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EYE ON THE MARKET | 15TH ANNUAL ENERGY PAPER | MARCH 2025

Heliocentrism

Objects may be further away than they appear

Solar capacity is booming around the world, both utility scale and residential applications, and is often accompanied by energy storage whose costs are declining as well. Yet after $9 trillion globally over the last decade spent on wind, solar, electric vehicles, energy storage, electrified heat and power grids, the renewable transition is still a linear one; the renewable share of final energy consumption is slowly advancing at 0.3%-0.6% per year. Our 15th annual energy paper covers the speed of the transition, electrification, the changing planet, the high cost of decarbonization in Europe, nuclear power, the Los Angeles fires, Trump 2.0 energy policies, renewable aviation fuels, superconductivity, methane tracking and the continually wilting prospects for the hydrogen economy.

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

Heliocentrism: Objects may be further away than they appear

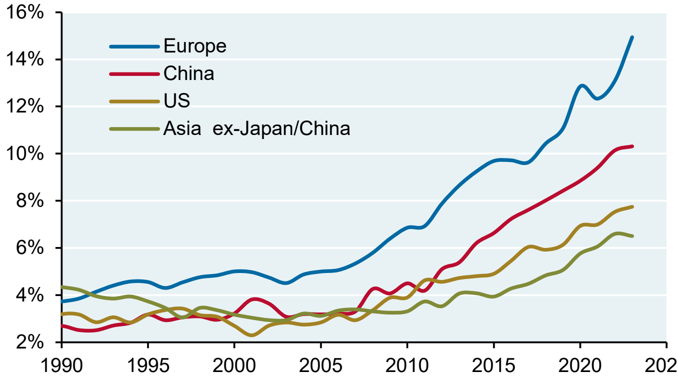
The renewable transition exists in the eye of the beholder. Some see an accelerating transition, while others retreat from prior optimistic transition forecasts[1]. As usual, our annual energy analysis sticks to the facts on the ground: decarbonization is best described as an industrial transition and so far, the speed of this transition is linear. Even in Europe, the world's transition leader, the renewable share of final energy consumption is rising at just 0.6% per year. Some prior industrial transitions were faster such as the 20-year shift away from open hearth furnace steel production that began in 1960. But there's a simple reason for this: at the time, new steel technology reduced production times and energy use by 80%-90%. In other words, the steel transition paid for itself and rewarded early adopters. That's not the case today: global spending of US$9 trillion since 2010 has been needed to move the renewable transition along at the linear pace shown below on the left. Human prosperity, in most places where it thrives, will still be reliant on natural gas for many years.

This year's topics. We begin our 15th annual energy paper with an Executive Summary on the surge in global solar capacity, the speed of the energy transition and an update on electrification. We follow with exhibits on how the planet is changing and our collection of over 70 essential energy transition charts. We explore the high price of decarbonization in Europe, the rebirth of interest in nuclear power in the West, the configuration and cost of deeply decarbonized US grids, the Los Angeles fires, Trump 2.0 renewable energy policies, the challenging thermodynamics of renewable aviation fuels, a cautionary tale on superconductivity, findings from new methane tracking efforts and the ongoing demise of hydrogen economy visions.

There's a lot in here but you don't have to read the whole thing. If you're looking to understand the big picture, start with the 7-page executive summary. The rest of the details are for people, like myself, that are trying to separate fact from fiction given the hyperbole used by both advocates and skeptics of the energy transition.

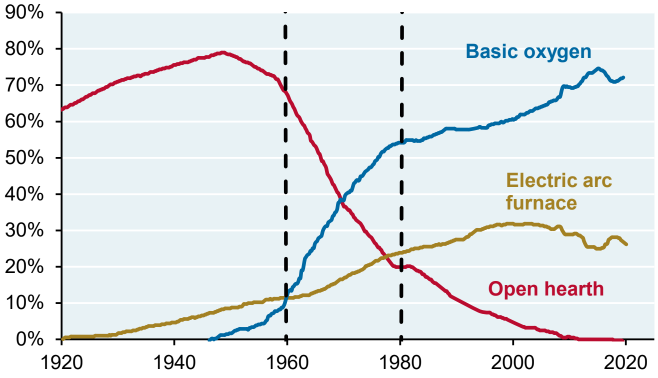
Michael Cembalest
JP Morgan Asset Management

Decarbonization is a linear industrial transition
Renewable share of final energy consumption



Source: EI Statistical Review of World Energy, JPMAM, 2024

Rapid energy-saving steel transition of the 1960s/1970s
Percent of global steel production



Source: Lauri Holappa, Aalto University, March 2019; Boston Metal, May 2022

See pages 8-9 for more details on both charts

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[1] **Reality Bites**. Goldman Sachs has been at the forefront of aggressive renewable transition projections in its *Carbonomics* series. However, they struck a much more cautious tone in their October 2024 piece, particularly as it relates to slow progress on hydrogen, carbon capture and coal decommissioning. Goldman now assumes a "longer life for hydrocarbon assets", growing demand for natural gas as a transition fuel until 2050, and the need for new oil & gas development beyond 2040. What a difference a year makes.

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An important note on energy math. We base our calculations on **final energy consumption** rather than primary energy consumption. Since oil, natural gas and coal suffer substantial heat loss when combusted in furnaces, vehicle engines or generation turbines, we convert fossil fuel primary energy figures into exajoules of usable final energy consumption. We account for energy efficiencies for each type of combustion, and the energy consumption mix in each country. This allows us to compare nuclear and renewable energy to fossil fuels on a usable energy basis without “input-equivalent” or other conversion techniques used by the EIA, EI and IEA.

Acknowledgements. I would like to acknowledge the comments generously provided by Paul Joskow at MIT, Paul Martin of SpitFire Research (sustainable aviation fuel pathways and non-electrolytic pathways for green hydrogen), Brad Ramshaw at Cornell (superconductivity), Sarah Kapnick (currently JP Morgan, formerly NASA/NOAA), Level Ten Energy, Darcy Partners (nuclear) and Stephen Comello at the Energy Futures Initiative.

Politics. I hope that the DOGE firings and other changes taking place in DC do not materially affect the ability of people like myself to source data from the US Energy Information Administration or the National Labs.

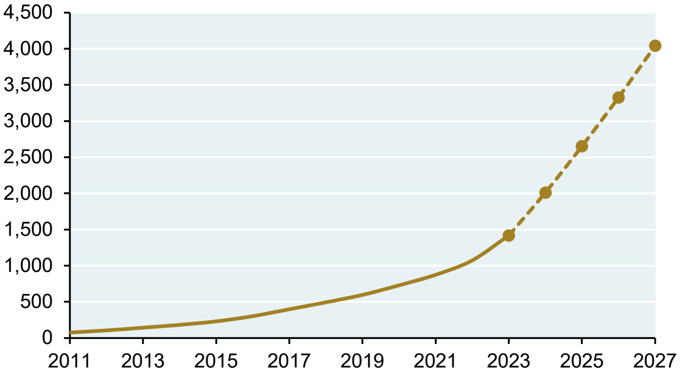
Acronyms: BEV battery electric vehicle; **BNEF** Bloomberg New Energy Finance; **BTU** British thermal unit; **CAISO** California Independent System Operator; **CCS** carbon capture and storage; **CO_2** carbon dioxide; **COP** coefficient of performance; **DBB** Deutsche Bundesbank; **E&P** exploration & production; **ECB** European Central Bank; **EI** Energy Institute; **EIA** Energy Information Administration; **ELCC** effective load carrying capacity; **ERCOT** Electric Reliability Council of Texas; **EV** electric vehicle; **GHG** greenhouse gas; **GW** gigawatt; **IAEA** International Atomic Energy Agency; **ICE** internal combustion engine; **IEA** International Energy Agency; **INE** Instituto Nacional de Estadística; **INSEE** Institut National de la Statistique/Economique; **IRENA** International Renewable Energy Agency; **ISO** independent system operator; **ISTAT** Istituto Nazionale di Statistica; **kV** kilovolt; **kWh** kilowatt-hour; **LBNL** Lawrence Berkeley National Laboratory; **LCOE** levelized cost of energy; **LDES** long-duration energy storage; **LFP** lithium iron phosphate; **LNG** liquified natural gas; **MISO** Midcontinent Independent System Operator; **MJ** megajoule; **Mtpa** million tonnes per annum; **MW** megawatt; **MWh** megawatt-hour; **NREL** National Renewable Energy Laboratory; **PHEV** plug-in hybrid electric vehicle; **PJM** Pennsylvania-New Jersey-Maryland Interconnection; **PPA** power purchase agreement; **PPI** producer price index; **ppm** parts per million; **PV** photovoltaic; **RTE** round-trip efficiency; **SEIA** Solar Energy Industries Association; **SPP** Southwest Power Pool; **TWh** terawatt-hour; **UK ONS** UK Office for National Statistics; **USGS** US Geological Survey; **ZJ** zettajoule

Executive Summary: Heliocentrism and the speed of the energy transition

Heliocentrism*: the belief that the earth revolves around the sun. For purposes of this paper, heliocentrism refers to the view that rapid growth in solar power and energy storage are at the heart of the energy transition, and that new investment in complementary thermal power generation is no longer required*

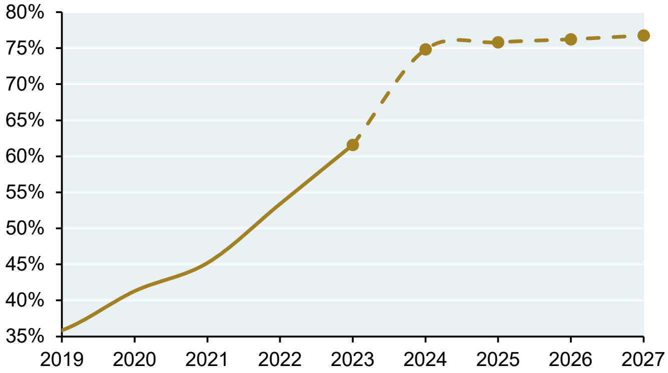
Believers in heliocentrism point to rapid growth in global solar capacity which more than doubled over the last three years. If BNEF projections are correct, solar capacity will double again from 2024 to 2027. Solar is now the dominant form of global capacity additions, comprising 60% of new capacity in 2024 and by our estimates ~75% in 2027. According to Carbon Brief, the International Energy Agency underestimated solar capacity growth for years and has been trying to catch up as shown below[2]. Globally, the combination of wind and solar power generation has soared past nuclear and should surpass hydropower in 2025. If you don't mind China's domination of most solar supply chains[3], this is good news regarding displacement of more carbon intensive forms of power.

Global solar capacity
GW



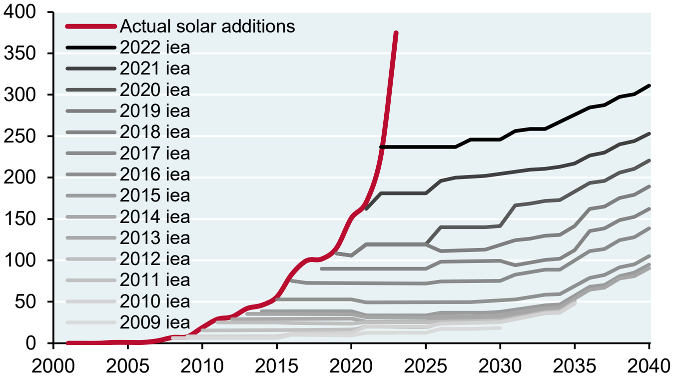
Source: EI Statistical Review of World Energy, BNEF, JPMAM, 2024

Solar share of global electricity generation capacity additions, Percent of new gigawatts installed



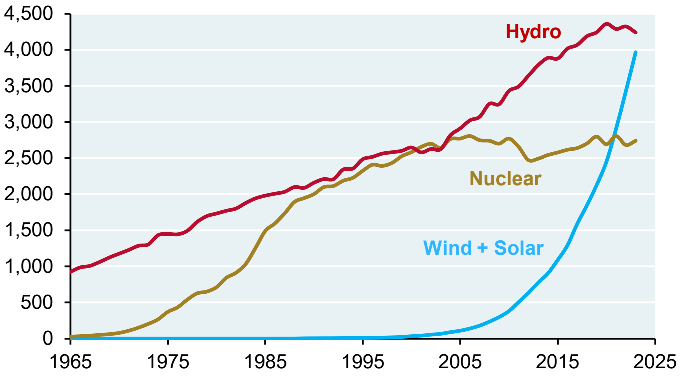
Source: Ember Climate, BNEF, JPMAM, September 2024

IEA consistently underestimated solar capacity growth
GW of global annual solar additions vs IEA forecasts



Source: Carbon Brief, 2024. IEA = International Energy Agency.

Global electricity generation
Terawatt-hours



Source: EI Statistical Review of World Energy, JPMAM, 2024

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[2] Simon Evans, Carbon Brief, February 20, 2023

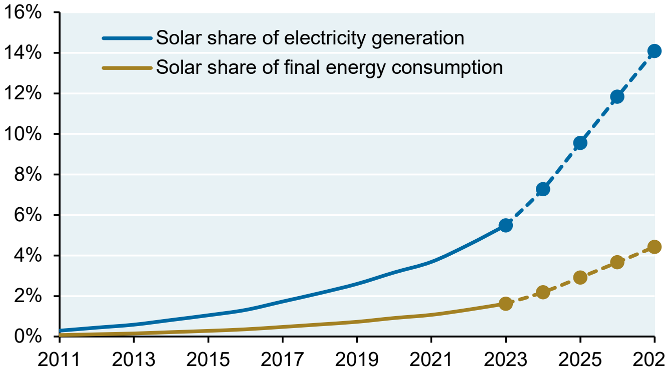
[3] China's global market share in manufacturing stages of solar (polysilicon, ingots, wafers, cells and modules) exceeds 80%, more than double China's share of global PV demand [IEA]. The US is in the process of building out its own PV module supply chain, but substantial import reliance remains; see page 14 for details

There are a couple of "buts" to keep in mind. Given global solar capacity factors of 15%-20%, solar's share of electricity generation is smaller than capacity additions suggest. Solar power accounts for ~7% of global electricity generation, a figure we project will double by 2027.

And as we discuss each year, electricity typically accounts for under one third of final energy consumption in most countries. Electricity is primarily used for space cooling, refrigeration, computers and other electronic equipment, and a small share of space heating in commercial/residential buildings. Transport, industrial production and most building space heating still rely on fossil fuels. **As a result, when you boil it all down, solar power accounts for ~2% of global final energy consumption, a figure we expect to reach 4.5% by 2027.**

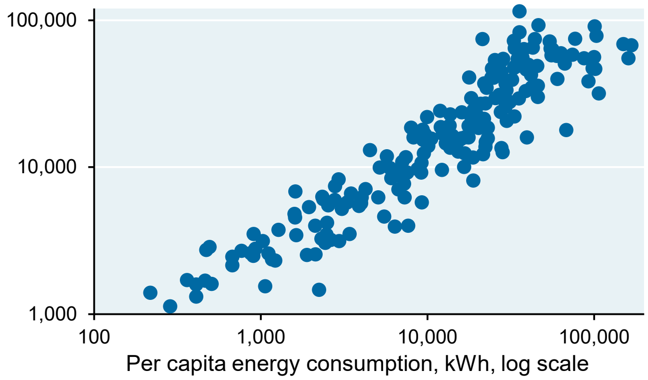
Even if these solar trends continue into the 2030's, human prosperity will be inextricably linked to affordable natural gas and other fossil fuels for many years. Human prosperity, in places where it thrives, relies heavily on steel, cement, ammonia/fertilizer, plastics, glass, chemicals and other industrial products which are energy-intensive to produce[4]. As shown in the pie charts, these products currently rely on fossil fuels for 80%-85% of their energy. And remember, prosperity itself is energy-intensive: among the tightest relationships in economics is the connection between a country's per capita GDP and its per capita energy consumption.

Solar shares of global electricity and final energy
Percent



Source: EI Statistical Review of World Energy, BNEF, JPMAM, 2024

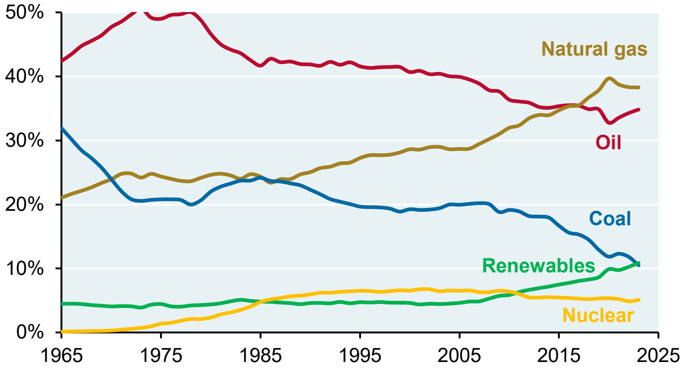
Per capita energy consumption and GDP by country
2023 per capita GDP, log scale



Source: OWID, JPMAM, 2024

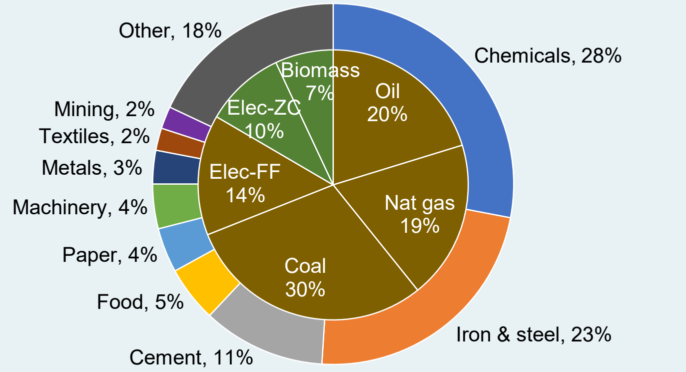
As shown below, the OECD reduction in coal combustion has been driven mostly by natural gas additions and to a lesser extent by wind and solar. Battles over baseload dispatchable power are made more critical by the moribund state of nuclear development in the OECD, which has essentially ground to a halt (see page 31).

OECD, shares of final energy consumption
Percent



Source: EI Statistical Review of World Energy, JPMAM, 2024

The fossil fuel intensity of global industrial production



Source: IEA, 2023. ZC: electricity derived from renewables and nuclear. FF: electricity derived from fossil fuels

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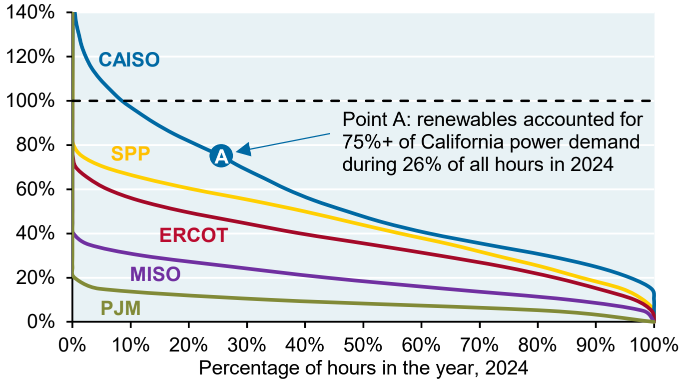
[4] The same is true for **national security**, which is also very energy-intensive and reliant on fossil fuels

Solar blindness. LinkedIn is a mecca for academics posting every time wind, solar and hydro comprise most of the power consumed on a given day, in a specific place. It's like reading a newspaper that only reports on baseball games in which catchers hit home runs. In other words, that happens *some* of the time, but not *most* of the time.

To see what I mean, see the next two charts. For the five large US ISO regions, we show the percentage of all hours in which renewable power (wind, solar, hydro, biomass and geothermal) plus energy storage[5] met a given share of the load in 2024. Take California (CAISO) as an example. There were times when renewables plus storage met a large share of power demand, but not as frequently as those LinkedIn posts suggest. Point A shows that renewables plus storage met 75%+ of the load in California, **but only in 26% of all hours in the year**. So, while renewables do meet substantial shares of the load in California from time to time, in most hours of the year, **California's power demand is still highly reliant on fossil fuels, nuclear power and electricity imports**. This is something that those LinkedIn posts usually fail to mention[6].

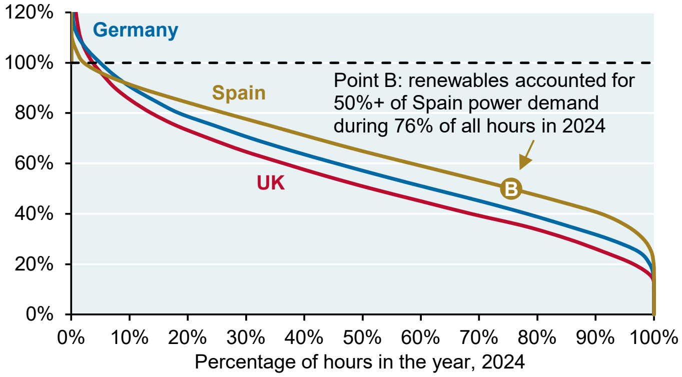
On the right: European curve levels are higher than California and the other US ISOs. Spain is in the lead with renewables providing at least half of the load in 76% of all hours in the year (point B).

California Dreaming: renewable share of demand by hour
Renewables+batteries as a share of hourly demand



Source: CAISO, SPP, ERCOT, GridStatus, MISO, PJM, JPMAM, January 2025

Renewable share of demand by hour
Renewables+batteries as a share of hourly demand



Source: Fraunhofer Institute, NESO, Emblemsvåg, JPMAM, January 2025

Heliocentrists believe that future growth in renewable capacity and energy storage will keep shifting the US curves up and to the right (as they currently exist in Europe), and that no new US natural gas capacity is needed. EIA analysts I spoke with cite a "staggering" amount of battery storage being added to the US grid: another 38 GW by 2027 on top of 22.5 GW already in place. This suggests that some natural gas peaker and baseload plants could eventually be displaced. But as a general principle, the charts above suggest that the US and Europe are a long way off from no longer needing both baseload and backup thermal capacity.

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[5] Hourly energy storage draws are available for CAISO, ERCOT, PJM, MISO and the UK

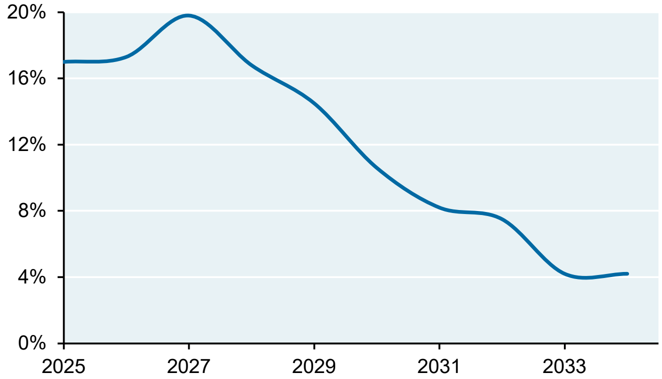
[6] **What about Stanford's Mark Jacobson and his claim on LinkedIn that in California, "wind-water-solar electricity exceeded 100% of demand for a record 98 out of 116 days" from March to June 2024?** I learned many years ago to read the fine print when it comes to Jacobson claims. Jacobson includes 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. Trust, but verify.

To be clear, Independent System Operators like MISO disagree with the Heliocentrists. MISO warns of serious challenges to grid reliability due to increased exposure to wind/solar intermittency, having averted a capacity shortfall in 2023 only due to postponement of planned thermal capacity retirements. MISO also warned of adverse consequences from prior EPA proposals to require coal plants, some existing gas plants and new gas plants to (a) retire by a certain date, (b) retrofit with carbon capture or (c) co-fire with green hydrogen; MISO has cited cost and technological readiness issues as major constraints[7]. I understand MISO's concerns: look how rapidly their summer reserve margin is set to shrink in the next decade due to a shift from baseload to intermittent power.

The Independent System Operator PJM recently expressed similar concerns[8]. PJM has increased its projected capacity needs by 40% in its Long Term Load Forecast, with PJM's President saying "We need capacity… a lot of capacity". PJM's report concluded that as demand growth and thermal resource retirements accelerate, the region may experience a shortfall in power supply as early as 2026/2027.

