnace efficiency	75%	13	
Gas well to furnace efficiency	85%	8	Net of extraction, refining, distribution & compression losses
Oil well to furnace efficiency	82%	8	
Coal mine to furnace efficiency	92%	8	
Gas well to heat efficiency	**77%**		
Oil well to heat efficiency	**70%**		
Coal mine to heat efficiency	**69%**		

Electricity grid and balance of plant functions

Description	Losses	#
Transmission & distribution losses	5%	11
Nuclear balance of plant energy consumption	5%	11

Sources: 1=Rystad Energy, 2=NREL, 3=International Council on Clean Transportation, 4=National Academies, 5=Copenhagen Center on Energy Efficiency, 6=Polish Scientific Society of Combustion Engines, 7=Mikura International, 8=Environmental and Climate Technologies Journal, 9=Vaclav Smil 10=PCI Energy Solutions, 11=EIA, 12=International Petroleum Industry Environmental Conservation Association, 13=University of Connecticut

Some details on our methodology:

- **Our efficiency measures represent estimates for the existing *stock* of energy converting devices, rather than the most improved versions now commercially available**. In other words, if we are trying to capture current final energy consumption, it makes more sense to use current fleet averages than to use efficiencies for the latest models. For example: before 1970, coal plant efficiencies were 32%-35%; from 1970 to 2000, 35%-40%; from 2000 to 2024, 40%-45%; and in 2025, efficiencies range from 45%-49%. Since the average coal plant can last 40 years or more (the average age of the global fleet is 25 years, and in the US, 40 years), we use 40% as an estimate for the global fleet
- For passenger car internal combustion engines, we assume a 100% gasoline fleet and back into the efficiency rate using NREL data on the relative efficiencies of EVs vs gasoline cars (EVs are 4.4x more efficient). Based on an EV efficiency of 80%, we determined the gasoline passenger car engine efficiency to be 18%
- For nuclear power we adjust for the energy required to run the plant itself since reported nuclear generation data is gross of these amounts. For wind and solar, balance of plant consumption is much smaller and as a result we do not adjust for it
- We adjust for the energy consumed in the extraction, refining, compression, distribution and transmission of all forms of energy since these amounts are not available to final users
- We account for efficiency differences across gasoline cars, diesel trucks, commercial airliners and maritime ships. However, the share of each engine type in each country's transport consumption is difficult to find for a lot of countries in the dataset, so we use the global average vehicle shares as a proxy
- Electric motors are not 100% efficient, and to be consistent, we would ideally adjust for energy losses in the conversion of electricity to final transport energy as we do with internal combustion engines. Estimates for EV electric motor energy losses in passenger cars vary from 10% (Yale Climate Connections) to 20% (Applied Energy/SINTEF). While we don't currently account for these losses, even if we did, they would be quite small. Let's use China as an example: in 2024, EVs were ~10% of the Chinese car fleet (BNEF) and consumed 110 TWh of electricity (China Daily). In theory we would reduce the 110 TWh by 10%-20% in estimating transport final energy. But at most this would reduce overall China useful final energy consumption by just 0.1%. So: we are not concerned (yet) about the drawback of our current approach
- Conversion efficiencies differ between simple cycle and combined cycle gas plants. We use the relative amount of both in the US as a basis for determining weighted average gas plant efficiency for all countries
- A comment on heat pumps. We define useful final energy consumption as the amount of energy purchased and consumed by end users since that's the amount of energy that each country must produce or import. However, this does not capture all energy consumed by final users since some energy consumption involves process heat. One example: a heat pump can consume 1 joule of electricity and produce 3 joules of heat due to its engineering (i.e., use of ambient temperature differentials to do some work for it). However, this does not change the amount of electricity purchased/consumed by final users which is 1 joule, not 3. As heat pump adoption rises, joules of electricity consumption will go up and the joules of displaced fossil fuels will fall by an even greater amount depending on the coefficient of performance of the heat pumps used

Appendix II: on wind turbines and birds

Some fossil fuel advocates frequently trot out criticisms of wind farms due to bird deaths. A recent 190-page study concluded that migratory birds almost completely avoid wind turbines in the North Sea and Baltic Sea, and that collision risk is significantly lower than previously assumed. In this study commissioned by the German Offshore Wind Energy Association (a substantial caveat), scientists analyzed collision risk in a near-shore wind farm in northern Germany, encompassing four million bird movements over one and a half years. The results:

- Over 99.8% of diurnal and nocturnal migratory birds avoided turbines, a much larger share than previously assumed
- There was no correlation between migration intensity and collisions: contrary to previous assumptions, the collision rate did not increase with the number of migrating birds. Even during periods of high nocturnal migration activity, very few birds flew through the rotor area.
- The combination of radar and AI-based cameras allowed for unprecedented accuracy in recording bird flight movements in the rotor plane and collision frequency

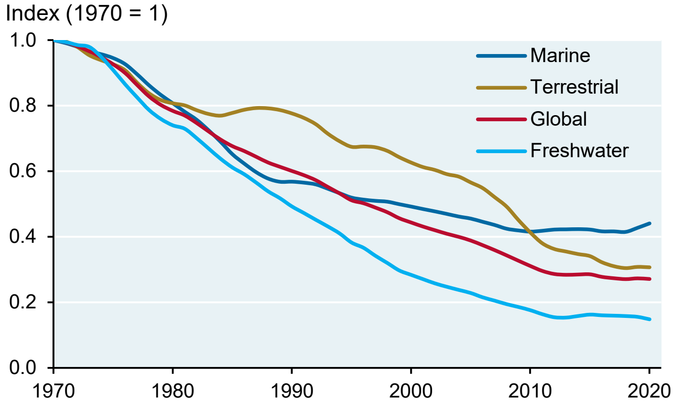
While cats, windows and climate change kill more birds than wind turbines, they often don't kill the same kind of birds. Ecologically important seabirds and birds of prey that breed slowly and whose populations can't quickly recover from losses are more at risk from wind turbines. South Africa's endangered black harrier, a medium-sized raptor with a declining population of fewer than 1,300 birds, could become extinct in less than a century with the loss of just three to five adults per year.

Some solutions are simple, like painting turbine blades in contrasting colors. Painted blades reduced bird deaths by 70% in Norway and by 80% in South Africa, but in other locations the impact was negligible. Other solutions are complex and expensive, like using cameras with AI technology to shut down or slow turbines when birds approach. A large shutdown on demand project in Spain covered 269 turbines at 20 wind farms; mortality of large soaring birds like storks and raptors declined by more than 60% and only cut energy production by 0.51%.

All of that said, given the decline in vertebrate biological diversity over the last 50 years, there's something very disingenuous about some of the people who cite bird deaths as an objection to wind turbines. I think you all know what I mean.

Vertebrate biological diversity index

Index (1970 = 1)



Source: World Wildlife Fund and Zoological Society of London, 2024

Sources: "*The collision risk of migrating birds at wind farms*", BioConsult SH, Dr. Jorg Welcker, November 2025; and "*Birds vs. Wind Turbines: New Research Aims to Prevent Deaths*", Yale Environment 360, June 4, 2025

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