MISO's plummeting reserve margin

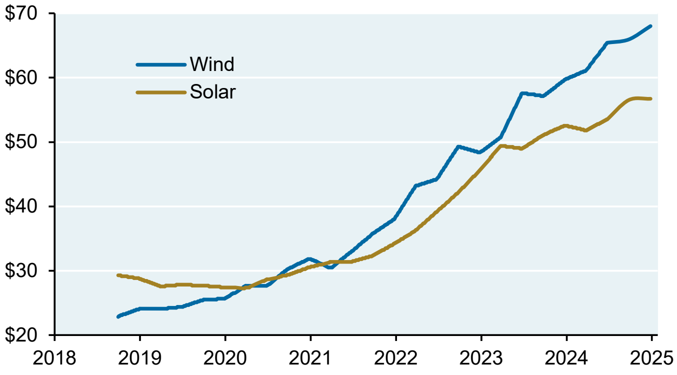
Anticipated reserve margin during peak summer demand



Source: "2024 Long-Term Reliability Assessment", NERC, December 2024

US wind and solar PPA prices

US$ per MWh



Source: LevelTen Energy, January 2025

How much will it cost to decarbonize US grids further? The chart on the right shows increasing US wind and solar power purchase agreement prices since 2020. These increases are the result of higher US tariffs on China solar panels[9], a tripling of insurance premiums in MISO, ERCOT and SPP regions due to weather events, supply/demand gaps due to permitting delays, higher interest rates and increased corporate demand for green power. But PPA costs are just part of the picture; a thorough cost assessment should include all capacity required to provide power on a 24/7 basis, and should also exclude taxpayer subsidies since these are not free[10].

Are data center power demand forecasts overstated? From Paul Joskow at MIT: "There are strong incentives to reduce both training and computation cost by developing more energy efficient chips and to develop and apply software innovations that require less training, fewer model solutions and much less movement of model solutions between nodes/chips on the network. The recent DeepSeek announcement from China should be a warning that such improvements are on the horizon".

Consider this: in 2007 when US electricity generation was ~4,500 TWh, the EIA projected 5,200 TWh of demand by 2023 due to growing computer and electronics usage. Actual 2023 demand: ~4,500 TWh, since efficiencies increased along with rising demand.

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[7] "*MISO Response to Reliability Imperative*", February 2024

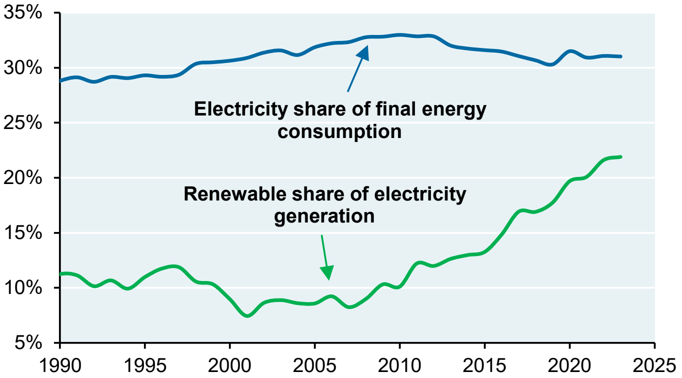
[8] "*2024 in Review: Maintaining an Adequate Generation Supply*", PJM Interconnection Report, January 2025

[9] In May 2024, US tariffs on Chinese PV cells doubled from 25% to 50%. Solar tariffs were part of a broader increase in tariffs on China which included an increase from 25% to 100% on EVs and from 7.5% to 25% on steel/aluminum

[10] An August 2023 article in Bloomberg cited Biden energy bill costs to taxpayers of $1 to $3 trillion. The cost of ITC/PTC subsidies alone are projected at $420 billion from 2025-2034 [Source: US Treasury Tax Exp. FY26]

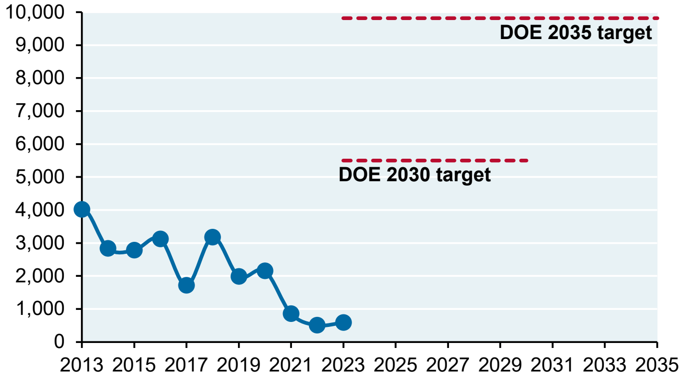
"Objects may be further away than they appear". Remember this key aspect of the energy transition: until an energy use is electrified, it's hard to decarbonize it using green grid electrons. And while grid decarbonization is continuing at a steady pace, the US has made little progress increasing the electricity share of final energy consumption for the reasons discussed in last year's "*Electravision*" piece. One major obstacle: **transmission line growth is stuck in a rut**, way below DoE targets for 2030 and 2035. Another obstacle: **shortages of transformer equipment**, whose delivery times have extended from 4-6 *weeks* in 2019 to 2-3 *years*. Around 70 million transformers step voltages up and down across the US grid and require special steel to reduce power losses. Half of all US transformers are near the end of their useful lives and will need replacing, along with replacements in areas affected by hurricanes, floods and wildfires. Transformer manufacturing investment by Schneider Electric and Hitachi North America should help, eventually.

US grid decarbonization outpaces electrification of energy use, Percent



Source: EI Statistical Review of World Energy, JPMAM, 2024

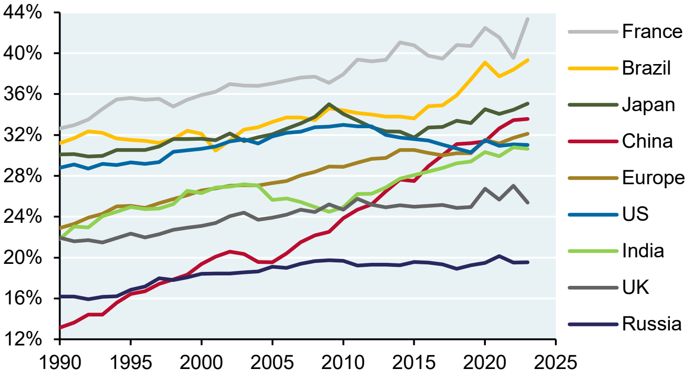
US transmission line growth
Miles added per year



Source: S&P Global, JPMAM, 2024. Note: Transmission lines > 100 kV.

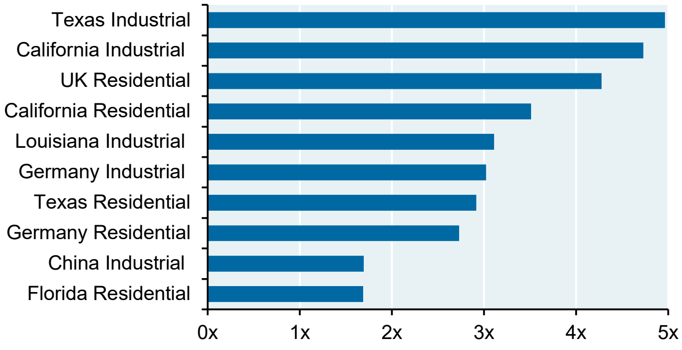
The US is not unique with respect to the slow pace of electrification, although a few countries are making faster progress[11]. Over the last decade China made the largest advance, bringing it in line with the OECD. Part of the challenge may simply be the long useful lives of existing industrial plants, furnaces, boilers and vehicles. In other words, electrification might accelerate as their useful lives are exhausted. But as shown on the right, **the high cost of electricity compared to natural gas**[12] (particularly in places without a carbon tax) is another impediment to electrification that is not easy to solve since this ratio reflects relative total costs of production and distribution.

Major countries: electricity share of final energy consumption, Percent



Source: EI Statistical Review of World Energy, JPMAM, 2024

Electrification is expensive compared to gas
Electricity cost per MJ divided by natural gas cost per MJ, 85% industrial and 90% residential furnace efficiency



Source: EIA, Eurostat, CEIC, JPMAM, 2024

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[11] What about small countries with much higher shares of renewables like Panama, Uganda, Norway and Iceland? They're generally irrelevant to discussions about larger countries. See "Ignore the PUNIs" from our 2024 energy paper for more details

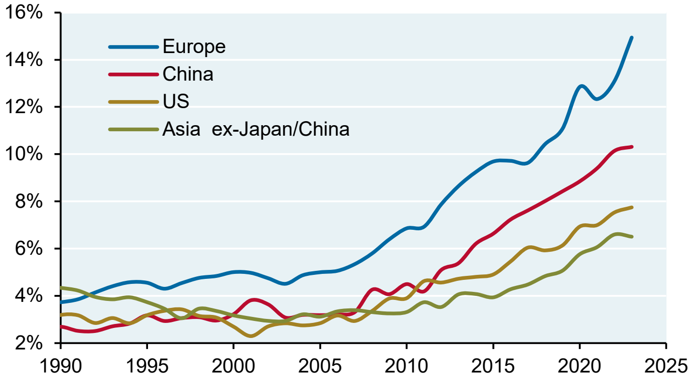
[12] Electricity is subject to a lot more "time of use" pricing than gas, in which case the ratios shown above could be overstated at night and possibly understated during daytime periods of peak electricity demand

To understand the big picture on the transition, the next chart is the one I focus on most. The renewable share of final energy consumption incorporates all the widgets associated with the energy transition. Whatever you've read about in the world of renewable energy, it's in there someplace[13].

How fast is the transition going? Europe leads with its renewable share growing at 0.6% per year since 2010, followed by China at 0.4% and the US at 0.3%. At that pace, Europe needs ~20 years to reach a 30% renewable share. Policymakers should be prepared for a long journey unless there's a step change in the production, transmission and consumption of energy. There's a big difference between high-tech transitions and S curves of accelerating adoption and this generation's energy transition which has been **much more linear**, at least so far.

Decarbonization is a linear industrial transition

Renewable share of final energy consumption



Source: EI Statistical Review of World Energy, JPMAM, 2024

"It's in there": drivers of the transition that are included in the renewable share of final energy consumption

- Wind and solar displacement of coal on the grid
- Li-ion battery storage displacement of gas peaker plants
- Rooftop solar power co-located with batteries
- Electric cars, trucks, buses, vans and motorcycles
- Electrolytic green hydrogen displacing brown hydrogen
- Decarbonized production of steel, ammonia and cement
- Electric heat pump displacement of residential, commercial and industrial furnaces/boilers
- Biofuel displacement of fossil fuels for transport
- Biomass and waste heat used for district heating
- Deep supercritical geothermal systems
- Synthetic fuels created from green hydrogen and CO_2 sourced from direct air carbon capture
- Pumped hydro formations
- Iron air batteries, vanadium redox batteries and other forms of long duration energy storage

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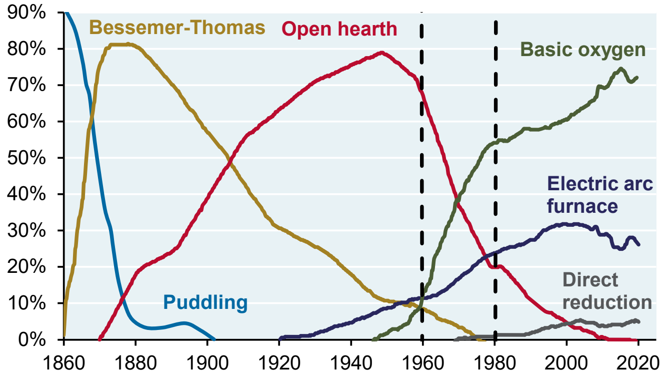
[13] I refer to this exhibit as the **scorpion bowl chart**, since scorpion bowls at the old Hong Kong Bar in Harvard Square also had everything in them (vodka, gin, rum, tequila, etc)

Are all industrial transitions as gradual as the current one? No, but it's important to understand why. Rapid industrial transitions can occur but usually require substantial improvements in terms of cost, time and energy. One example is shown on the left: the rapid 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 technologies cut steel production times to **less than a tenth** of open hearth furnaces, allowing for 80%-90% energy savings[14].

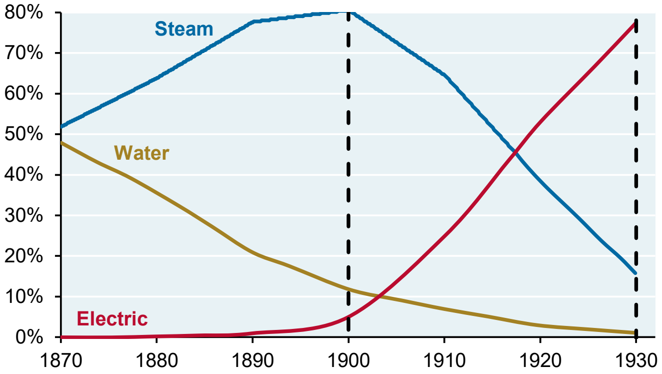
Another rapid transition: when electricity replaced steam engines and turbines in industrial plants in ~30 years in the early 1900's. Electricity offered enormous economic benefits: fewer power losses, more reliable and consistent power than belt-driven systems they replaced, elimination of linear production paths connected to overhead belts and the ability to organize production by the flow of parts rather than transmission of power[15].

Rapid energy-saving steel transition of the 1960s/1970s
Percent of global steel production



Source: Lauri Holappa, Aalto University, March 2019; Boston Metal, May 2022

Electricity replaces steam in the early 20th century
Percent of US industrial mechanical power use



Source: Warren Devine, Journal of Economic History, 1983

In contrast: most renewable technologies do not entail massive improvements in cost or energy efficiency. They can sharply reduce carbon footprints, but that does not create substantial economic incentives in a world without a large universal price on carbon. **The bottom line: fast historical industrial transitions financed themselves via returns accruing to innovators and early adopters, while the gradual and linear renewable transition shown on the prior page has required $9 trillion of global spending since 2010 to move along**.

While learning curves can be steep (wind, solar, lithium ion batteries), they usually reflect declining costs per unit of production rather than step-change improvements in technology efficiency. This is important when thinking about potential for efficiency improvements in electrolyzers, fuel cells, solar and wind capacity factors, direct air carbon capture, power transmission and other drivers of the transition.

That's the end of the Executive Summary. The rest of the paper contains the individual sections, starting with some charts on a changing planet and our annual collection of essential energy charts.

Michael Cembalest
JP Morgan Asset Management

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[14] "*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

[15] "*Routes of Power*", Christopher Jones, 2014; "*From Shafts to Wires: Historical Perspective on Electrification*", Warren Devine, Journal of Economic History, 1983; Brian Potter, Institute for Progress

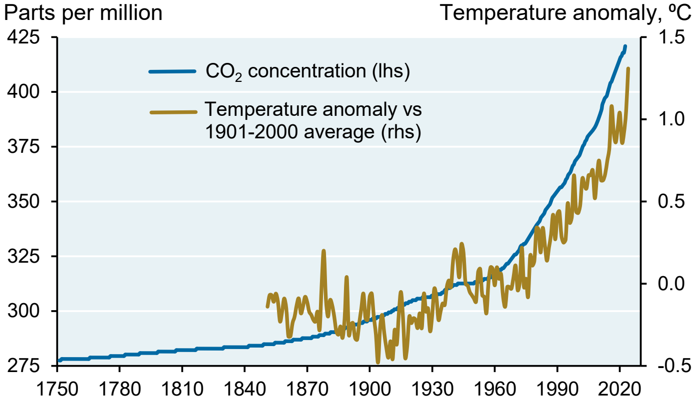
Comments from Vaclav Smil and charts on a changing planet

For many years, Vaclav served as our science advisor on this paper. His insights were invaluable and the opportunity to learn from him is one of the highlights of my 37 years at JP Morgan. Vaclav turned 81 last year and we still correspond on a variety of topics. Some passages from one of Vaclav's latest pieces (bolding is mine)[16]:

> "In mass terms, we will never run out of fossil fuels: enormous quantities of coal and hydrocarbons will remain in the ground after we end their use because it would be too expensive to extract them. Although the world of the early 2020s is in no imminent danger of running out of fossil fuels, **in the long run they would have to be replaced even in the absence of any connections to global warming**. Their conversions made the modern civilization possible, but their production, processing and transportation are often environmentally disruptive, with impacts ranging from land dereliction to water pollution; their combustion generates not only CO_2 but also such pollutants as carbon monoxide, nitrogen and sulfur oxides and particulate matter; their highly uneven distribution contributes to worldwide economic inequalities, and the quest for secure fossil fuel supplies has led to many detrimental policies and contributed to recurrent conflicts"
>
> "Clearing of forests, large-scale cropping and animal husbandry have been with us throughout recorded history but **the rising combustion of fossil fuels has been by far the greatest contributor of CO_2 during the past two centuries**, followed by methane (from rice fields, landfills, cattle, and natural gas production), and nitrous oxide (mostly from nitrogenous fertilizers). Realization that these trace gases could affect climate is more than 150 years old"
>
> "There has been an exponential rise of attention paid to global climate change. **Much has been learned, much remains uncertain but basic facts are indisputable**. Ice core analyses show CO_2 levels close to 270 parts per million (ppm) by volume during the preindustrial era; in 1958 when Mauna Loa monitoring began they reached 313 ppm; by the year 2000 they were 370 ppm and by the end of 2023 they reached 420 ppm, more than 50% above the late 18th-century level…This rise, together with contributions by methane and nitrous oxide, has translated to about 1°C of global warming compared to the 19th-century mean[17]. All continents have been affected, recent decadal warming gains have been steadily rising and the eight years between 2015 and 2022 were the warmest years on record"

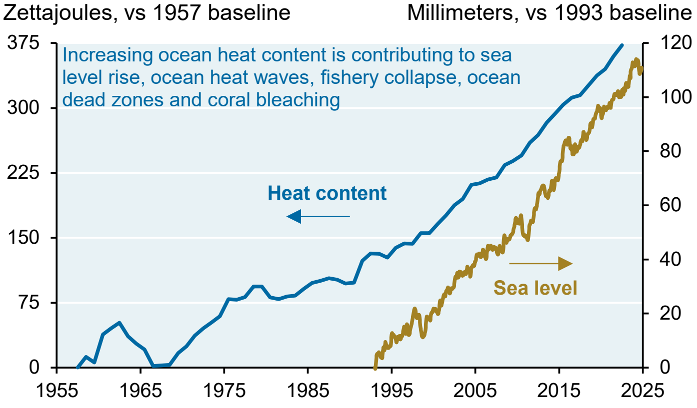
In that regard, here are several charts on the way the planet is changing. I wonder how many of them we will be able to update in the future given the 650 people fired so far at NOAA by the DOGE team.

Atmospheric CO_2 and global temperatures



Source: NOAA, JPMAM, 2024

Ocean heat content and sea level



Source: NASA/NOAA, JPMAM, 2024. 1 ZJ = 10^{21} joules.

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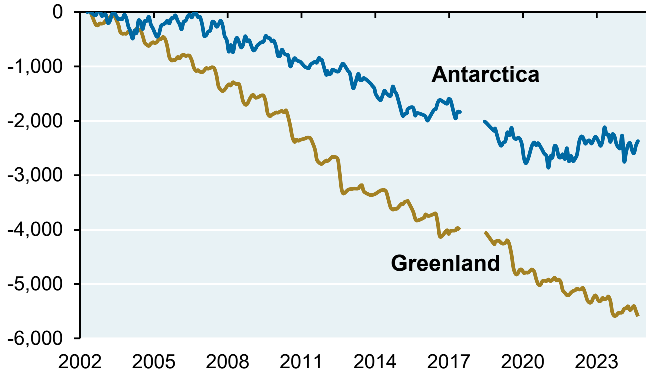
[16] "*Halfway between Kyoto and 2050*", Vaclav Smil, Fraser Institute, 2024

[17] The most recent annual average is reportedly now closer to 1.5° C of warming

The changing planet (continued):

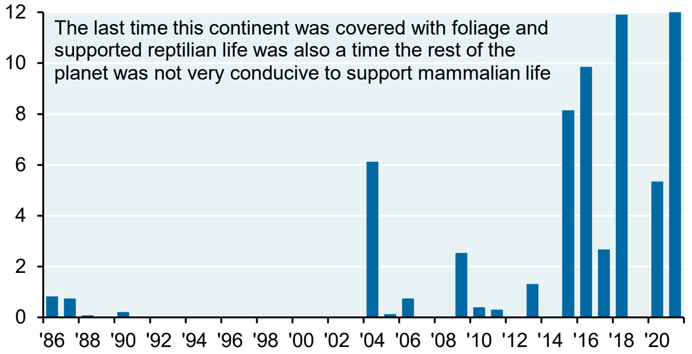
Antarctica and Greenland ice sheet mass

Mass variation, gigatonnes



Source: NASA, JPMAM, August 2024

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



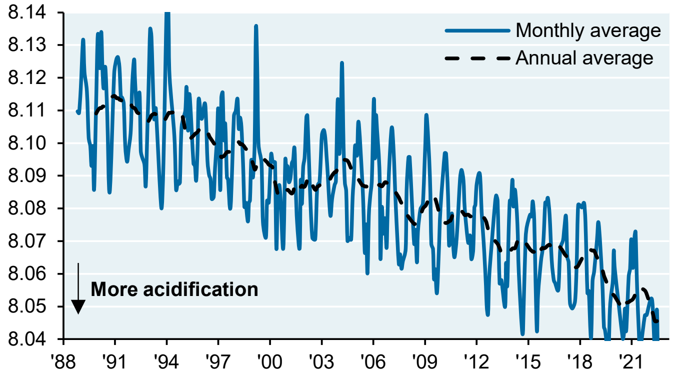
The last time this continent was covered with foliage and supported reptilian life was also a time the rest of the planet was not very conducive to support mammalian life

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

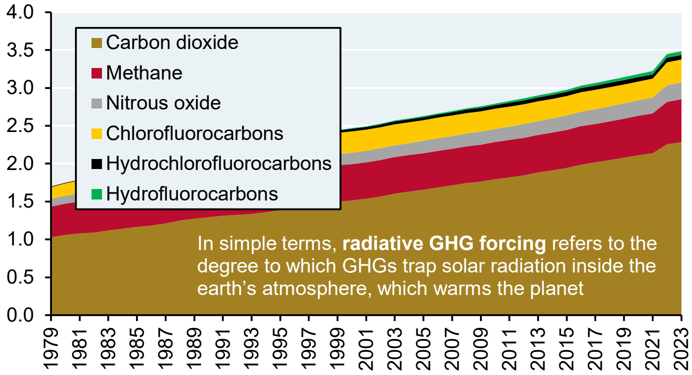
Mean seawater pH level



Source: University of Hawaii SOEST, 2023

Greenhouse effect: radiative forcing by GHG

Watts per square meter

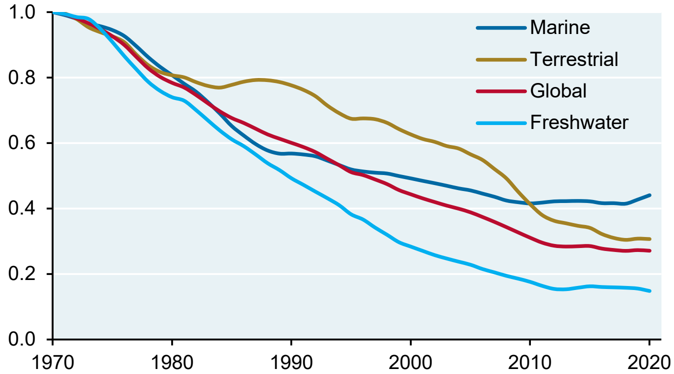


In simple terms, **radiative GHG forcing** refers to the degree to which GHGs trap solar radiation inside the earth's atmosphere, which warms the planet

Source: NOAA Global Monitoring Laboratory, 2024

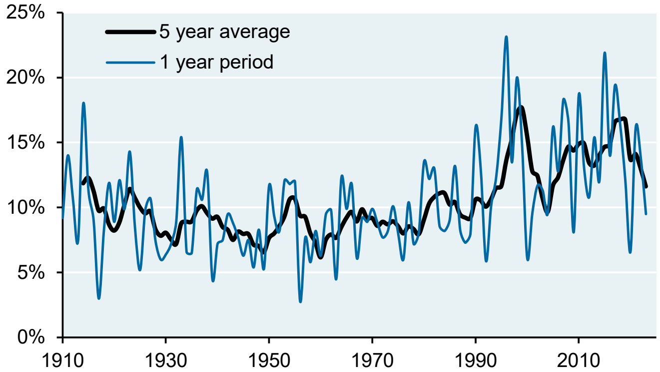
Vertebrate biological diversity index

Index (1970 = 1)



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

Extreme one day precipitation events in the continental US, Percent of land area



Source: EPA/NOAA, 2024

Essential charts on the energy transition

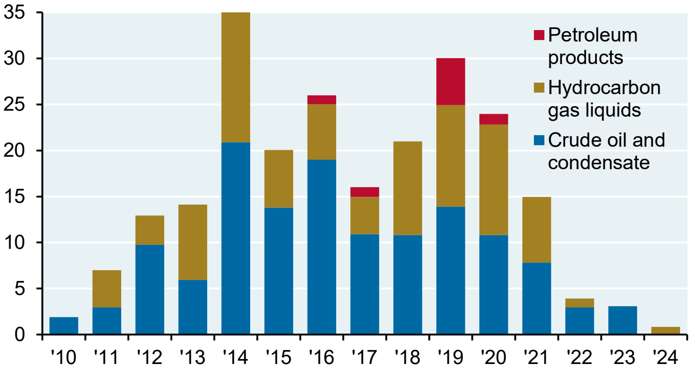
We added a lot of new ones this year.

New US liquids and gas pipeline projects

Completion of new liquids and gas pipelines in the US has ground to a halt. If US energy demand keeps growing, either these trends would need to reverse, or renewable capacity/transmission projects need to accelerate. Low renewable interconnection completion rates (p.15), high costs for offshore wind and the inability to build gas pipelines from Pennsylvania amplify power cost and reliability challenges for regions like New England[18].

Annual US liquids pipeline project completions

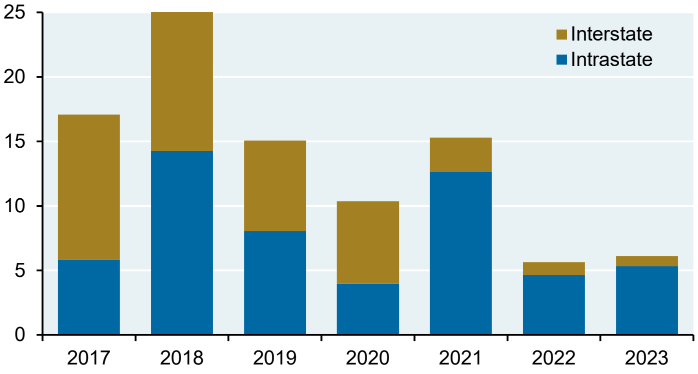
Number of projects



Source: EIA, October 2024

Annual US natural gas pipeline capacity additions

Billion cubic feet per day



Source: EIA, March 2024

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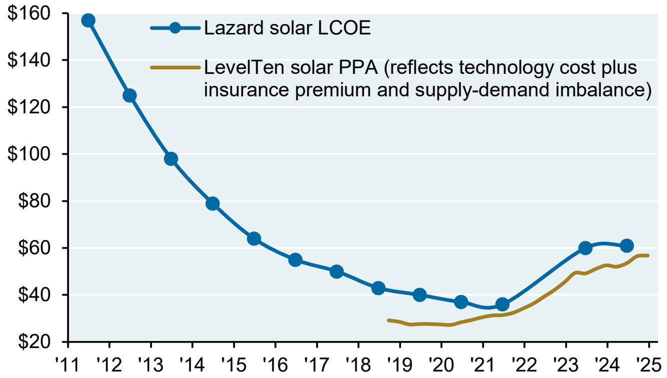
[18] "*Energy Report Puts New England at Elevated Risk of Electricity Shortages*", NH Journal, December 2024

Solar costs, supply chains and capacity factors; renewable share of electricity generation

Solar costs/PPAs increased from 2020-2024 after a sharp decline from 2010-2020; polysilicon prices collapsed after the 2022 surge. Most renewable supply chains go through China. Onshore/offshore wind and solar power are mature technologies as indicated by stable capacity factors. Onshore wind improvements reflect larger turbine blades and higher towers, a process which is approaching its physical limits. Solar generation is converging with wind as rapidly growing solar capacity more than offsets its lower capacity factors. Solar is also the fastest growing component of global renewable electricity generation.

Solar levelized costs vs PPA prices

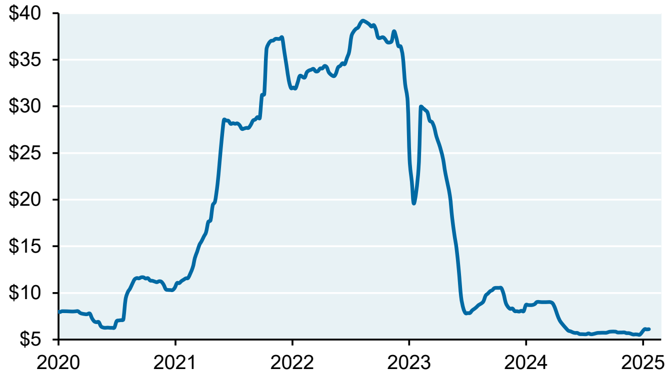
US$ per MWh



Source: Lazard, LevelTen Energy, January 2025

Solar grade polysilicon price

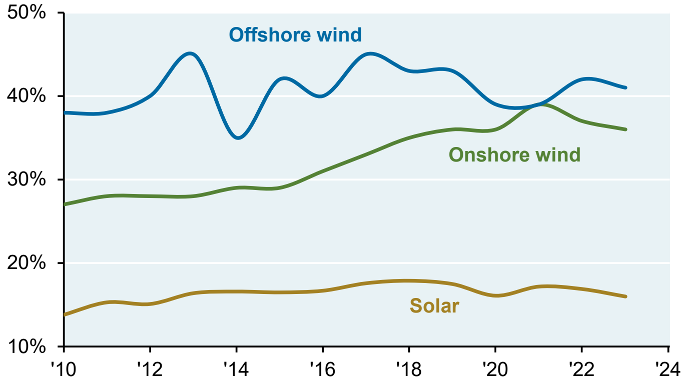
US$ per kilogram



Source: Bloomberg, JPMAM, January 22, 2025

Global capacity factors

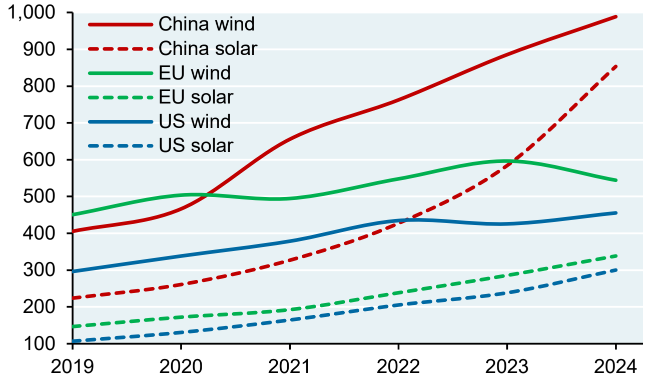
Capacity weighted percentage



Source: International Renewable Energy Agency, 2024

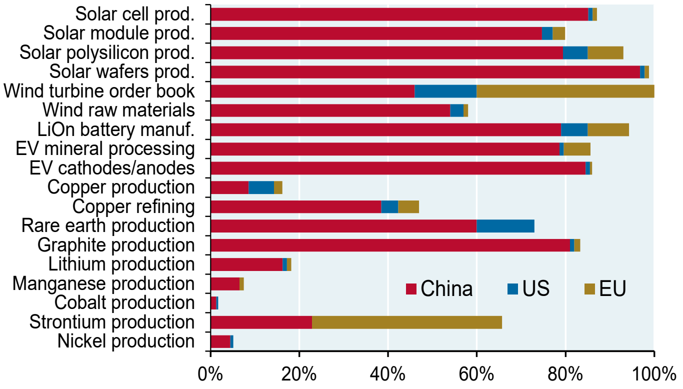
Solar generation converging with wind

TWh



Source: Ember, JPMAM, 2024

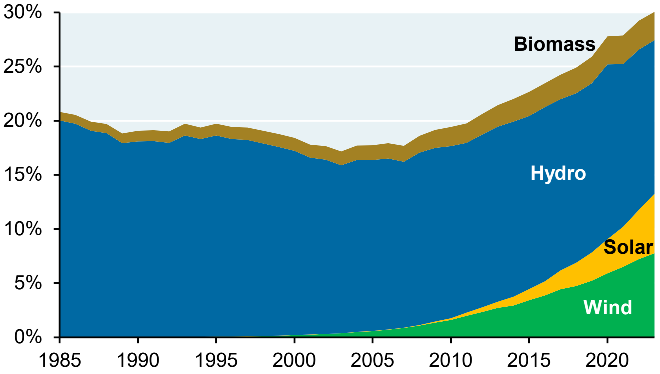
Many renewable supply chains go through China, for now



Source: Benchmark Mineral Intelligence, BNEF, EC, IEA, S&P, USGS, JPMAM. 2022.

Renewable share of global electricity generation

Percent



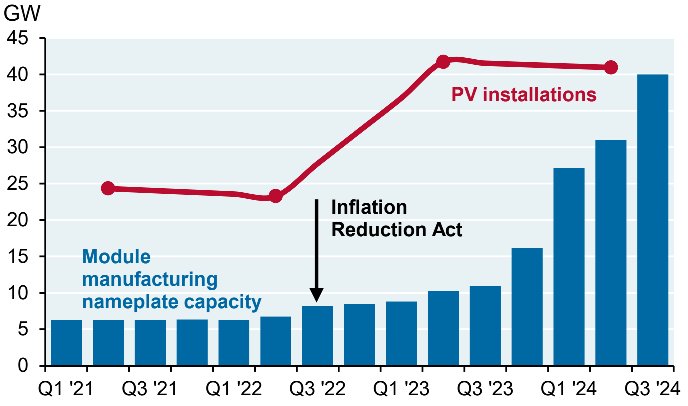
Source: EI Statistical Review of World Energy, JPMAM, 2024

The gradual and partial path to US solar self-sufficiency

You may have seen reports that US solar manufacturing capacity has reached the same level as US solar capacity installations, implying that the US has attained solar self-sufficiency. Not quite. The US installed 40-45 GW of solar in 2024, a figure projected to remain roughly constant in the next few years according to SEIA. Separately, Wood Mackenzie reports US module manufacturing capacity at 40 GW as of Q3 2024. However, there's a very important caveat here: this 40 GW of manufacturing capacity represents **nameplate** capacity, which refers to the amount of production a facility *could* produce when/if all its equipment is installed. In contrast, **ramped/operational** capacity refers to potential production based on equipment that **IS** installed. As shown below on the left, there were only ~9 GW of ramped and operational module capacity in the US as of June 2023 and no operational cell manufacturing. There's plenty under construction, but the US is still on the path to solar module self-sufficiency. That's why solar cell and module imports were still ~60 GW in 2023 and running at an even higher pace in 2024.

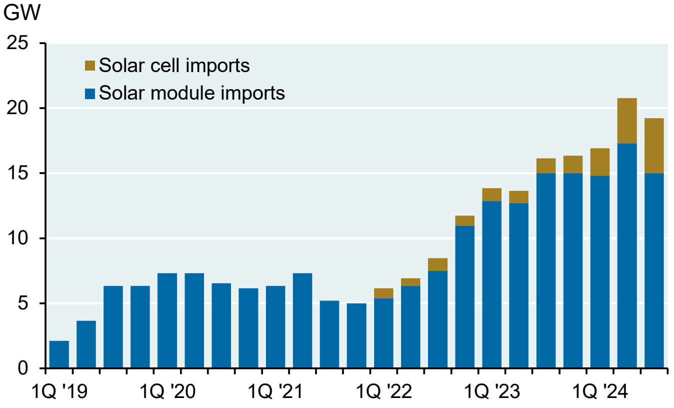
Another important point: even if US ramped solar **module** manufacturing capacity reaches the level of solar installations, the US would still have to import solar **cells** which make up the solar panels in these modules, unless US cell production increased sharply as well.

US solar module manufacturing capacity & PV installations



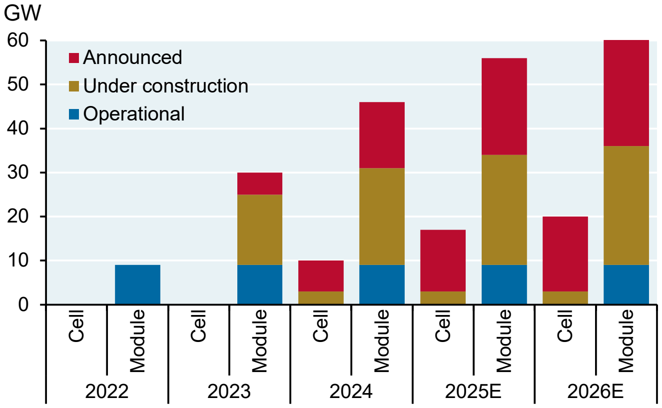
Source: SEIA, Wood Mackenzie, JPMAM, 2024

Quarterly US solar module and cell imports



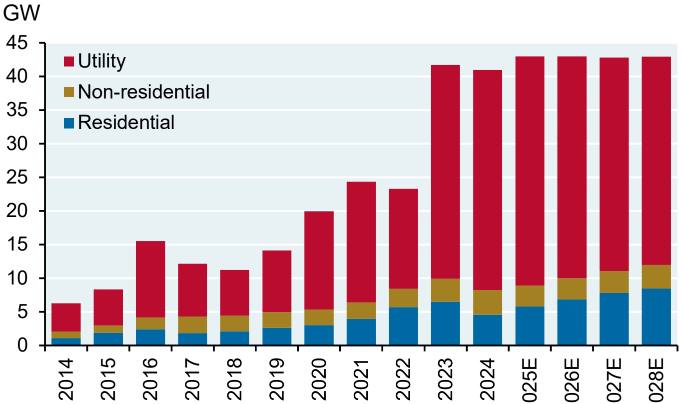
Source: "US solar imports surge", Carbon Credits, November 2024

US solar cell and module manufacturing capacity



Source: Wood Mackenzie, June 2023

Annual US solar PV installations



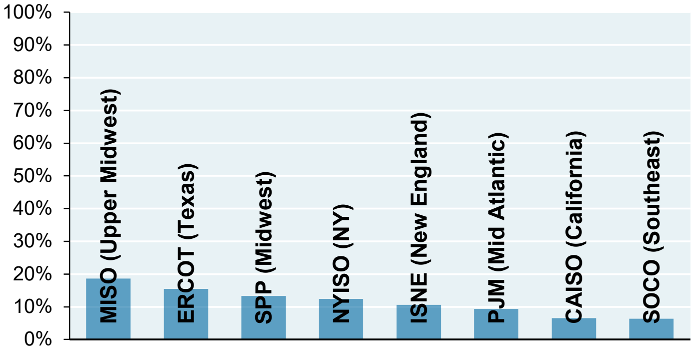
Source: SEIA, Q4 2024

US grids: capacity credits/transmission/reserve margins/capacity queues/gas vs electricity prices

Capacity credit estimates indicate that only 10%-20% of natural gas capacity can be displaced when adding 1 MW of wind or solar. Transformer and other transmission equipment have seen the second highest inflation of all producer goods in the US since 2018. The decline in transmission line growth has been an issue across all ISO regions. Reserve margins are declining due to decommissioning of baseload power and more renewables. I don't pay much attention to the large amount of wind and solar in the queue since most queued projects never get built due to high interconnection costs or other financing delays (5th chart). Residential electricity prices per MJ are 2x-4x higher than natural gas prices, which impedes faster heat pump adoption.

How much natural gas capacity can be reduced per MW of new wind and solar power?

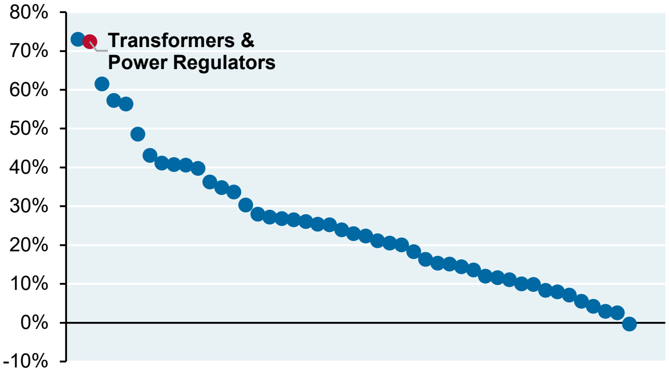
%, computed for 2023, assuming new wind and solar = 10% of demand



Source: EIA data, JPMAM computations, 2023

Producer price inflation: core goods

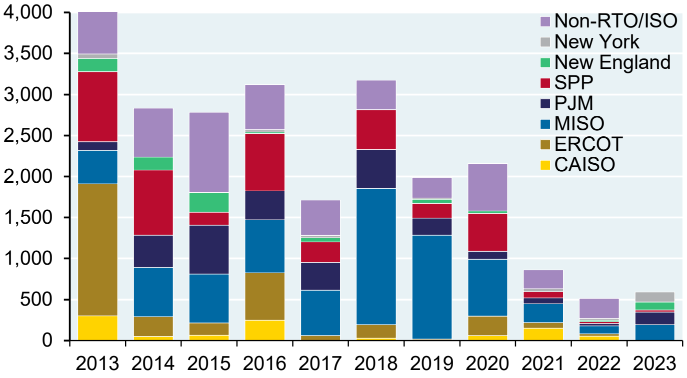
% increase vs 2018 for each of the 47 core goods categories



Source: Bloomberg, JPMAM, January 31, 2025

US transmission line growth by ISO

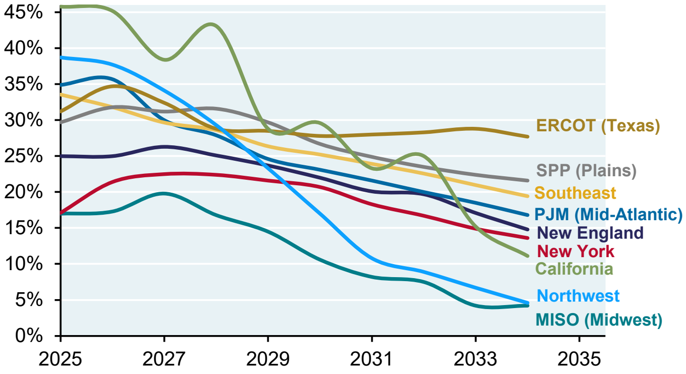
Miles added per year, total grid size = ~200,000 GW-miles



Source: S&P Global, JPMAM, 2024. Note: Transmission lines > 100 kV.

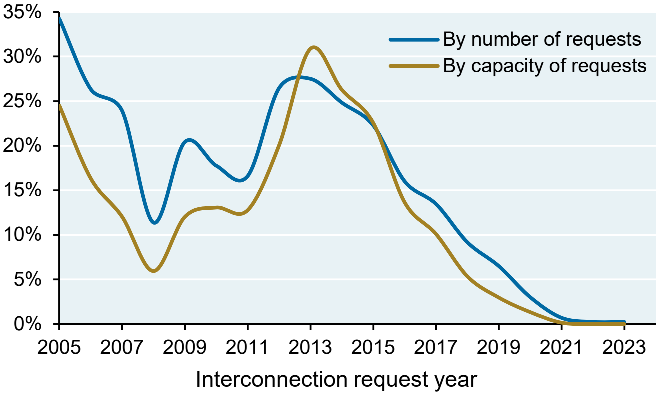
Generation capacity buffer during peak summer demand

Anticipated reserve margin



Source: "2024 Long-Term Reliability Assessment", NERC, December 2024

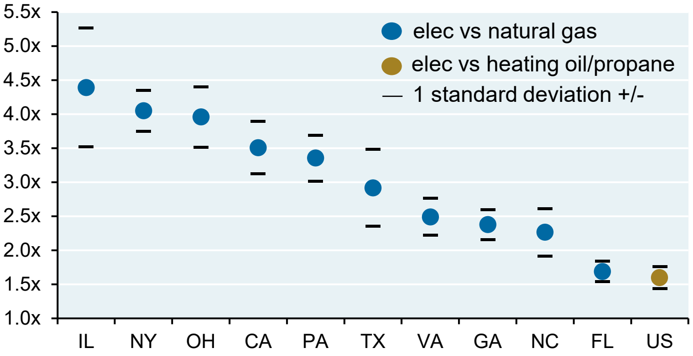
US grid queue: capacity completion rates



Source: LBNL, "Queued Up: 2024 Edition"

Residential winter heating options: electricity vs fossil fuels

Ratio of electricity to fossil fuel price per MJ



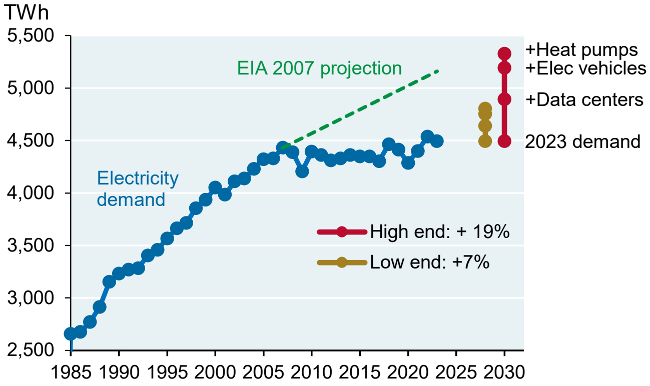
Source: EIA, JPMAM, 2024. Top 10 states by electricity consumption; assuming 90% gas furnace efficiency. Residential pricing, 2019-2024 average

Data centers and negative power prices/energy storage

The first chart shows projections for US electricity demand due to more data centers, EVs and electrification of heat; and also shows how far off the EIA's 2007 demand forecast was. Hyperscalers will probably have to walk back green power commitments and run data centers primarily on natural gas, as they have been. The pie chart shows power consumption of US data centers based on their respective locations, their MW of maximum power consumption and the grid mix in that state. Wood Mackenzie projects ~75 GW of new gas capacity in the US by 2030, and a shrinking number of gas plant retirements.

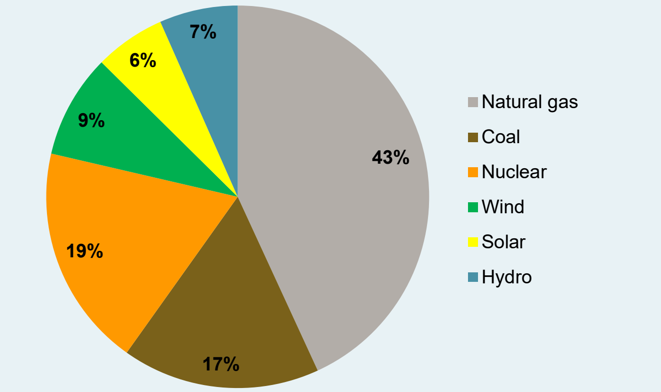
New data centers may eventually be built in places like the Texas Panhandle and Southern California where there are many hours in the year with negative electricity prices. So far, data centers are highly concentrated near DC, which might explain who its primary customers are (military applications with less tolerance for time lags). Global energy storage is booming as the cost of energy storage continues to fall.

US electricity demand forecast



Source: EI, LBNL, Rystad, Evolved Energy, EIA, NREL, JPMAM, 2025

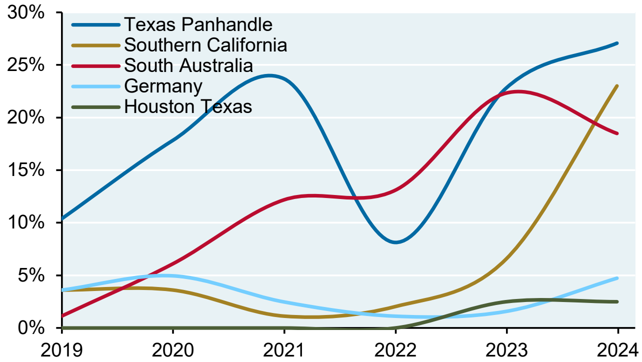
US data center power consumption by energy source



Source: EIA, Aterio, JPMAM, 2024

Negative electricity prices

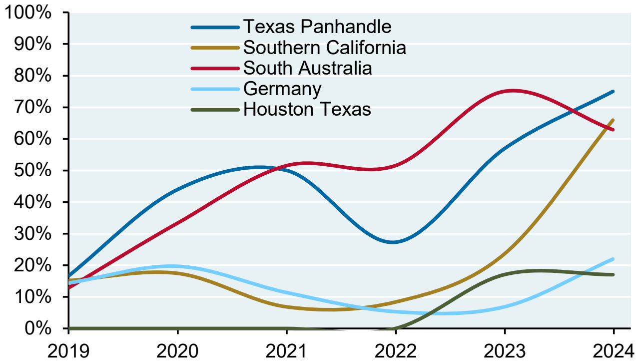
Percent of negatively priced hours



Source: "*Electricity Mid-Year Update*" IEA, July 2024

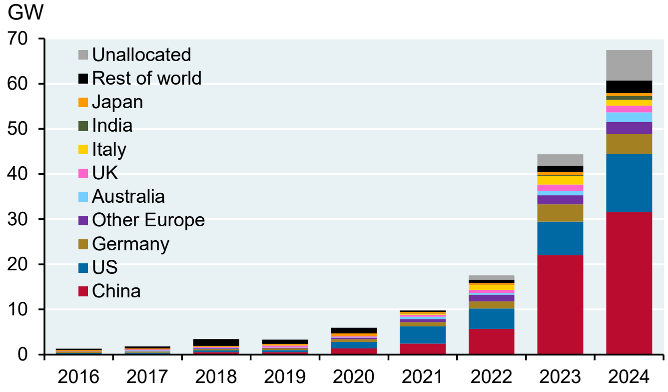
Negative electricity prices

Percent of days with at least 1 negatively priced hour



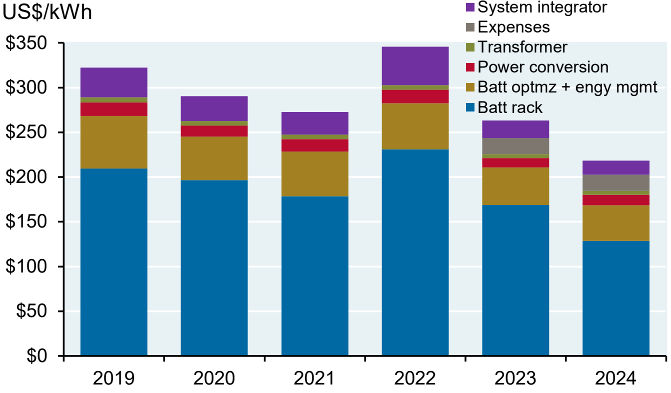
Source: "*Electricity Mid-Year Update*" IEA, July 2024

Global gross energy storage additions by market



Source: BloombergNEF, JPMAM, April 2024

Price of a 4hr utility-scale energy storage system

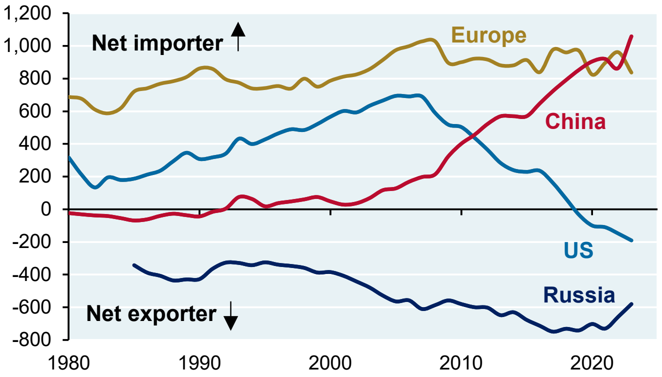


Source: BloombergNEF, JPMAM, April 2024

Energy independence/energy-intensive manufacturing/gas reserves, China and Taiwan

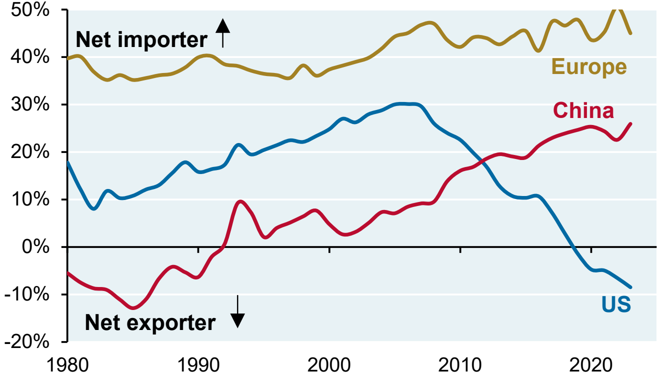
The US has achieved US energy independence for the first time in 40 years while Europe and China compete for global energy resources. China's imports are similar to Europe in energy terms but half as much as a share of domestic energy consumption. Energy intensive manufacturing has shifted to the developing world since the mid 1990's. China is negotiating with Russia and Turkmenistan regarding future gas pipeline projects. China has the benefit of time: China gas imports are projected to reach 250 bcm by 2030 vs 170 bcm in 2023, almost all of which can be met by already contracted supplies. What was Taiwan thinking by shutting down nuclear power which has fallen from 50% to 5% of generation? Taiwan is now one of the most energy dependent countries in the world, resulting in rising economic costs if China were to impose a blockade.

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



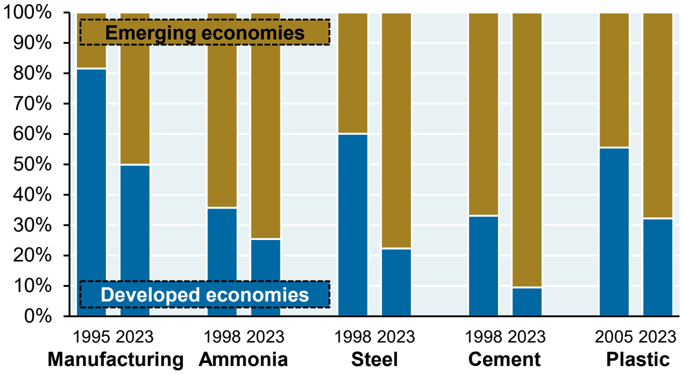
Source: EI Statistical Review of World Energy, JPMAM, 2024

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



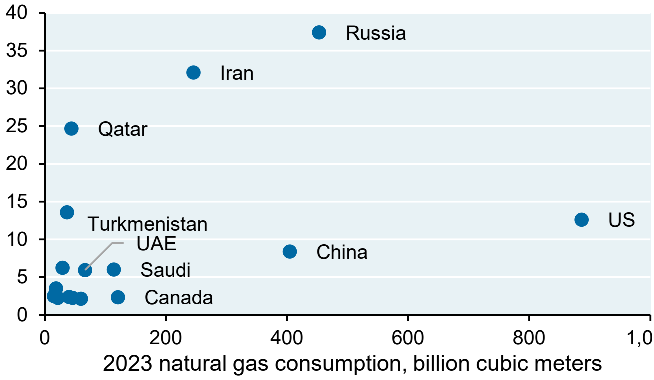
Source: EI Statistical Review of World Energy, JPMAM, 2024

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



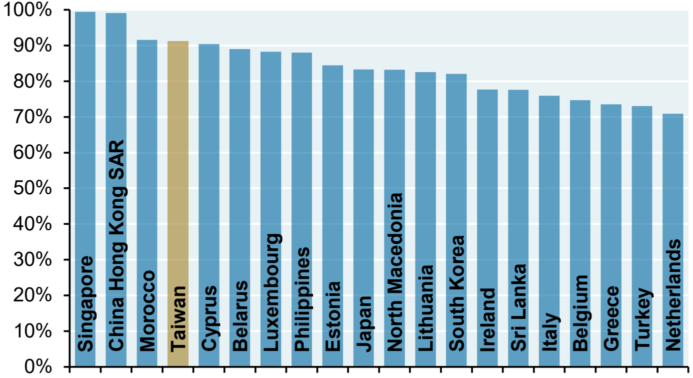
Source: UN DESA, Worldsteel, Plastics*Europe,* USGS, JPMAM, 2025

Natural gas proven reserves vs consumption
Proven reserves, trillion cubic meters



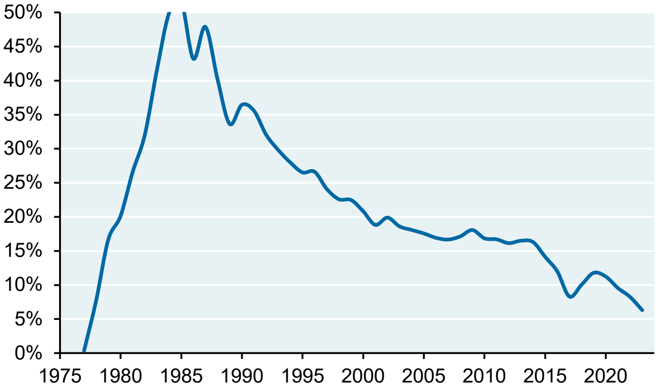
Source: EI Statistical Review of World Energy, JPMAM, 2024

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



Source: EI Statistical Review of World Energy, JPMAM, 2024

Taiwan nuclear share of electricity generation



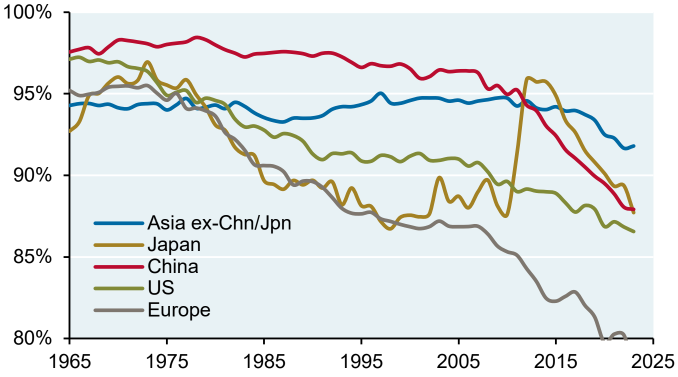
Source: EI Statistical Review of World Energy, Taiwan Power, JPMAM, 2024

Fossil fuels/US fracking dependence/LNG/coal

Fossil fuel shares of final energy are falling faster in China, Japan and Europe than in the US. Growth in fossil fuel consumption is slowing but no clear sign of a peak on a global basis. Hydraulically fractured oil and gas account for 60%+ of US primary energy consumption. Global LNG export capacity is set to expand by one third by 2030. Coal consumption is roughly flat in final energy terms as rising EM consumption offsets falling OECD consumption.

Fossil fuels as a share of final energy consumption

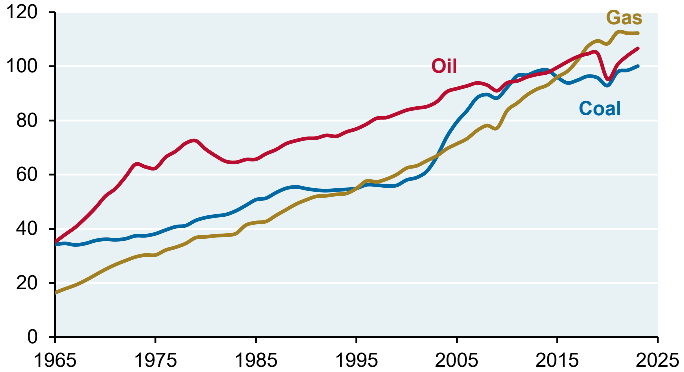
Percent



Source: EI Statistical Review of World Energy, JPMAM, 2024

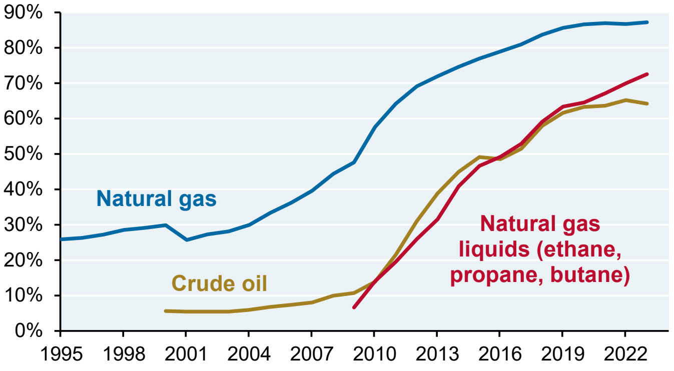
Global fossil fuel consumption

Exajoules of final energy



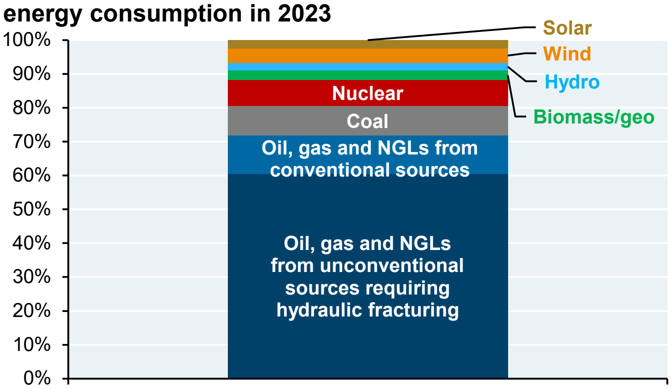
Source: EI Statistical Review of World Energy, JPMAM, 2024

Percentage of US oil and gas production derived from hydraulic fracturing through year-end 2023



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

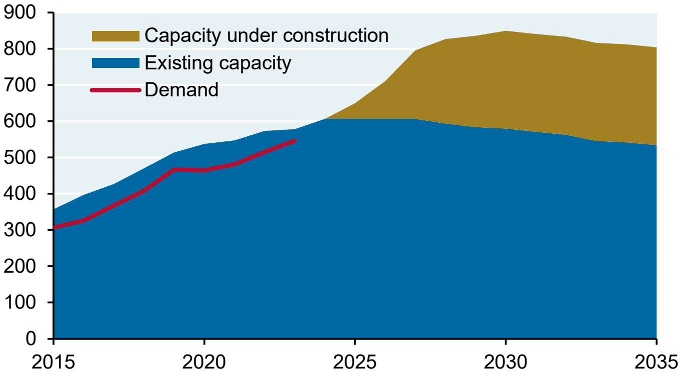
Hydraulic fracturing accounted for 61% of all US primary energy consumption in 2023



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

Global LNG capacity

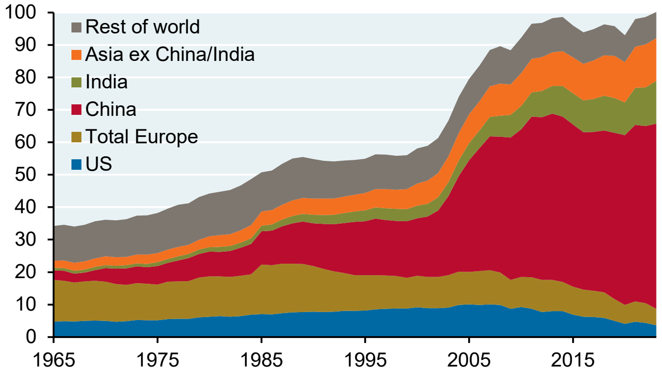
Bcm of demand and export capacity



Source: IEA, JPMAM, 2024

Coal final energy consumption by country

Exajoules



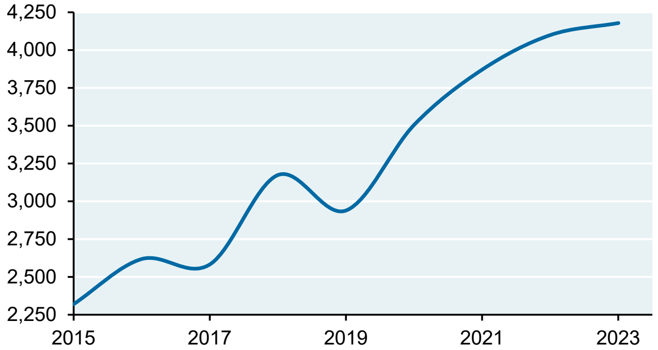
Source: EI Statistical Review of World Energy, JPMAM, 2024

Carbon capture and storage

The CCS citation-to-usage ratio is still the highest ratio in the history of science. Planned CCS capacity is 2.0%-2.5% of current emissions in the US and Europe but CCS project completion rates have been low, so projections are speculative. 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. IEEFA concluded that CO_2 capture rates from most CCS projects fall well below original targets and well below standard assumptions of 90%. Meta/Entergy plan a $10 bn Louisiana data center powered by gas + CCS; but even Mark Zuckerberg cannot alter the laws of physics. Rather than bending the CCS cost curve, Meta may establish a new high price point for "green" power (at least for the portion that ends up green). In other words, cash-rich tech companies may be price inelastic for green power but other companies won't be.

The highest ratio in the history of science

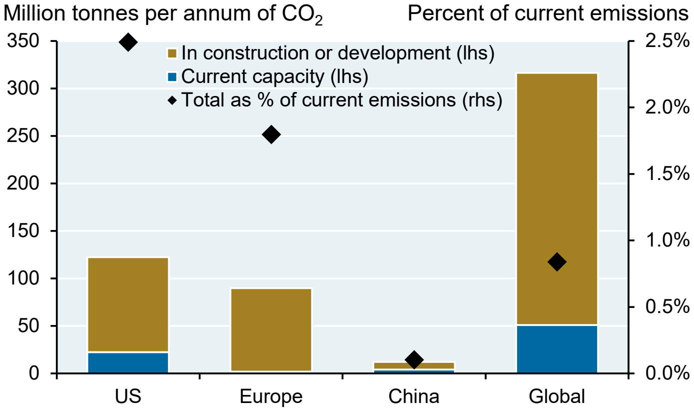
Carbon capture research citations per year divided by million tons of annual global operational CCS capacity



Source: Dimensions.AI, Global CCS Institute, 2023

Current vs planned carbon capture capacity by 2030

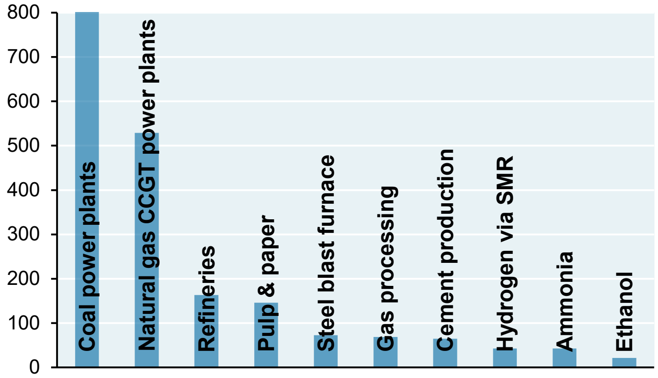
Million tonnes per annum of CO_2



Source: Global CCS Institute, OWID, JPMAM, 2024

Annual US GHG emissions from industrial sector

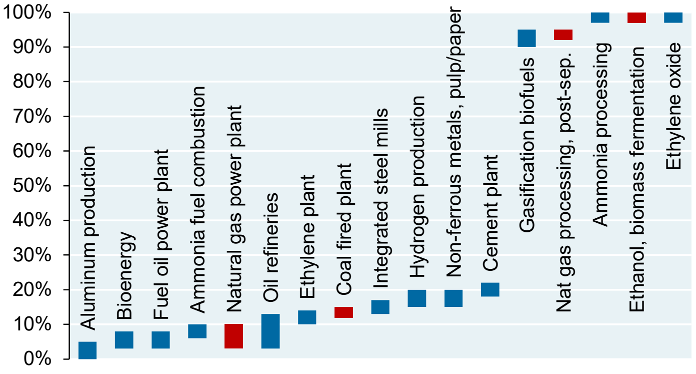
Million tonnes of CO_2 equivalent



Source: Energy Futures Initiative. February 2023.

CO_2 concentration in flue gas streams

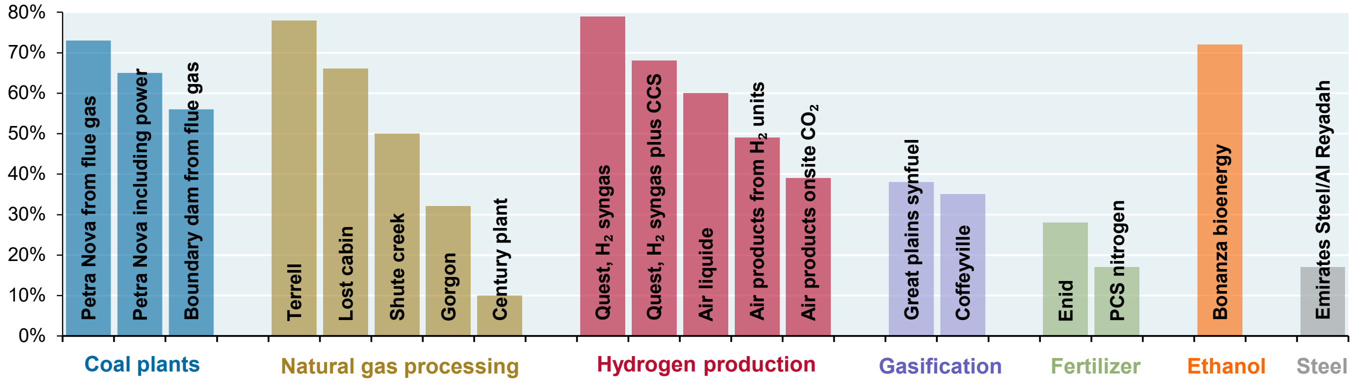
Percent by volume



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

Real-world CO_2 capture

Percent of total emissions captured

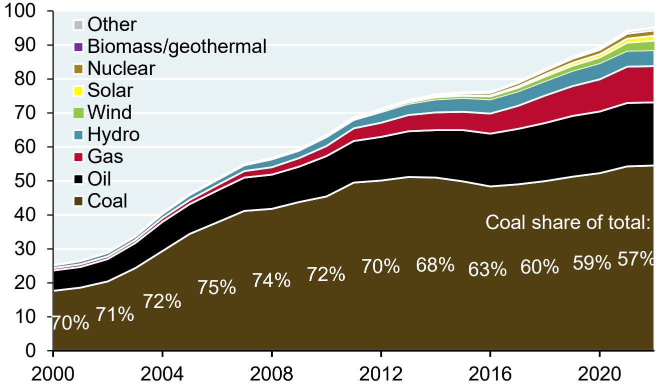


Source: Institute for Energy Economics and Financial Analysis, Schlissel and Juhn, December 2023

China

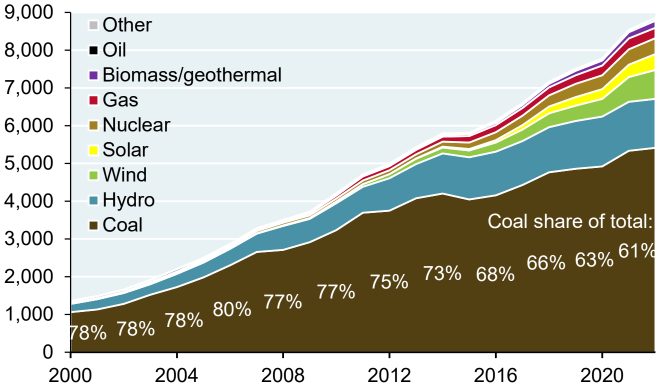
China is a renewable energy juggernaut: it now accounts for 50%-60% of all global new renewable capacity additions. But this does not mean the end of China coal consumption: while its coal *share* of final energy consumption and electricity is falling, its absolute coal consumption *levels* are still rising. In other words, China's renewables add to its energy mix rather than displace legacy fossil fuels. China hydropower generation has now reached OECD levels, while OECD levels have been roughly unchanged for 30 years. [Note: in 2022, Oak Ridge Labs analyzed the hydropower potential of US national conduits: irrigation canals and ditches, pipes in municipal water and wastewater systems and cooling water discharge pipes at thermoelectric power station stations. The potential increase: ~9,000 TWh per year, an increase of just 4% in existing US hydro generation].

China final energy consumption by type
Exajoules



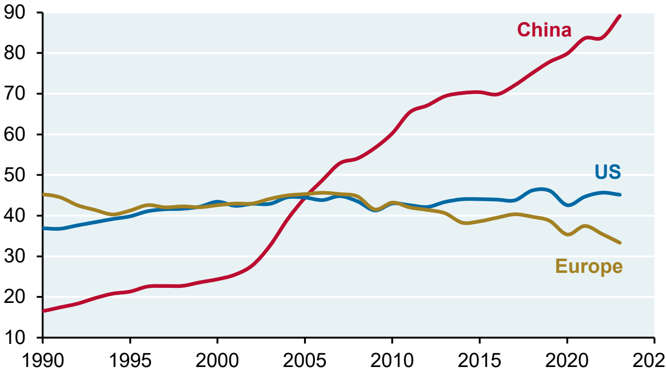
Source: EI Statistical Review of World Energy, JPMAM, 2024

China electricity generation by source
Terawatt-hours



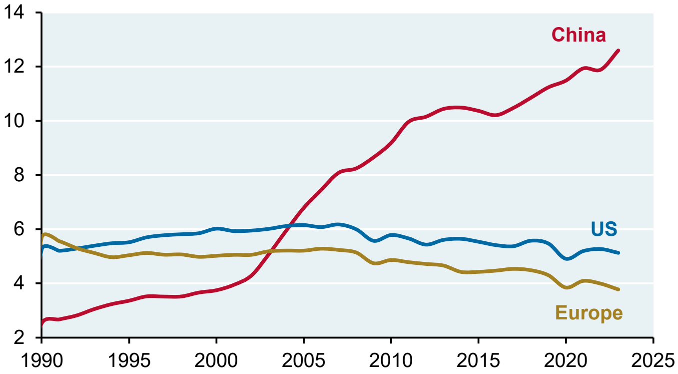
Source: EI Statistical Review of World Energy, JPMAM, 2024

Fossil fuel final energy consumption
Exajoules



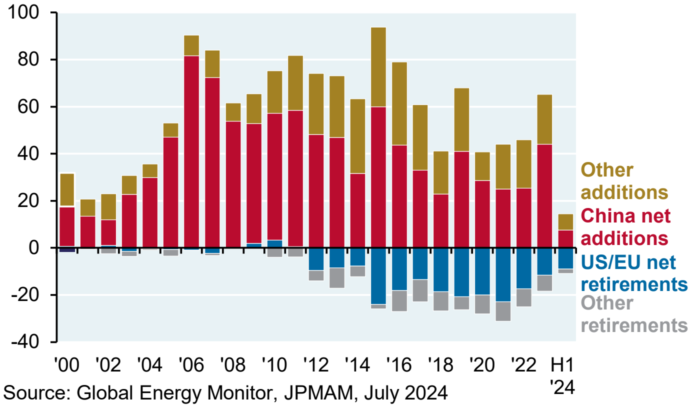
Source: EI Statistical Review of World Energy, JPMAM, 2024

Greenhouse gas emissions from energy, Billion tons, including the GHG impact of process emissions, flaring and venting



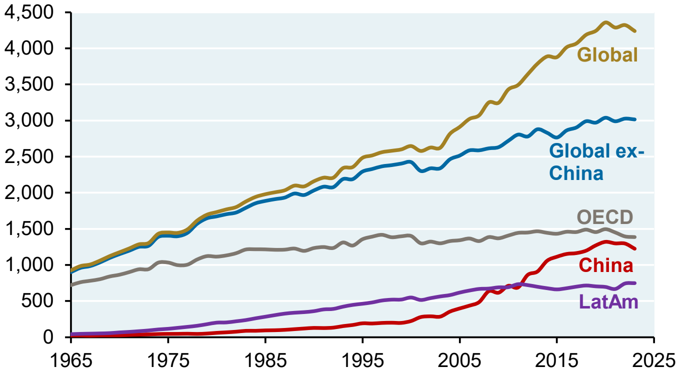
Source: EI Statistical Review of World Energy, JPMAM, 2024

The impact of China on global coal capacity
Coal capacity: additions and retirements, gigawatts



Source: Global Energy Monitor, JPMAM, July 2024

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



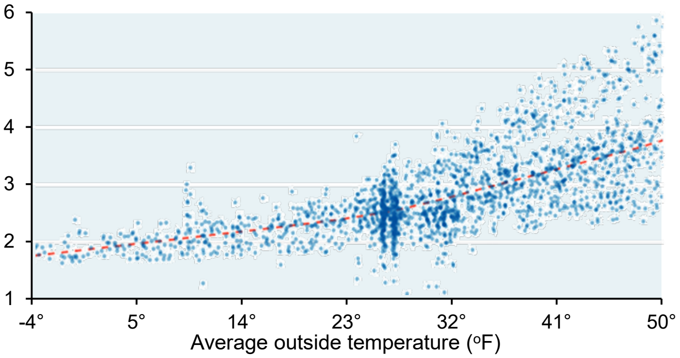
Source: EI Statistical Review of World Energy, JPMAM, 2024

Heat pumps/industrial energy use and electrification

Coefficients of performance measure the production of heat per unit of electricity. Even in cold temperatures, heat pumps can deliver COPs > 2x. Also: ~30% of industrial emissions require temperatures below 130°C, which is within performance ranges of existing heat pump technology. If so, why did heat pump sales decline globally in 2023 vs 2022? The decline was particularly steep in Europe, falling by ~50% in the first six months of 2024 vs 2023. Probable reasons: fewer subsidies and lower gas prices. Note how electricity costs 2x-4x more per MJ than natural gas per unit of energy for industrial consumers across countries. That could also partially explain why the electricity share of US industrial energy consumption has been unchanged for decades, despite advances in heat pump technology.

Air-source heat pump COP vs ambient temperature

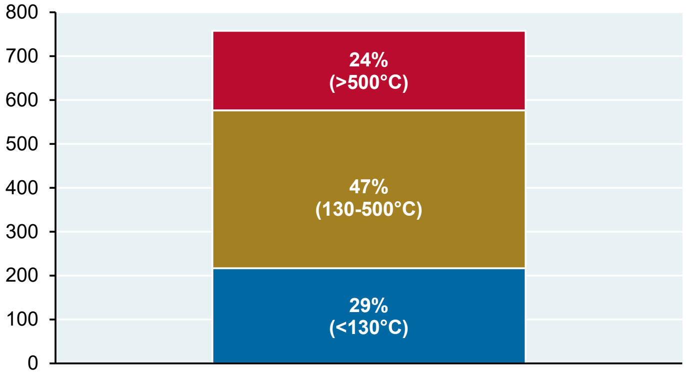
Avg coefficient of peformance



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

US industrial thermal emissions by temperature range

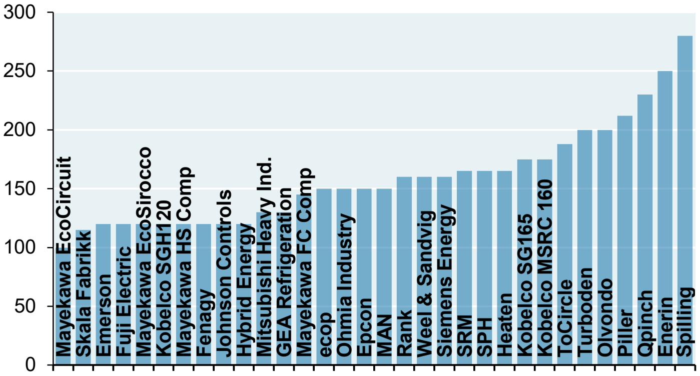
Million tons of CO_2e, 2018



Source: *"Industrial Thermal Decarbonization"*, RTC, September 2023

Maximum heat supply of industrial heat pumps

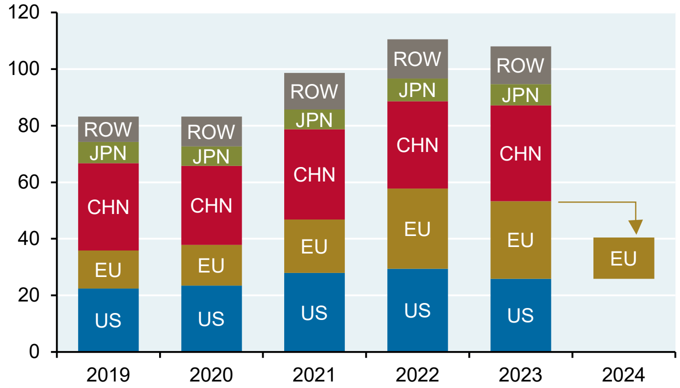
Temperature, °C



Source: Jan Rosenow, Regulatory Assistance Project, September 2024

Heat pump sales by region

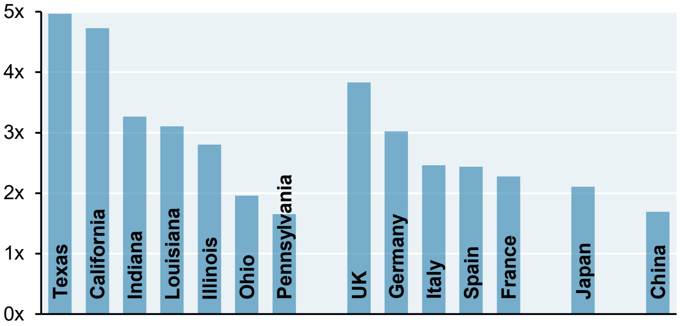
GW



Source: IEA, JPMAM, 2024

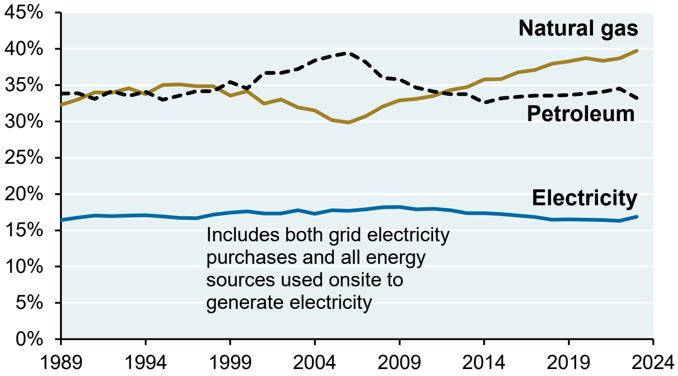
Electricity: 2x-5x more costly than gas for industrial heat

Electricity cost per MJ divided by natural gas cost per MJ, industrial users, assuming 85% industrial furnace efficiency



Source: EIA, Eurostat, CEIC, JPMAM, 2024. States shown are largest industrial users of US primary energy

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



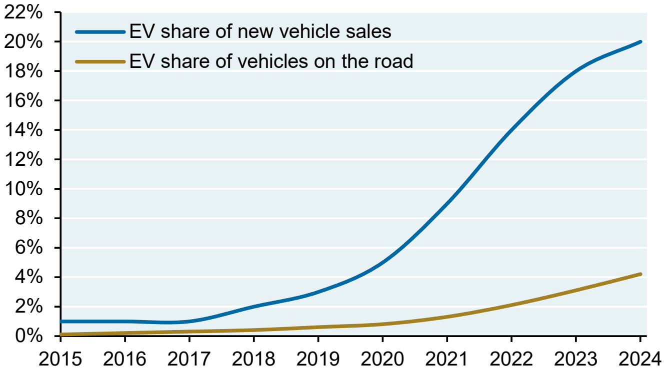
Source: EIA, JPMAM, 2024

EVs: battery packs, battery metals, EV shares of sales and fleet

Globally, EVs represent ~20% of new passenger car[19] sales and ~4% of the fleet. The fastest transition is in China which is approaching a tipping point in favor of EVs. Country dispersions are large as shown in the second and third charts. Lithium ion battery pack prices continue to decline after a temporary spike in 2022. EV metals costs explain why LFP is preferred by automakers (i.e., no cobalt or nickel). SUVs and pickup trucks account for ~70% of US vehicle sales.

Global passenger vehicles

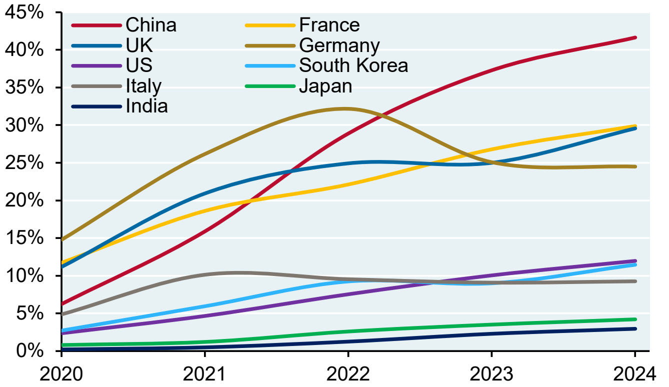
Percent, non-commercial use, includes BEVs & PHEVs



Source: BNEF, 2024

EV share of passenger vehicle sales, largest car markets

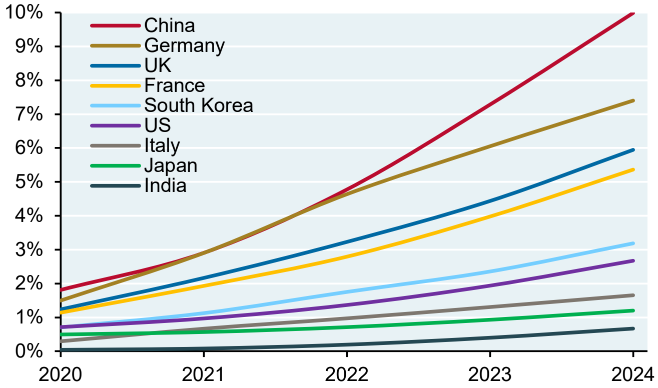
Percent, BEV + PHEV



Source: BNEF, JPMAM, 2024

EV share of passenger vehicle fleet, largest car markets

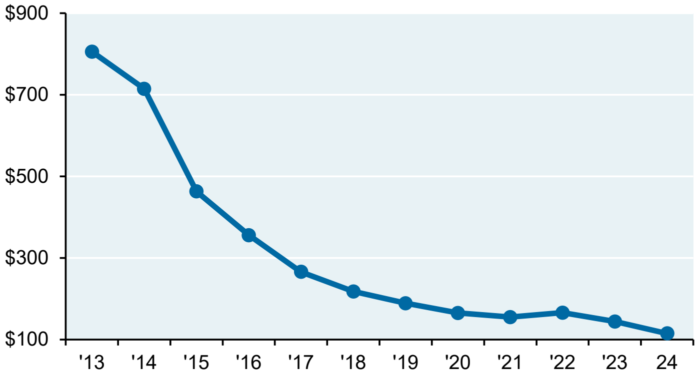
Percent, BEV + PHEV



Source: BNEF, JPMAM, 2024

Volume-weighted average lithium-ion battery pack price

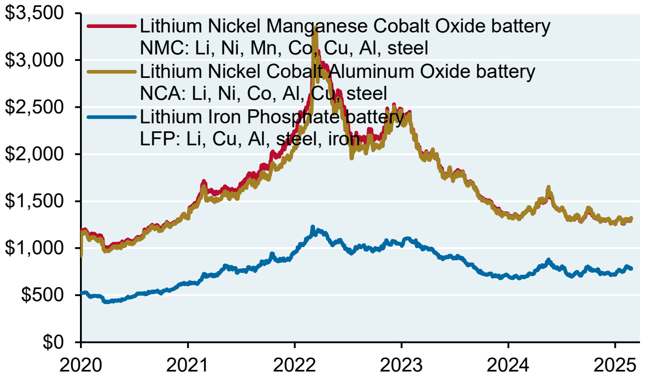
2024 US$ per kWh



Source: BNEF, December 2024

Estimated metals cost per EV battery type

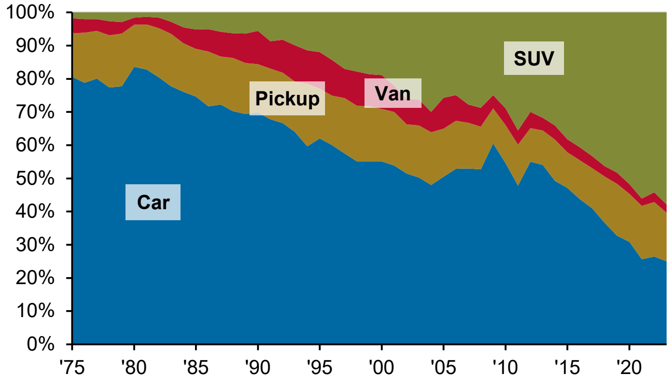
US$ per 60 kWh battery



Source: Uni. of Birmingham (UK), ANL, Bloomberg, JPMAM, Feb 28, 2025

US new light-duty vehicles by type

Percent share



Source: EPA, JPMAM, 2024

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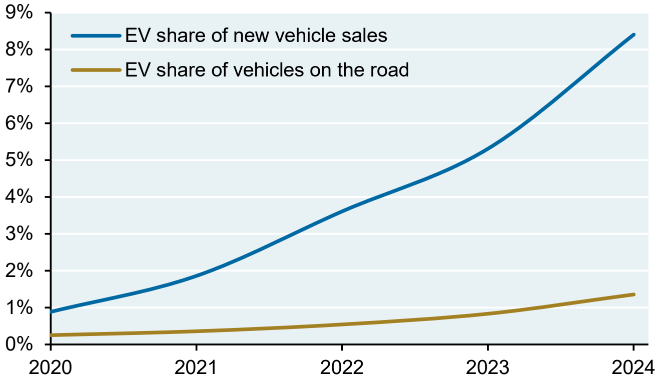
[19] BNEF passenger vehicles include station wagons, sedans, SUVs, pickups and vans whose purpose is non-commercial

EVs: light duty vehicles, commercial fleet penetration, charging type and battery density/US gasoline demand

Commercial light duty sales and fleet shares of 8.5% and 1.5% are around half of passenger car levels with China as the global leader. Lithium iron phosphate (LFP) battery cells in China cost around half of RoW levels, which may explain China's lead. In China, roughly half of BEV trucks rely on battery swapping rather than charging only. LFP chemistry dominates the commercial truck category. US gasoline demand appears to have peaked since miles traveled have reached pre-COVID levels while gasoline demand has not.

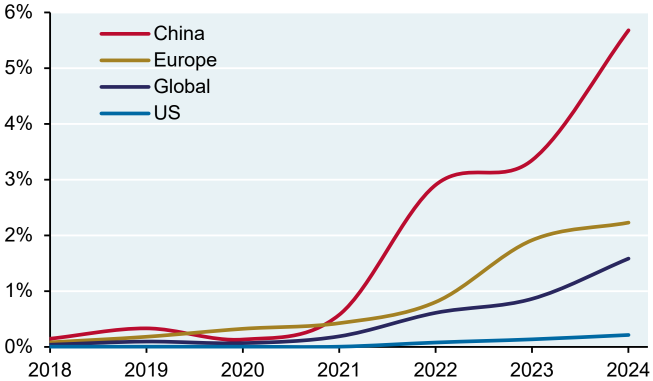
Since 2017, EV truck battery performance has improved: longer ranges (from 100 km to 200 km) and higher battery pack density of ~195 Wh/kg with some reaching 250 Wh/kg using NMC chemistry. In 2025, some producers aim to introduce packs with energy density of 280-300 Wh/kg.

Global light-duty vehicles
Percent, commercial use, <3.5 tonnes, includes BEVs & PHEVs



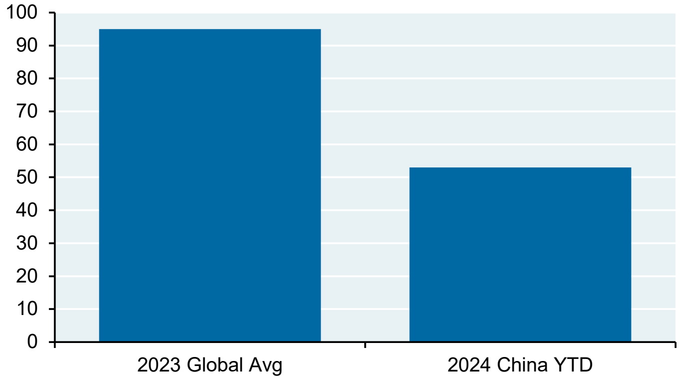
Source: BNEF, 2024

EV share of medium/heavy trucks
Percent share of truck sales



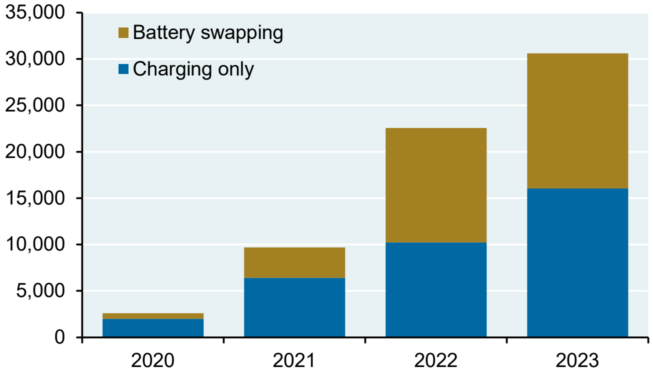
Source: BNEF, 2024

Lithium iron phosphate battery cell prices
US$/kWh



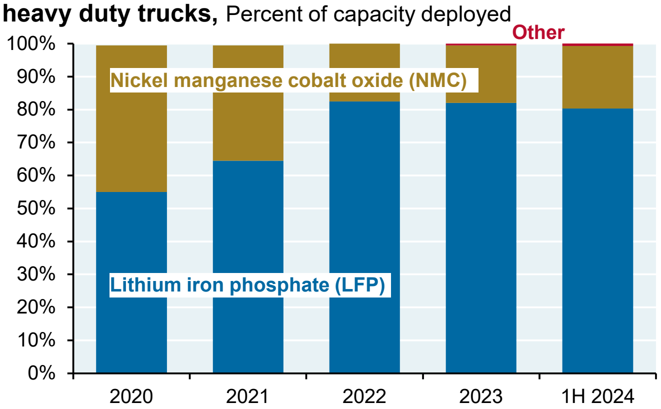
Source: BNEF, 2024

Sales of battery-electric heavy-duty trucks in China
Units



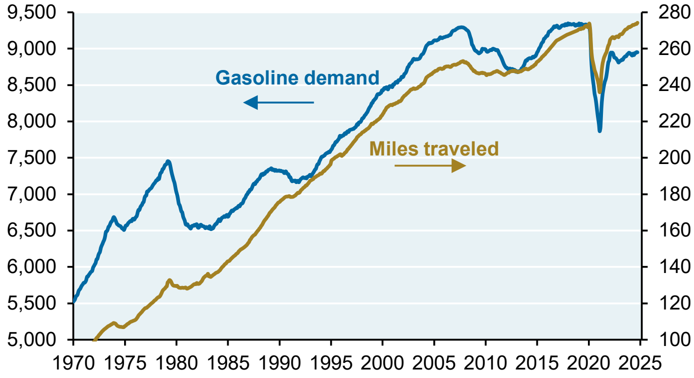
Source: BNEF, Evpartner, 2024

Battery chemistry of electric and fuel cell medium and heavy duty trucks, Percent of capacity deployed



Source: BNEF, 2024

US gasoline consumption vs vehicles miles traveled
Thousand barrels per day
Billion miles traveled



Source: Bloomberg, JPMAM, October 2024

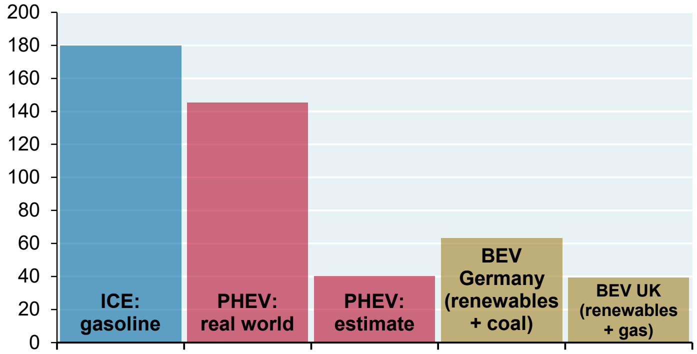
EV research: real world PHEV emissions reductions, and real-world EV collision repair costs

CO_2 emissions reductions from PHEVs appear to be overstated. As shown in the first chart, empirically measured PHEV emissions per km in Europe are not that different than internal combustion engine cars and well above initial EU estimates. The second chart uses real-world data from commercial settings and highlights the issue of driver behavior: the average PHEV is used more like an ICE car most of the time, rather than being battery-powered.

Two recent studies[20] suggest that EV collision repair costs might exceed internal combustion engine cars. The first study from Mitchell International found that the cost of EV collision repairs is ~30% higher than ICE cars. The data was sourced from vehicle insurance claims from 300 insurance providers and 20,000 collision repair facilities. A separate analysis from Solera came to similar conclusions: much higher collision repair costs for EVs compared to ICE cars. Bottom line: higher repair costs might need to be included in any lifetime assessment of EV vs ICE total ownership costs.

Average CO_2 emissions from ICE, PHEV and BEV cars

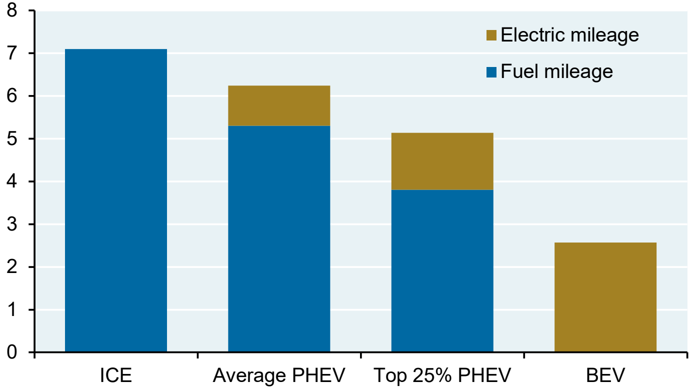
Grams of CO_2 per km



Source: BNEF, PHEV estimates by EU Commission using worldwide harmonized light vehicle test procedure, 2024

Fuel/electric mileage contribution for-light duty vehicles

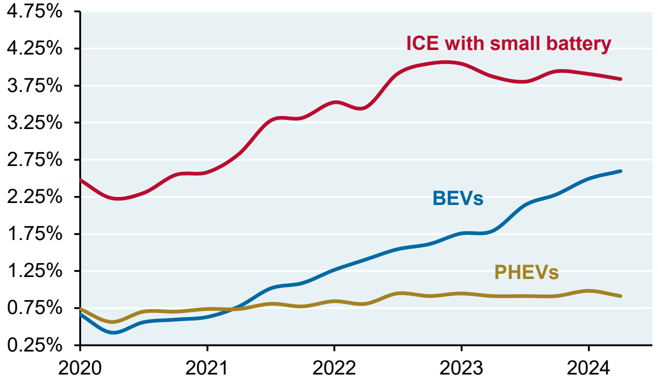
Litres/Litres equivalent/100km



Source: Geotab, 2024

While EV collision repairs are less frequent...

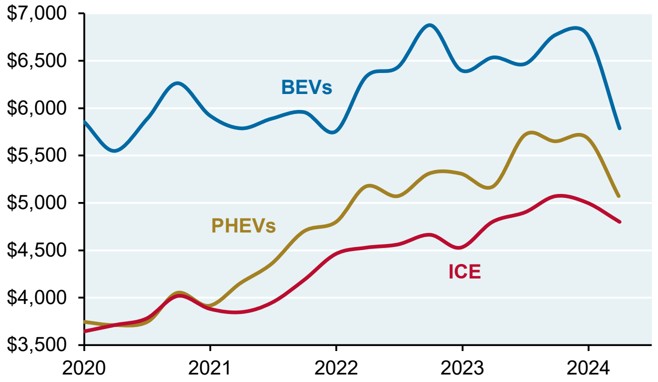
Frequency of repairable claims



Source: Mitchell, August 2024

...EV collision repairs cost more money

Average cost, US$



Source: Mitchell, August 2024

Solera November 2023 comparison of EV and ICE collision repair costs. An analysis of 92,000 insurance claims across 20 countries for the Hyundai Kona EV and its ICE counterpart from 2021 to 2023 found the following:

- Overall EV collision repair costs are on average 29% higher than ICE collision repair costs
- EV parts costs are 48% higher than ICE parts costs
- EV battery system collision repairs represent the highest parts cost, making up 24% of the total EV parts cost
- Driver airbag systems, rear bumper absorbers and rear bumper reinforcements are replaced more frequently on EVs

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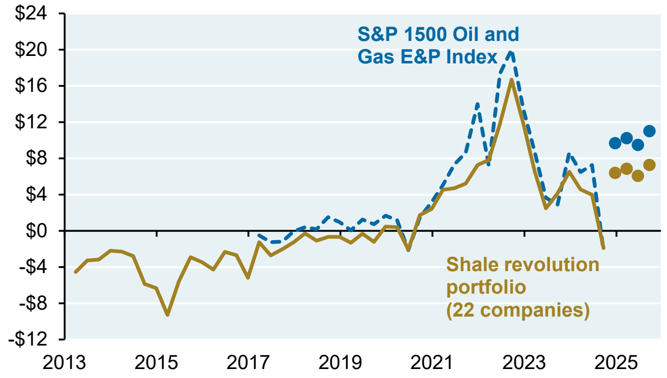
[20] *"Unveiling the Cost Dynamics: EVs Face Higher Repair Bills Than ICE Models in Global Study"*, Solera Holdings, November 2023; and *"Plugged-In: EV Collision Insights Q2 2024"*, Mitchell International, August 2024

Markets: oil & gas stocks vs renewables/renewable operating margins

The lost decade of unprofitable shale companies came to an end in 2021. With more capital discipline, shale revolution companies began generating more free cash flow despite low US natural gas prices. In Q3 2024, the free cash flow margins of the shale industry declined again but appears to be temporary given forecasts for a rebound in 2025-2026. The 2024 decline is reportedly a consequence of $7.8 billion in property acquisitions by Diamondback Energy and $3.6 bn in acquisitions by Devon Energy.

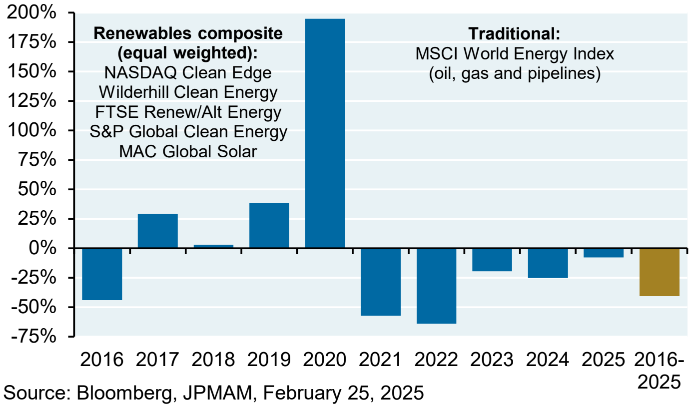
In public markets, renewables underperformed traditional energy since 2020, in part due to lower operating margins than other industries. In private markets, renewables have struggled as well: a February 2025 article in Bloomberg[21] cited BlackRock, Riverstone, Caisse de Depot et Placement du Quebec, Greenbacker and Tikehau Capital as examples of firms suffering large writedowns of renewable investments. At the same time, KKR, TPG and Brookfield continue to raise money for future energy transition funds, citing cheaper valuations.

Oil & gas unprofitability decade ended in 2021
Free cash flow, $ billions



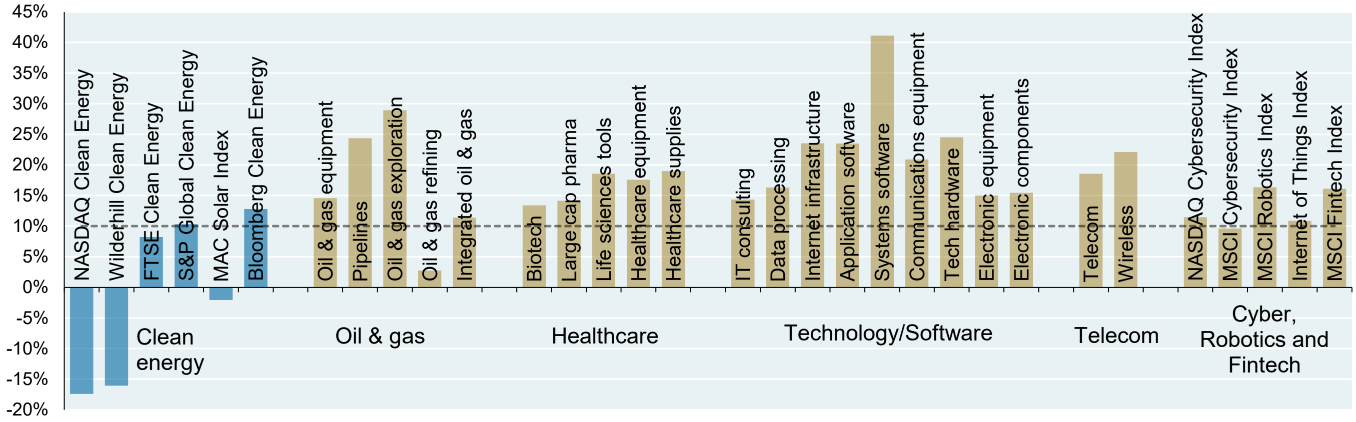
Source: Bloomberg, JPMAM, Q3 2024

Renewables vs traditional energy: annual outperformance
Renewables composite return minus traditional energy return



Source: Bloomberg, JPMAM, February 25, 2025

Operating margins by sector and index



Source: Bloomberg, JPMAM, February 12, 2025

The origins of some environmental objections to clean energy might surprise you. Alliances of environmental NGOs and fossil fuel companies have used the National Environmental Policy Act (NEPA) to delay clean energy and transmission projects by arguing they would harm the environment. The majority of project-blocking lawsuits invoking the NEPA have been filed by a few NGOs that have lost > 70% of their cases...however, often not before months of costly appeals. In more contentious cases, delays reached over 4 years. According to the Breakthrough Institute, such NGOs include the Sierra Club, the National Resources Council of Maine and the Appalachian Mountain Club. See "*NEPA Nightmares*", Breakthrough Institute, August 2024

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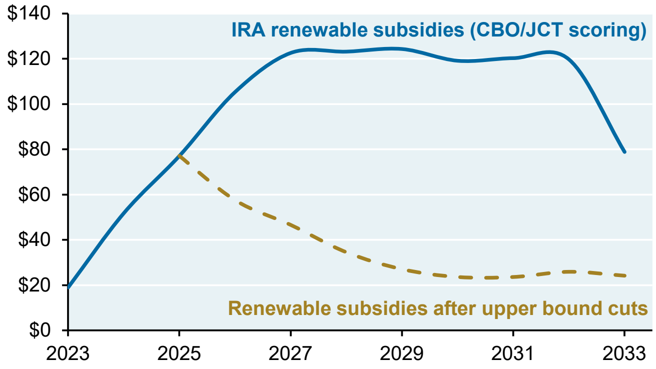
[21] "*PE Firms Look to Cut Losses After Renewable Energy Bets Fizzle*", Bloomberg, February 27, 2025

Trump 2.0 energy policies: the pendulum swings, yet again

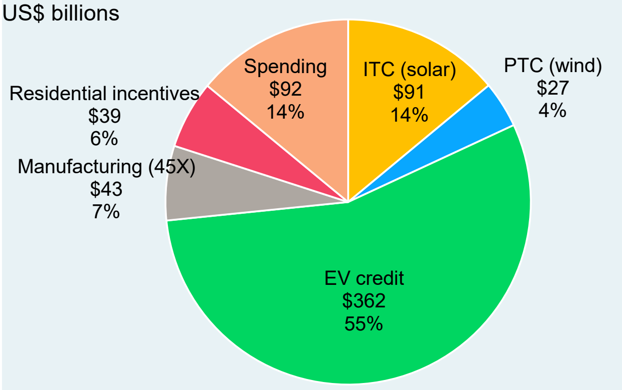
While the details are not entirely clear, the Trump Administration is clearly downshifting renewable priorities in favor of fossil fuels, national security and a desire to bring down inflation. With respect to renewables, let's begin with the upcoming reconciliation bill. As far as we can tell, the primary revenue raisers the White House will use to partially offset the $4-$5 trillion cost of full tax cut extensions will result from a scaled back version of the energy bill. Don Schneider at Piper Sandler has estimated the boundaries of energy bill cuts that he expects from the budget reconciliation process, illustrated below. **Bottom line: energy bill subsidies could decline by as much as $650 billion, which would be a 2/3 reduction vs original projected costs of the bill.** The bulk of the projected reductions: reduced EV credits, a smaller expansion of wind/solar production/investment tax credits, reduced 45x manufacturing tax credits (mostly EV battery projects) and a decline in certain renewable spending categories. Subsidies that survive are likely to be related to projects that have already broken ground in order to appease moderate GOP members that sent an August 6th letter to Speaker Johnson.

Cost of clean energy subsidies: present law & after potential reductions from budget reconciliation, US$, bil



Source: CBO, JCT, Piper Sandler, November 2024

Possible savings from energy bill modifications
US$ billions



Source: CBO, JCT, Piper Sandler, JPMAM, November 2024

In addition to restructuring the energy bill, Trump policies also might…

- …represent an existential threat to offshore wind on the Atlantic seaboard if the DoE does not approve new leases/permits, or disrupts existing ones (i.e., Dominion in VA). In 2023 the US offshore wind pipeline was 52 GW but some projects have been plagued by rising costs, terminated PPAs and interconnection delays
- …impede onshore wind permitting on public lands, but such projects only account for 2% of US wind generation; the rest is on private lands
- …relax or eliminate fleet-level GHG targets for 2032 and fuel economy standards
- …end DoE efforts to ban gas appliances, but for context, gas stoves only account for 2% of residential gas consumption, which in turn is only 14% of US natural gas use
- …compel the EPA to withdraw its "endangerment finding" which was used by Obama/Biden to regulate GHG emissions from vehicles, power plants and other sources due to potential harm to public health/welfare
- …speed up development of transmission projects linked to renewable power, but as explained earlier, new transmission projects have ground to a halt for reasons related to state and local hurdles in addition to federal ones. A notable development: an Interim Final Rule repealing the White House Council for Environmental Quality (CEQ) regulations which instruct Agencies how to comply with the National Environmental Policy Act. This could make projects easier to site and permit, but we will have to see how it plays out since environmental groups will probably challenge invocation of emergency rulemaking powers rather than waiting for normal notice-and-comment rulemaking. Notably, the DC Circuit ruled last year that CEQ has no rulemaking authority. If there are no successful Supreme Court appeals, CEQ would no longer be able to mandate legally-binding requirements for detailed environmental impact statements. Each Agency would then issue its own guidance on environmental impact statements, after typical rulemaking

As for Trump 2.0 fossil fuel policies, the Administration has a steep hill to climb to meaningfully ramp up production and reduce energy price inflation. While Biden policies provided plenty of carrots to renewables, there were few sticks in practice when it came to US oil & gas production which rose to all-time highs by the end of 2024. Treasury Secretary Bessent's target of another 3 mm barrels of oil equivalent is just a 7% increase in fossil fuel production. That might not be enough to meaningfully reduce US energy price inflation given:

(a) the need to replenish the strategic petroleum reserve which Biden raided in an attempt to dampen the inflationary consequences of his economic policies

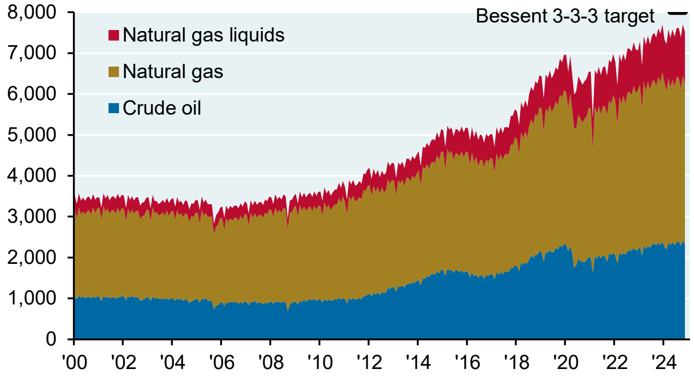
(b) planned reductions in US gasoline refining capacity

(c) the possible export of any new US natural gas production, particularly since Trump may offer reduced US tariff increases in exchange for more purchases of US LNG exports

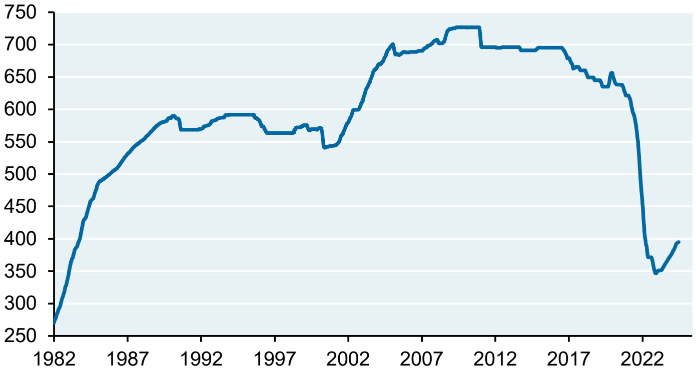
(d) proposed 10% tariffs on US imports of Canadian energy

(e) the low correlation between retail, commercial and industrial electricity prices and natural gas prices, despite natural gas comprising the largest share of US power generation. The reason: electricity prices mostly reflect the ongoing capital cost of building generation and transmission infrastructure…which as we explain in the next section on Europe, is being duplicated due to the energy transition

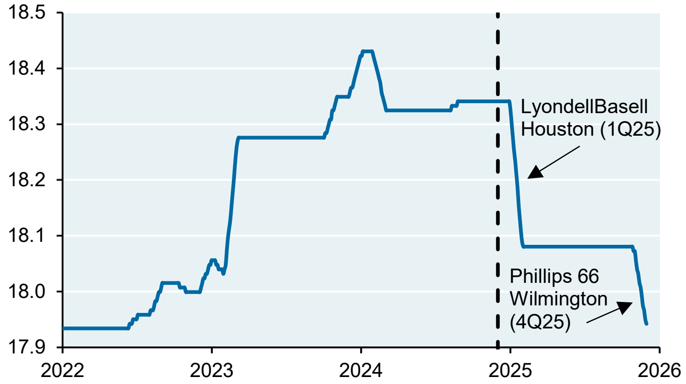
As for the Trump Administration's limited professed interest in international carbon protocols, US emissions intensity has been falling mostly due to a shift from coal to gas (even when including estimates for the GHG impact of flaring and venting), and secondarily due to wind and solar power. Trump 2.0 energy policies will likely slow the rate of decline in the last chart, but I would be surprised to see US GHG emissions actually rise.


US production of crude oil, natural gas and natural gas liquids, Trillions of BTUs per month

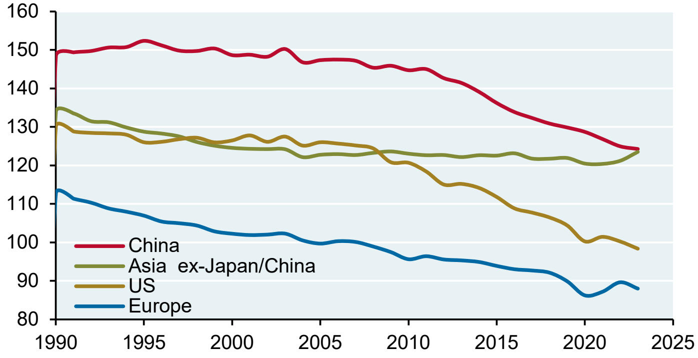
Source: EIA, JPMAM, November 2024


Strategic petroleum reserve total inventory
Barrels (millions)

Source: US Department of Energy, JPMAM, January 31, 2025


US refinery capacity and upcoming closures
Million barrels per calendar day (atmospheric distallation capacity)

Source: EIA, JPMAM, November 2024

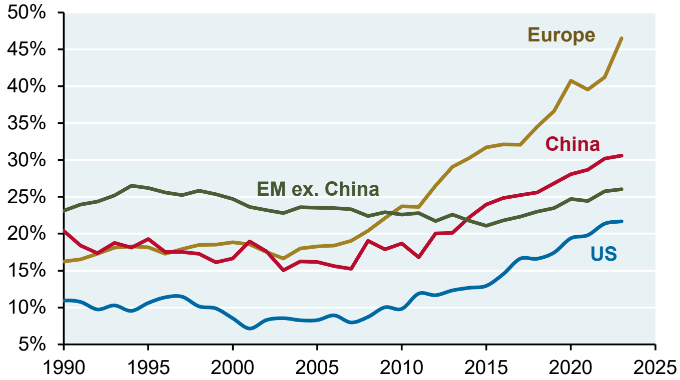

Emissions intensity of energy consumption
Million tons of GHG emissions per exajoule of final energy consumption, including the GHG impact of process emissions, flaring and venting

Source: EI Statistical Review of World Energy, JPMAM, 2024

No good deed goes unpunished: the high cost of European decarbonization

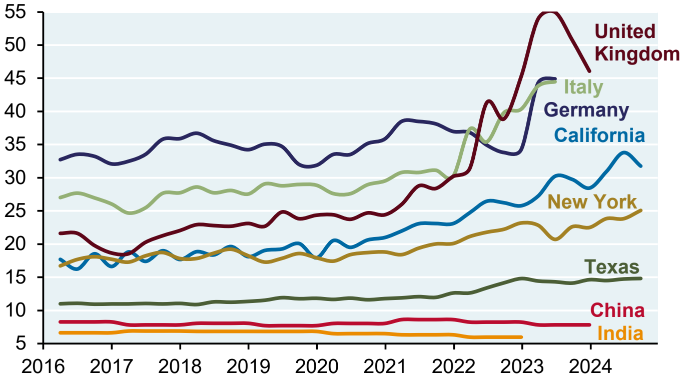
Europe is the world leader with respect to the pace of decarbonization. Despite multiple jurisdictions, complex permitting requirements, high population density and wind/solar locations far from urban centers, **Europe has demonstrated the realm of the possible on decarbonization, reaching a 50% renewable share of electricity consumption by the end of 2024**.

Renewable share of electricity consumption
Percent



Source: EI Statistical Review of World Energy, IEA, JPMAM, 2024

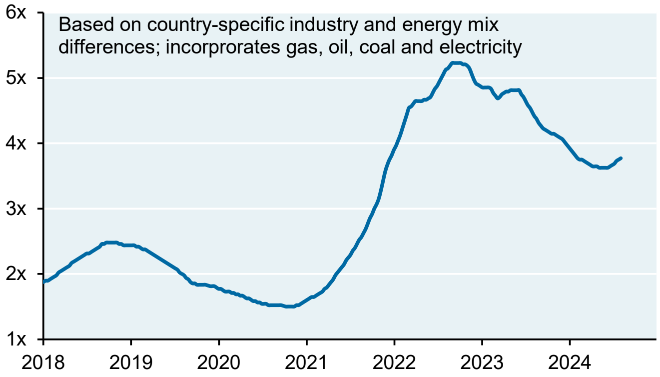
Residential electricity prices
US$, cents per kWh



Source: EIA, IEA, JPMAM, Q3 2024

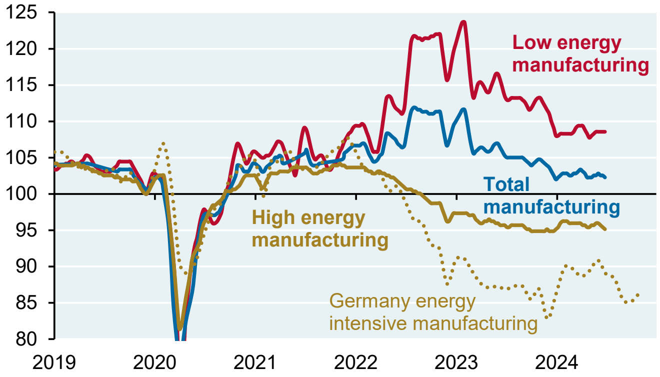
However, Europe is paying a steep price for this transition[22]. Its energy prices have risen from 2x to 4x US levels, and its residential electricity prices are now 5x-7x higher than in China and India. There have been many articles on European deindustrialization due to rising absolute and relative energy costs. The spike in relative prices is not just a function of the renewable transition; higher energy prices also reflect Europe's transition from pipeline Russian gas to more expensive imported LNG. It will be interesting to see if an end to the Russia-Ukraine war results in resumed Russian pipeline gas flows to Europe or not.

Energy prices in the Euro area relative to the US
Ratio, 12 month moving average



Source: ECB Monetary Policy Report, 2024

European manufacturing output by energy intensity
Index (100 = December 2019)



Source: ECB, German Federal Statistical Office, November 2024

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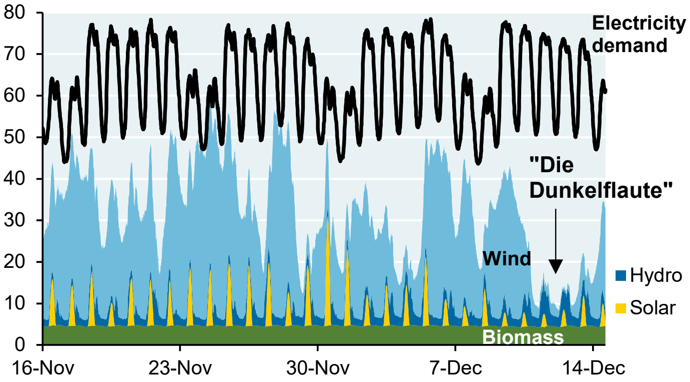
[22] According to former Belgian PM Guy Verhofstadt, European defense capabilities are only 10% of US levels. Higher energy prices, intermittent power and deindustrialization are not going to make the task of European rearmament any easier. But it looks like that's what the new US administration will require after Europe took 16 years to finally comply with the 2% of GDP defense spending commitment that NATO agreed upon in 2006.

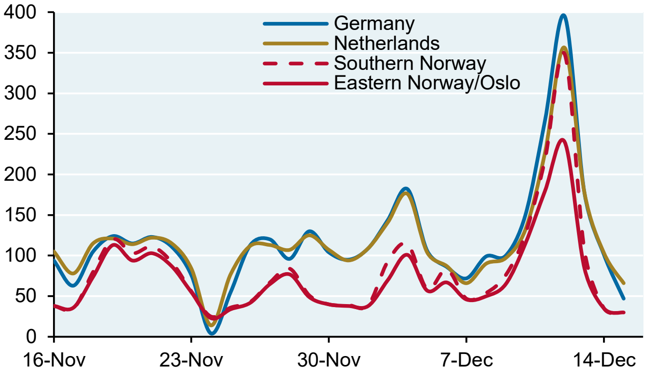
The consequences of Europe's changing electricity grid are showing up in strange places. After another "Dunkelflaute" event during which wind speeds collapsed in Germany, electricity prices soared in Norway and the Netherlands as well. For related reasons, Sweden recently decided not to pursue a new grid interconnector project with Germany due to problems with Germany's electricity market[23]. Referring to Germany's decision to decommission nuclear, the Swedish Energy Minister stated that she's "furious" with the Germans: "**They have made a decision for their country, which they have the right to make. But it has had very serious consequences**" …including the collapse of the Norwegian government in January when the Centre Party withdrew over European energy market rules[24].

Another Dunkelflaute wind collapse in Germany...
Germany electricity generation and load, MW, thousands



Source: Fraunhofer ISE, JPMAM, December 14, 2024

...led to soaring electricity prices across Europe
EUR / MWh

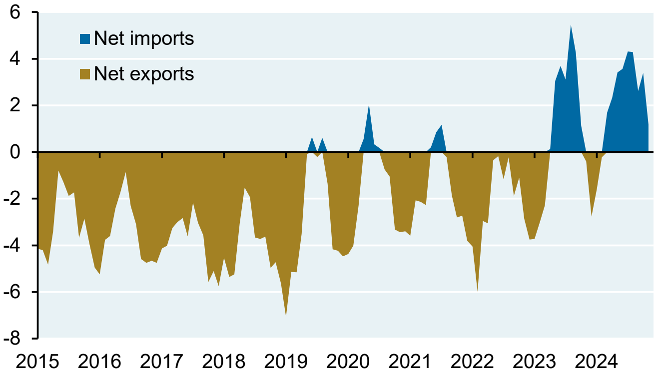


Source: Energy Prices EU, ENTSO-e, JPMAM, December 15, 2024

Two consequences of Germany's energy transition: rising import reliance and generation capacity duplication. From 2012 to 2019, German electricity EXPORTS consistently peaked at ~4 TWh each year. After its nuclear plants were shut down in favor of intermittent wind and solar, Germany became an electricity IMPORTER with imports peaking at ~4 TWh, a complete reversal in balance of power terms and which is illustrated below.

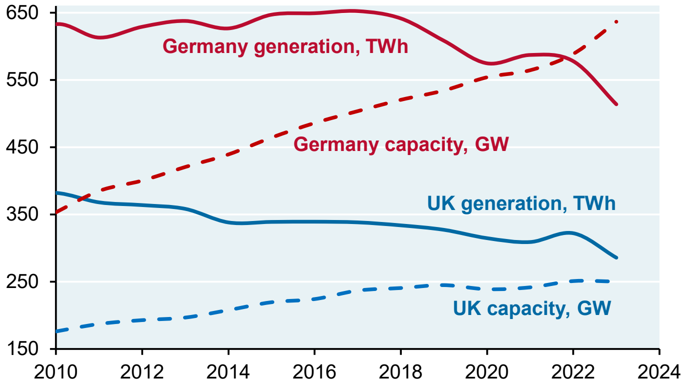
Duplication of generation capacity, a feature of grids with large shares of renewable power, is part of the reason for higher electricity prices in Europe. Note in the chart on the right how generation capacity in the UK and Germany has been *rising* while electricity generation in both countries is actually *falling.* This by-product of renewable intermittency may become more common as grids are decarbonized.

German electricity imports and exports
Monthly cross border physical flows, TWh



Source: Fraunhofer ISE, JPMAM, November 30, 2024

Rising capacity & falling generation in the UK & Germany



Source: EI Statistical Review of World Energy, JPMAM, 2024

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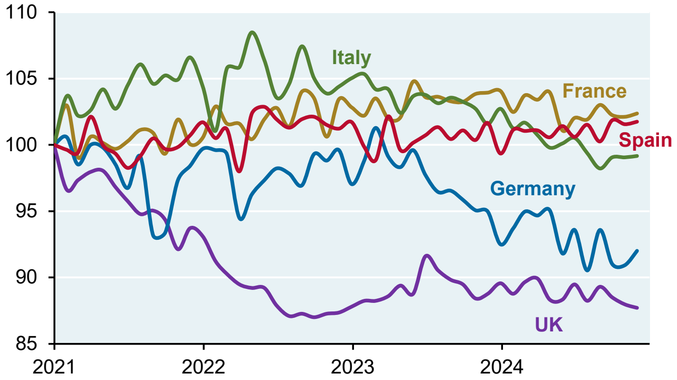
[23] "*Sweden rejects application for a new power interconnection line with Germany*", June 20, 2024

[24] "*Sweden open to measures to tackle energy crisis, blames German nuclear phase-out*", Euractiv, Dec 13 2024, and "*Norwegian finance minister blames EU energy policy for government collapse*", EuroNews, Jan 20, 2025

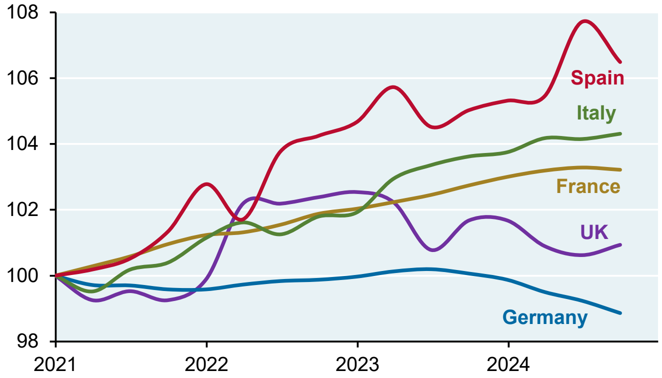
The UK and Germany are also experiencing sharper declines in manufacturing output and employment. British Labor PM Starmer has talked about the UK becoming a center of excellence on AI; that's hard to imagine given just 12 days of natural gas storage supply, shrinking dispatchable power, heavy gas import reliance, a 50-year low in offshore UK gas production and soaring electricity prices. The UK's Labor Government intends to shutter aging nuclear plants by 2028 and ban fracking for good, leaving shale gas formations in Lincolnshire untouched, and "sprint to clean power by 2030".

European industrial production: manufacturing
Index (100 = January 2021), seasonally adjusted



Source: DBB, INE, ISTAT, INSEE, UK ONS, JPMAM, November 2024

European manufacturing employment
Index (100 = January 2021), seasonally adjusted



Source: Eurostat, INSEE, UK ONS, StBa, JPMAM, Q3 2024

"**Qatargeted**". The EU Corporate Sustainability Due Diligence Directive may require large companies operating in the EU to comply with its rules on carbon emissions and labor/human rights or face fines as high as 5% of the company's global revenues. The rules would go into effect in 2027. In response, Qatar has already threatened to halt all LNG exports to the EU if it is fined under the new law. The rules require EU standards to apply to a company's entire global supply chain, which in the case of Qatar would require due diligence on 100,000 separate companies.[25] In 2023, Qatar accounted for 14% of the LNG imported into Europe.

Update: if approved by the European Parliament/Council and transposed into national laws, a recent Omnibus bill could shrink the number of companies affected by the Directive, reduce mandatory reporting requirements and lessen enforcement mechanisms.

Renewable shares of electricity generation by country

Country	2019	2020	2021	2022	2023	2024
Austria	76%	79%	73%	70%	86%	100%
Belgium	17%	22%	21%	24%	28%	28%
Croatia	41%	43%	50%	42%	58%	52%
Czechia	10%	11%	12%	12%	13%	16%
Denmark	60%	59%	60%	71%	73%	73%
Estonia	16%	20%	18%	25%	26%	33%
France	22%	25%	23%	23%	29%	32%
Germany	43%	46%	42%	47%	52%	54%
Greece	25%	29%	37%	40%	45%	51%
Hungary	8%	10%	13%	15%	19%	25%
Ireland	34%	37%	32%	34%	39%	37%
Italy	33%	36%	34%	30%	36%	41%
Latvia	38%	45%	44%	47%	65%	62%
Lithuania	18%	18%	16%	21%	30%	41%
Luxembourg	13%	16%	17%	18%	21%	24%
Netherlands	19%	27%	33%	42%	50%	53%
Norway	98%	114%	112%	108%	111%	111%
Poland	12%	14%	15%	19%	25%	29%
Portugal	49%	57%	58%	49%	59%	71%
Romania	40%	41%	42%	41%	52%	46%
Serbia	30%	30%	35%	27%	39%	33%
Slovakia	19%	21%	19%	18%	23%	25%
Slovenia	33%	38%	35%	26%	43%	49%
Spain	38%	46%	49%	48%	57%	64%
Sweden	71%	82%	81%	87%	86%	88%
Switzerland	63%	66%	62%	54%	67%	79%
Turkey	41%	39%	32%	38%	38%	43%
UK	32%	39%	34%	40%	41%	44%
Europe	**37%**	**42%**	**40%**	**41%**	**47%**	**51%**

Source: Ember, JPMAM, 2024

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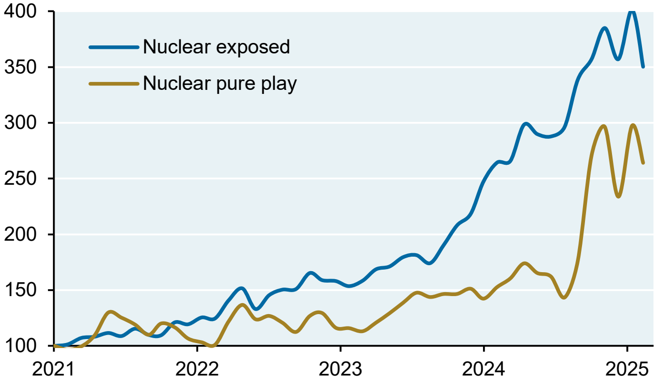
[25] "*I will stop sending LNG: Qatar's Al-Kaabi hits out at new EU law*", Upstream, December 2024

A nuclear renaissance in the OECD? Wake me when we get there

Investors have gotten excited about prospects for more nuclear power in the US, driving shares of nuclear pure play and nuclear-exposed shares higher. There are several components behind all of this: bipartisan support for government regulations to speed up nuclear power development; the restart of old nuclear plants; the gaggle of companies competing to deliver next-gen nuclear plants and the first small modular reactor; and the belief that even a small number of new nuclear projects would benefit from Nth-of-a-kind workforce experience and standardization. The stakes are high: a single nuclear plant typically costs 10% of a utility's market cap.

Nuclear pure play and nuclear exposed stock returns

Total return index (100 = June 2021)



Source: Bloomberg, JPMAM, February 25, 2025

Nuclear exposed: Constellation Energy, Silex Systems, Vistra, GE Vernova, Rolls-Royce, Honeywell, Lockheed Martin, Fluor, Mitsubishi, Duke Energy, Dominion Energy, Quanta Services, Fortum Oyj

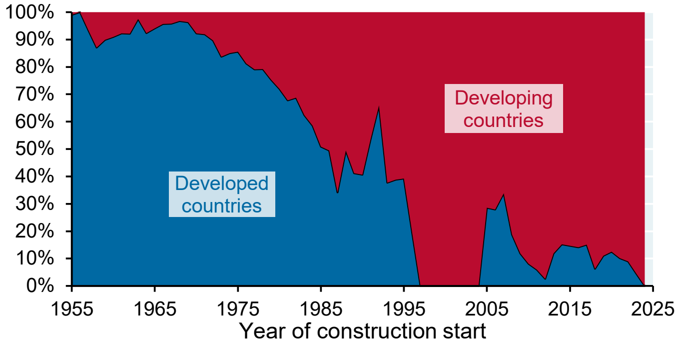
Nuclear pure play: Cameco, Oklo, Centrus Energy, NuScale, BWX

Traditional nuclear plant development

While the developed world dominated nuclear capacity additions from 1950 to 1980, a combination of factors led to a collapse in new projects. For the most part, the developing world took the baton from the OECD in the mid 1980's and little has changed since.

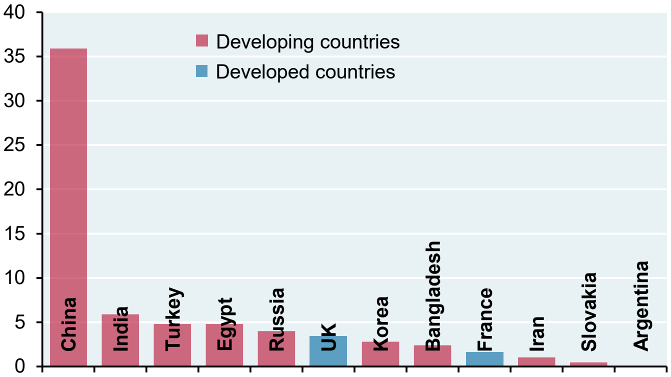
During the 1980's, nuclear development shifted from developed to developing countries

Market share of global MW of nuclear starts, 5yr avg.



Source: Power Reactor System Database, JPMAM, September 2024

Nuclear plants under development with estimated grid connection dates between 2024-2030, GW of capacity

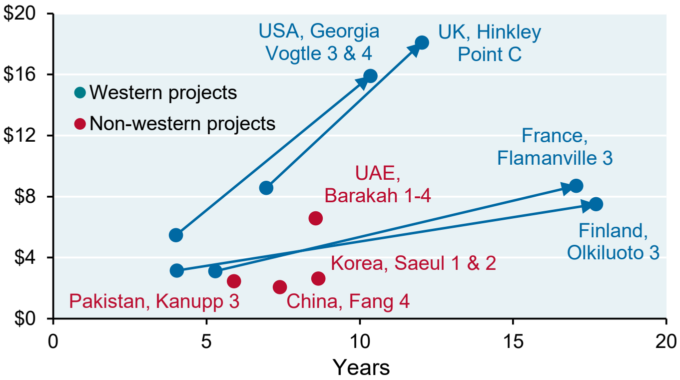


Source: World Nuclear Association, JPMAM, 2024

As shown at the top of the next page, the cost per MW of developing economy nuclear plants is usually a fraction of the four most recent OECD completions. Developing economy plants were also generally completed in 6-8 years; the handful of OCED completions have taken a lot longer than that. There are efforts underway to address this in the US: in June 2024, Congress passed the Advance Act (Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy) on a bipartisan basis. The Act streamlines permitting for advanced reactors, reduces regulatory fees for companies licensing advanced reactor technologies and updates outdated rules that limit international investment. It also requires the Nuclear Regulatory Commission to develop a pathway to license nuclear facilities at the sites of shuttered coal plants that already have a connection to the grid.

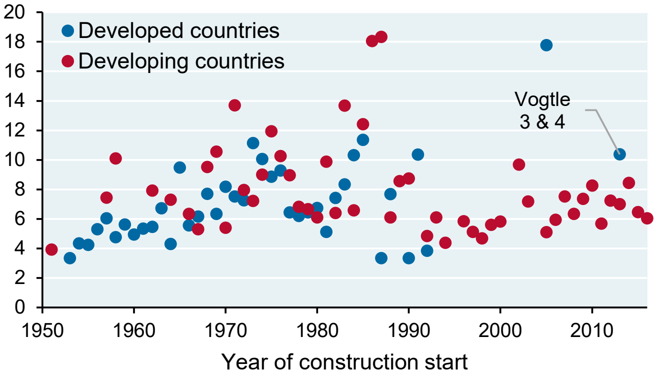
Will new US regulations make a difference? Too soon to tell. The industry has a lot to prove to investors and regulators: as shown below, nuclear power/storage projects are associated with the largest cost overruns of all megaprojects. Vogtle 3, completed in Georgia in 2023 after extensive delays and cost overruns, was offline for 9.5 out of its first 48 weeks in 2024 due to feedwater pump blockages or failed heat exchangers. The US is also reliant on imported uranium, needs more enrichment capacity and has practically no domestic supply of high assay low enriched uranium, the kind needed for the Gates Terrapower project (its Wyoming reactor is delayed to ~2030 as US HALEU supply chains are built out following the launch of the DoE HALEU availability program).

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



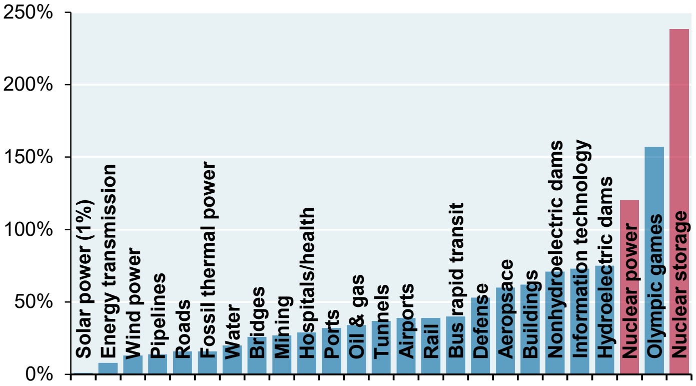
Source: IEA, Power Reactor System Database, JPMAM, February 2025

Average nuclear plant completion time by year and region
Years



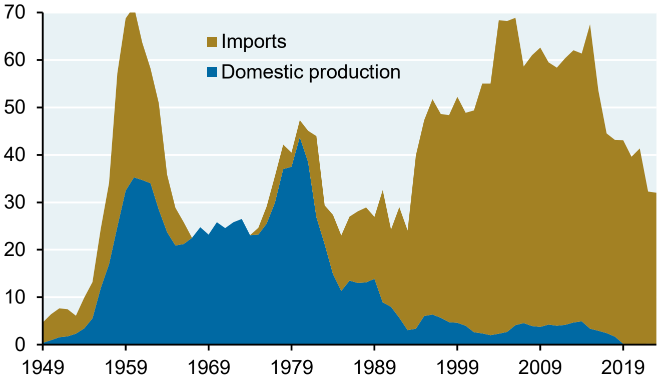
Source: Power Reactor System Database, JPMAM, September 2024

Average megaproject cost overruns
Percent



Source: Flyvbjerg database, 2024

US production vs imports of uranium oxide
Million pounds



Source: EIA, JPMAM, 2024

Nuclear plant reopenings

In the US, Holtec plans to reopen the 53-year old Palisades plant in Michigan that was closed two years ago. Palisades would be the first plant to begin decommissioning and restart[26]. Microsoft and Constellation Energy also announced a plan to reopen 50-year old Three Mile Island reactor #1 in 2028 for power at ~$100 per MWh, and NextEra is working on a restart of the 45-year old Duane Arnold plant in Iowa that was shut in 2020 after a fire. While it's possible to reopen older plants, most would probably not receive an operating license as a *new* facility given evolving safety standards. Reopening skeptics include Palisades' own director of engineering from 2006 to 2013 who cites Holtec's inexperience with nuclear plants[27]. While these projects have attracted a lot of attention from power market customers, the cost and timing of their reopening is uncertain.

Big picture: once substantial decommissioning begins, it would probably be too expensive to contemplate restarts. They will most likely be confined to the three plants cited above and a couple of reactors whose decommissioning has barely begun (San Onofre in California), or uncompleted plants whose construction was halted midstream (VC Summer in South Carolina). Also: large subsidies may be required by time they reopen.

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[26] Palisades decommissioning: fuel was removed from the reactor, transferred to spent fuel pools and then to dry cask storage; the control room was also stripped for parts

[27] *"Can a closed nuclear plant from the '70s be brought back to life?"*, WSJ, August 2024

Nuclear "uprates": increasing the output of existing plants

Uprates occur when plants use fresh or more highly enriched uranium, a process which can add anywhere from 1%-20% of a plant's capacity. The average US uprate since 1977 has been ~5%. The NRC indicates that there are 2.5 GW of uprate proposals on a base of 102 GW (i.e., the equivalent of two new light water reactors on national basis). Uprates peaked from 2001-2014 and have slowed materially since.

Small modular reactors and other next-gen nuclear designs

"I'm very skeptical with regard to SMRs. They are going to be very expensive and then you're going to be taking a bet on the technology. Right now, I look at SMRs as an opportunity to lose money in smaller batches"

- *NextEra CEO John Ketchum in 2022 at the Wolfe Research Energy Conference*

- **Most next-gen nuclear designs are based on sodium-cooled fast reactors, high-temperature gas-cooled reactors (HTGR) or molten salt reactors**. Adherents typically claim that their designs could lower costs, be built quickly, reduce accumulation of nuclear waste, use uranium more efficiently via waste recycling, improve safety (passive shutdown and cooling) and reduce risk of nuclear proliferation

- **Molten salt and HTGR nuclear plants were attempted in the past in the US and abandoned due to poor performance**[28]. Water-moderated/cooled reactors have proven superior in terms of reliability, operational ease, maintenance and economics: they have logged over 17,000 plant-years in operation with capacity factors of 80%-90% vs ~500 years for sodium cooled plants, 40 years for HTGR and 4 years for molten salt

- **While research into HTGR and molten salt reactors may one day yield dividends, few plants are in commercial operation**. The IAEA believes that at least another decade is needed to commercialize molten salt reactors[29], and no country/company has constructed a reliable pebble-bed HTGR. China's small modular HTGR, currently the only operational facility of its type in the world, was built 11 years behind schedule and is operating well below capacity (in 2022 it operated for 27 out 8,760 hours; this improved slightly in the subsequent three months when it operated at capacity factor of just 10%[30]). The DOE's Liftoff report acknowledges that some designs require a long "burn-in" period before achieving technological readiness[31]. Amazon made an equity investment in X-Energy and its plans for four HTGR reactors in the Pacific Northwest with initial operation planned for the early 2030's

- **While Russia and India forge ahead building sodium-cooled fast reactors, development in the US has been primarily confined to reactors for demonstration and experimental purposes.** In fast reactors, neutrons move more quickly, allowing them to split a wider range of uranium isotopes. Some fast reactor technologies are referred to as breeders since they "breed" more fuel than they consume, allowing the excess to be used as fuel by light water reactors (LWRs); spent fuel from LWRs can then be used as fuel by a fast breeder reactor

- **What about small modular reactors?** SMRs can be designed as smaller versions of traditional LWRs, or using next-gen designs. More than three dozen companies are working on plans to deliver SMRs, and there's a 6.5 GW SMR pipeline in the US with aggregate project costs of $176 billion. Here's an overview of public and private sector SMR activity:
  - There are three operating SMRs in the world (two in Russia and one in China), and another under construction in Argentina. The cost overruns[32] on the China SMR was 300%, on Russian SMRs 400% and on the Argentina SMR (so far) 700%. Their construction time frames were also nowhere near the projected 3-4 years; they all took 12-13 years instead to complete

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[28] Two previous HTGRs in the US: 40 MW Peach Bottom I and 330 MW Fort Vrain in the 1970's. The latter facility operated at a 17% capacity factor before it was shut down

[29] "*Molten Salt Reactor Technology Development Continues*", IAEA, April 2024

[30] "*The World Nuclear Industry Status Report 2023",* A Mycle Schneider Consulting Project, December 2023

[31] "*Pathways to Commercial Liftoff: Advanced Nuclear*", DOE, September 2024

[32] "*Small Modular Reactors: Still Too Expensive, Too Slow and Too Risky*", IEEFA, May 2024

- The US Dep't of Defense is building a 1-5 MW microreactor at Idaho National Labs (PELE project) with projected safety reviews and initial testing in 2026
- Google signed a deal with **Kairos** for 500 MW from several molten salt SMRs to be delivered in the 2030-2035 timeframe. Kairos has begun construction on its Hermes demonstration reactor in Tennessee which it aims to complete by 2027; it is the first Gen IV reactor project approved by the NRC in 50 years
- **Oklo** intends to build sodium-cooled fast SMRs. In Sept 2024, Oklo received approval to conduct site investigations (geotechnical assessments, surveys, infrastructure planning). Oklo has also been granted access to used nuclear fuel from a retired experimental breeder reactor operated by the DoE for 30 years, and approval to build its own fuel fabrication facility. While Oklo cites its order book as 14 GW, it is comprised of non-binding agreements that will be subject to customer offtake approval based on the ultimate cost of completing the project (just like NuScale's were)

  Oklo contends that its reactor is based on EBR-II, an experimental sodium-cooled fast breeder reactor which operated from 1964-1994 at capacity factors over 80%, and which performed well during simulated operational failures. EBR-II funding programs were shut down in part due to perceived proliferation risks[33]
- SMR construction has begun in Canada by Ontario Power Generation (BWRX-300, a **GE-Hitachi** design), if you count land grading and retaining walls. US utilities are reportedly cautious and waiting to see its ultimate price tag before proceeding. GE-Hitachi designers are attempting to reduce the volume of the building that houses the reactor by 90% via a more simplified design that eliminates the need for certain safety systems, by using steel plates that reduce the need for steel rebar and by reducing staff to just 75 people compared to 1,000 at most large pressurized water reactors. That said, some third-party estimates of the plant's possible cost are still way above the $2,000 per kW figure that the US National Academy of Sciences cites as necessary for nuclear to compete with other generation sources[34]

SMRs are still lottery tickets and will probably remain that way until 2030 at the earliest. I'm still skeptical of the ability to modularize and shrink the world's most capital-intensive projects; some Western SMR projects may cost between $15 and $20 million per MW by the time they're completed. While Westinghouse, NuScale and X-Energy claim they can build SMRs in 36-48 months, history suggests this is also too optimistic. I would be delighted to be proven wrong on both costs and project completion times for SMRs.

An interesting study on the question of SMRs and learning curves was published by the Institute of Electrical and Electronics Engineers[35]. According to the analysis, even after including the benefit of substantial learning curves, many leading proposed SMR designs would need a lot of production before being able to achieve economies of scale. For example, NuScale's VOYGR model was estimated to require 1,140 units (!!) produced before modularization would reduce costs sufficiently. For Holtec's SMR-160 model, 167 units; for the Westinghouse AP300, 32 units; and for the Rolls Royce design, just 10 units (the Czech nuclear power company CEZ has partnered with Rolls Royce with the goal of completing 470 MW SMRs in the 2030's).

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[33] In its 2021 assessment of non-light water reactors, the Union of Concerned Scientists expressed concern about safety and proliferation risks of FBRs and molten salt reactors. **Counterpoints**: EBR-II successful demonstrated passive safety mechanisms during its lifetime; FBRs maintain plutonium reserves mixed with actinides which render them unsuitable for weapons; industry recycling efforts reduce proliferation risks; MSRs are designed with passive cooling and negative reactivity feedback and are designed to operate at near-atmospheric pressure, eliminating risk of explosive coolant loss seen in PWRs; failsafe measures built into reactors include freeze valves that automatically drain fuel into passively cooled tanks if temperatures exceed safe limits, which halts fission

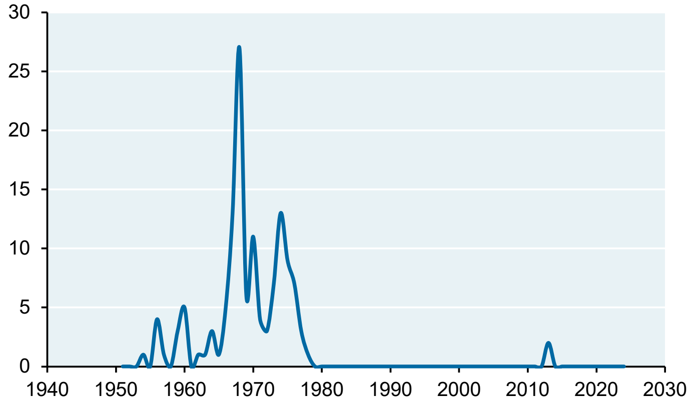
[34] While the National Academy figure was $2k per kW, costs of $4k-$6k per kW would probably be economically viable in deep decarbonization scenarios

[35] "*Small Modular and Advanced Nuclear Reactors and Their Role in the Energy Transition*", IEEE, April 1, 2024

Additional nuclear exhibits

Aside from Georgia Vogtle plants, there have been no US nuclear starts since the late 1970's. As per the exhibits below: France nuclear has been negatively affected by operational outages and low water levels; Japan has reopened 14 of 33 operable reactors shut after Fukushima with another 11 awaiting reapproval to reopen; Germany nuclear generation has now hit zero. When including projects under development, China nuclear generation would reach 700 TWh. Note that nuclear capacity factors do not differ much by technology or age.

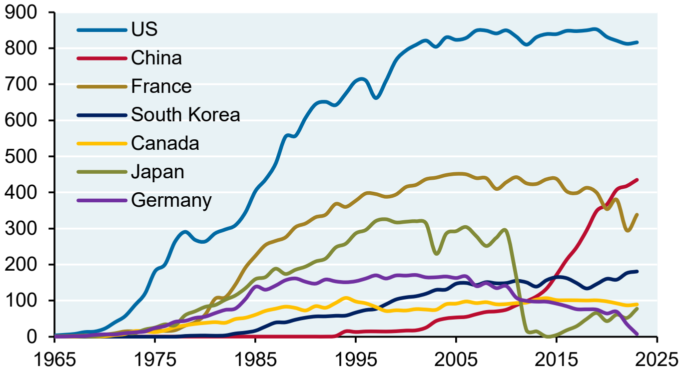
# of US nuclear plants built by year of construction start



Source: Power Reactor System Database, JPMAM, September 2024

Nuclear generation by country

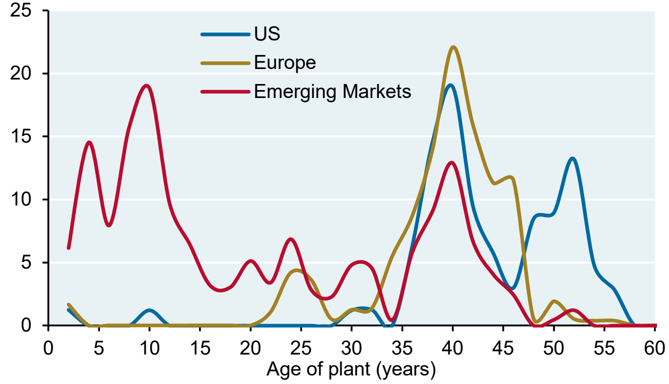
Terawatt-hours



Source: EI Statistical Review of World Energy, JPMAM, 2024

Age distribution of existing nuclear reactors

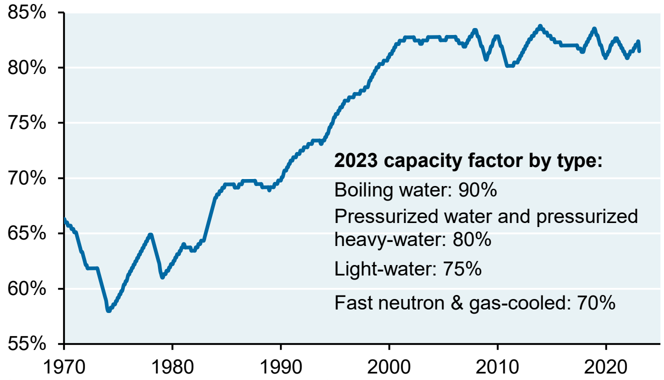
GW of capacity



Source: IAEA, JPMAM, 2024

Nuclear global average capacity factor

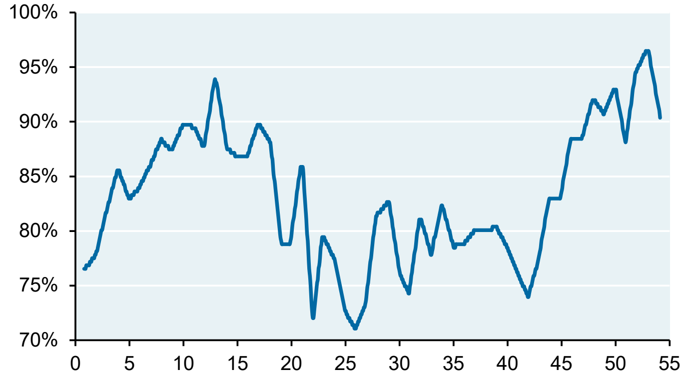
Capacity factor, percentage



Source: World Nuclear Association, October 2024

Nuclear global mean capacity factor by age of reactor

Mean capacity factor from 2019-2023, percentage



Source: World Nuclear Association, October 2024

Our grid optimization model: the cost and configuration of deeply decarbonized US grids

I've been critical of marginal levelized costs of electricity cited for wind and solar since such measures typically do not incorporate costs of backup power or energy storage. I also don't trust the rigor of back-of-the-envelope efforts by Lazard and others to estimate "grid firming costs" for wind and solar. That's said, I also see little value in computing levelized cost of wind or solar in isolation even when including necessary overbuilding and storage, since no one would build a wind/storage-only or solar/storage-only grid in the first place.

What matters most is the systemwide cost of deeply decarbonized grids. Our grid optimization model uses real-world data on hourly generation by source, demand and reserve margins for the five largest ISO regions. The goal: determine the configuration of solar, wind, gas, carbon capture and battery storage, combined with existing nuclear and hydro, that can meet demand at the lowest cost and reduce carbon intensity. For those interested in the mechanics, we describe the entire exercise in supplementary materials linked below.

The results: we estimate that systemwide levelized costs of electricity would increase by 15%-35% in today's dollars to increase the zero-carbon share of power by ~30%, with abatement costs of \$85-\$165 per metric ton of CO_2. I consider these results to be a lower bound since they exclude future increases in load due to electrification of transport and home heating, and due to increasing demand from data centers.

Grid optimization results: no contraints on new gas capacity or CCS

	Current zero carbon share of power	Future zero carbon share of power	Increase in system LCOE	Abatement cost per ton of CO_2	% increase in wind & solar capacity	Lithium ion batt % of W&S capacity	Long duration batt % of W&S capacity	Natural gas share of capacity	CCS share of total gas capacity
CAISO	41%	72%	32%	$166	182%	16%	0%	42%	8%
ERCOT	42%	73%	22%	$108	180%	5%	0%	47%	8%
MISO	31%	62%	16%	$84	214%	0%	0%	60%	6%
PJM	42%	73%	21%	$126	396%	1%	0%	58%	7%
SPP	48%	79%	18%	$100	153%	0%	5%	53%	9%

Source: JPMAM Grid Optimization Project, February 2025

A few comments:

- We assume here that natural gas and renewables displace coal on existing grids, and that there are no constraints on new CCS or gas capacity. To be clear, CCS might not be easy to build for cost/permitting/low capture rate issues mentioned elsewhere. If construction of new gas capacity or development of carbon capture were limited for political or geological reasons, systemwide levelized costs would rise further in most ISOs due to the need for more wind, solar and storage capacity (see supplementary materials)
- While natural gas utilization declines as wind/solar are added, gas still represents roughly half of installed capacity in most optimized grids, highlighting its importance in providing dispatchable power
- Long duration energy storage is most important when there are constraints on the ability to add more gas capacity or to develop CCS. Also: given logistical constraints *within* ISOs that prevent power from being easily moved, long duration energy storage can provide value in ways our model cannot capture
- Our optimized results entail significant expansion of wind and solar. However: the US grid is decarbonizing at just ~1% per year due to site permitting delays, interconnection costs, transmission & distribution bottlenecks and large queues of wind and solar already waiting to be connected. That raises substantial questions about the timing and feasibility of these optimized results

Supplementary materials: a 6-page section on the assumptions, methodology and results from our grid optimization model. Supporting exhibits include monthly capacity factors for wind, solar and hydro by ISO.

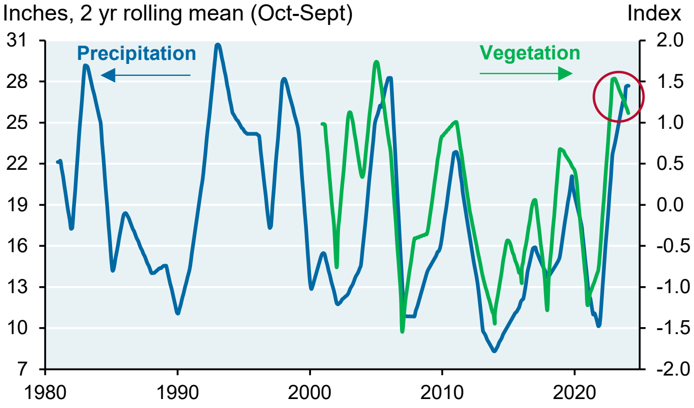
The Los Angeles Fires: climate change is not the entire story

Post-mortems on natural disasters and damage to infrastructure take time. In the wake of the 2021 Texas power outage, many people put blame primarily on wind turbine outages. Within a few weeks, it became clear this was completely wrong: the primary culprit instead was a collapse in gas-powered electricity generation, freezing of gas supply lines, electrification of gas production sites which created a critical loop problem, inadequate gas storage and prioritization of residential gas consumers over gas-fired power generation[36].

While it will take time for a full post-mortem on the LA fires, climate clearly played a major role:

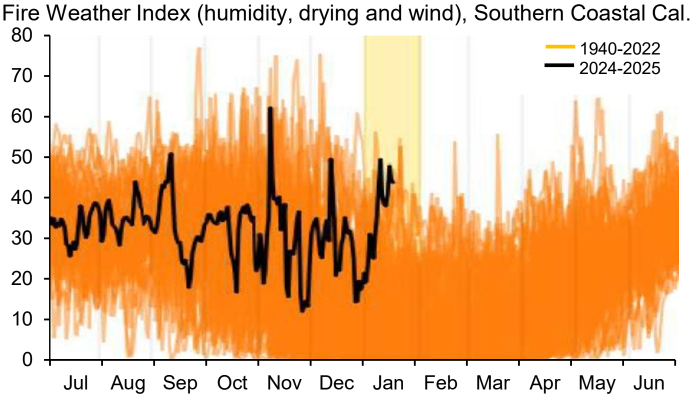
- After two wet winters which prompted a lot of plant growth (see chart below), the rain stopped. There was no more than one tenth of an inch of rain in Los Angeles after May 5, 2024, ranking the 2024 wet season which began on July 1st as the second dryest on record since 1877
- The US Drought Monitor described conditions in the area as moderate or severe drought on Jan 7, 2025, and temperatures in June-December 2024 were the third hottest on record since 1895
- Maximum hourly wind speeds on January 7th measured at LA, Van Nuys and Santa Monica airports hit the 98th percentile of measurements since their respective inceptions
- As shown in the second chart, the combination of rain, heat and wind conditions contributed to one of the highest fire risk conditions in Southern Coastal California in any January since 1940

Prior two wet winters increased flammable vegetation



Source: "Climate change a factor in unprecedented LA fires", UCLA, 2025

Climate related fire risks peaked in 2025 vs history



Source: World Weather Attribution, Imperial College of London, Jan 27, 2025

That said, I don't think climate is the beginning and end of the discussion on the degree of destruction and economic loss from the LA fires. The next two pages contain questions I have on fire policy issues in Southern California[37]. There are also a lot of other questions one could ask about California[38].

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[36] See 2021 Eye on the Market energy paper, "*Last words on the Texas power outage*", page 37

[37] Sources include:
"*How Well-Intentioned Policies Fueled LA Fires*", Atlantic, Jan 11, 2025
"*Climate change: a factor in unprecedented LA Fires*", UCLA, Jan 13, 2025
"*Realignment of federal environmental policies to recognize fire's role*", Fire Ecology, August 2024
"*How Red Tape Strangled California Forest Management Before LA Fires*", Newsweek, Jan 9, 2025
Other sources: NYT, WSJ, City Journal, ProPublica, University of Washington School of Environmental and Forest Sciences, Property and Environment Research Center, Governing.com and Congressional Budget Office

[38] When the Los Angeles Fire Department Deputy was asked in 2019 about firefighter capabilities by gender during difficult rescue situations, she replied as follows: "**Am I able to carry your husband out of a fire? He got himself in the wrong place if I have to carry him out**". Yikes. https://www.newsweek.com/lafd-deputy-chief-faces-backlash-past-remarks-fire-victims-2013351

Questions regarding the Los Angeles fires

Why are controlled burns so low in California in light of its history?

Between 4 and 12 million acres burned annually in prehistoric California. But by the year 2017, environmental restrictions reduced controlled burns in California to only 13,000 acres. The fires in 2018, 2020 and 2021 started in forests and would probably have been less severe had controlled burns been applied. There are debates among ecology research scientists on controlled burns since high winds can render firebreaks ineffective, but they have proven to be very effective on some occasions such as the 2017 Thomas Fire[39].

The National Environmental Policy Act (NEPA) review process which applies to controlled burns can take from 3 to 7 years before burning can begin. NEPA was designed to protect the environment but also creates challenging timelines for forest management; there have been several instances when areas have burned while waiting to receive the correct permit. A 2024 *Fire Ecology* study on the Clean Air Act, NEPA and Endangered Species Act concluded that beneficial fire is necessary to restore forest health and combat wildfires, but the regulatory landscape is inhibiting rather than enabling agencies and fire practitioners from doing it.

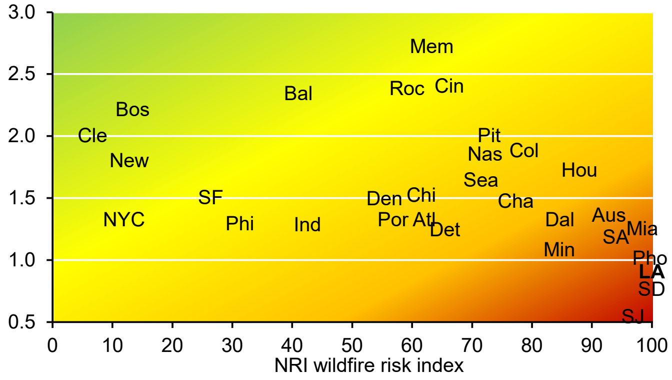
One more point: almost the entire footprint of the Palisades Fire burned acres that have burned consistently since the year 1900, and which fell inside the Very High Fire Hazard Severity Zone[40].

Why is LA firefighter staffing so low relative to other cities when LA fire risks are so high?

The charts tell the story using wildfire and wind risk data from FEMA's National Risk Index.

Firefighter staffing and fire risk

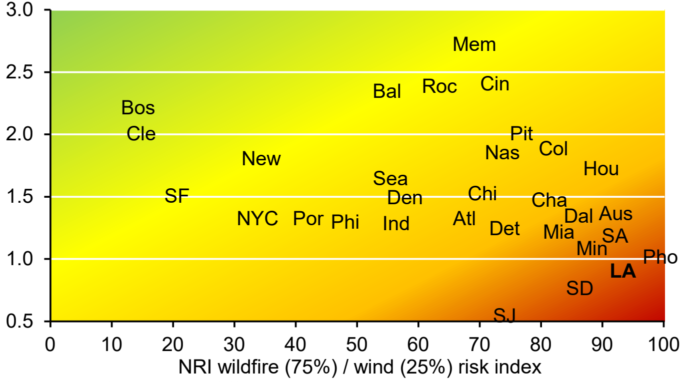
Number of firefighters per 1,000 residents



Source: Uniformed Fire Officers Association, FEMA, JPMAM, 2025

Firefighter staffing and fire/wind risk

Number of firefighters per 1,000 residents



Source: Uniformed Fire Officers Association, FEMA, JPMAM, 2025

Why are LA grid management protocols different from the rest of California?

The Los Angeles Department of Water and Power does not proactively shut down power lines during periods of high winds, unlike most other major California utilities [note: the LADWP is not regulated by the California Public Utilities Commission]. When the LADWP finally did cut power to the grid after the fires began, some areas didn't have enough backup generators in place to keep hydrant pumps working. According to water suppliers to the Western region of Altadena, the hydrant system relies on gravity; after water tanks were drained by firefighters and homeowners during the blaze, officials were unable to refill the tanks since their power had been cut.

Why has no major water reservoir been built in California since 1979?

The last major reservoir built in California was in 1979: the 2.4 million acre-foot Las Melones Reservoir located 340 miles north of LA near Modesto, which holds 782 billion gallons. While we're talking about reservoirs, why has it taken more than a year to repair the Santa Ynez reservoir which was offline at the time of the fire?

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[39] Despite extreme wind conditions and estimates of potentially hundreds of homes being consumed, only seven primary residences were destroyed by the Thomas Fire. Firefighters indicated that pre-fire mitigation activities played a central role in the outcomes (Dep't of Forest, Rangeland, and Fire Sciences, University of Idaho, 2019)

[40] From a Los Angeles fire analysis by 25 academics from UCLA, Imperial College of London, Berkeley, University of Redding, UC Merced, UC Irvine, Royal Netherlands Meteorological Institute, Vrije University of Brussels

What role did suppression of fire insurance premiums play in contributing to high density and lack of homeowner preparedness in fire prone areas?
California fire insurance premiums are artificially low due to passage of Prop 103 which subjects premium increases to public oversight. This law short-circuited market-based risk signals to homeowners to install fire-resistant roofs and siding materials, and to avoid moving into fire-prone areas. From 1990 to 2020, Californians built 1.5 million homes in the wildlife-urban interface.

Does government suppression of risk-based fire insurance premiums cause some insurers to leave California?
In California, if a property insurance company offers coverage in the state, it is required to participate in the FAIR plan. If FAIR plan policyholders have more losses than are covered by premiums and the plan's reserves (which are just $377 mm), insurers bear losses proportional to their market share. Since insurers might not recoup those losses, some insurers are less willing to make private coverage available in California[41]. From 2020 to 2022, insurance companies declined to renew 2.8 million homeowner policies in California. The FAIR bailout could cost Californians more than $1 trillion since the State Insurance Commissioner proposed that insurers can now apply a surcharge to all homeowners in California, even those not affected by the fires.

Have zoning regulations made Los Angeles less fire resistant?
While urban areas are generally more fire resistant, building in urban areas is more difficult and more expensive in California. More fire-resistant infill townhouses, apartments and shops are illegal to build in most California neighborhoods.

Why did some planned low-cost fire suppression projects never actually break ground?
Three dozen fire suppression projects (water tanks, pumping stations, water lines and links to neighboring systems) would only have cost $57 million. They were mapped out in 2013 but never broke ground.

Why did a fire risk reduction bill that passed the State Assembly and State Senate in 2020 fail to be enacted?
In 2020 a bill was proposed to require local governments to reduce building in fire-prone areas, and to introduce stricter building codes, brush management and road design standards in new homes and subdivisions that are at high risk. However, the bill was vetoed by Governor Newsom.

Given centuries of well documented fire risk in California, why are new innovative fire-resistant building standards only applied after the fact?
Paradise California, ravaged by fire in 2018, now requires homeowners to rebuild with fire-resistant materials and comply with "Wildlife Prepared Home" standards. Certification requires fire-resistant roofing and siding; non-combustible windows, decks, shutters and doors; ember-resistant metal vents and gutters; maintenance of a 5-foot vegetation perimeter around the house; and replacement of wood/vinyl fencing with metal. Annual inspections are also required.

California has some of the strongest fire codes in the US but it takes a long time for updated fire codes to affect the housing stock. There was a fire code update in 2008, but only ~5% of the structures in the area surrounding the Palisades Fire were built since that time and only 16% were built since 1990.

The bottom line: why don't firefighter staffing levels, insurance premia, grid-management policies, controlled burns, fire-resistant materials requirements and other policies reflect the long-standing fire-related risks in the Los Angeles area?

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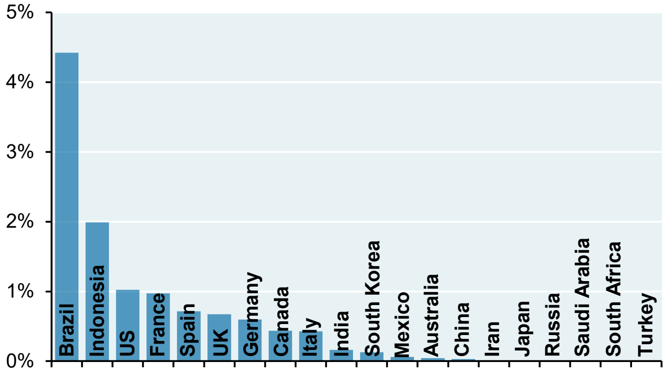
[41] In 2018, the California legislature enacted a law that prohibits insurance companies from canceling or refusing to renew a policy for one year in zip codes in or adjacent to areas where a wildfire state of emergency has been declared. But after moratoriums end, the number of non-renewals usually increases in affected areas

Renewable jet fuel: costs, constraints and chemical reactions

There are several ways to create biofuels: fermenting sugars in plants, anaerobic digestion of organic materials and transformation of animal fats and vegetable oils. Some biofuels are blended with existing fossil fuels; some are "drop-in" fuels which are directly used in existing engines; and some like green methanol require changes to existing engines. The challenge: most biofuel pathways are expensive, constrained by raw material supply or both. That's why other than in Brazil and Indonesia, biofuels represent less than 1% of final energy consumption.

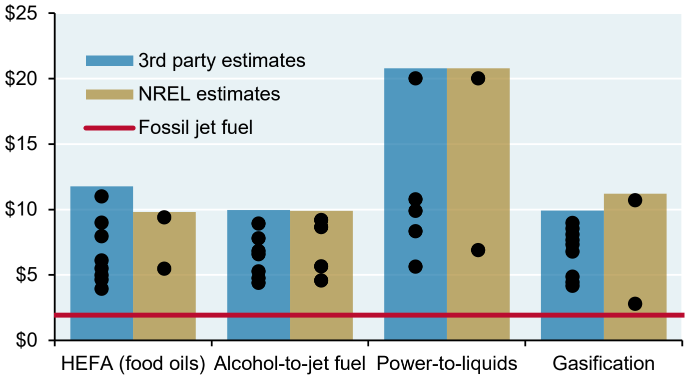
As one example, the chart on the right shows estimated costs for four types of **renewable jet fuel**. All estimates substantially exceed existing jet fuel costs, which is why sustainable aviation fuel was just 0.3% of global jet fuel consumption in 2024. High costs are affecting non-binding green fuel commitments by commercial airlines. In July 2024, Air New Zealand became the first major airline to abandon its 2030 goal to cut emissions, citing the lack of affordable sustainable jet fuel. Producing green jet fuel is a higher order challenge since it requires a specific range of molecules with only trace amounts of oxygen to work in existing plane engines, as opposed to gasoline or diesel truck/car engines which can handle oxygen-containing molecules.

Biofuels as a share of final energy consumption
Percent



Source: EI Statistical Review of World Energy, JPMAM, 2024

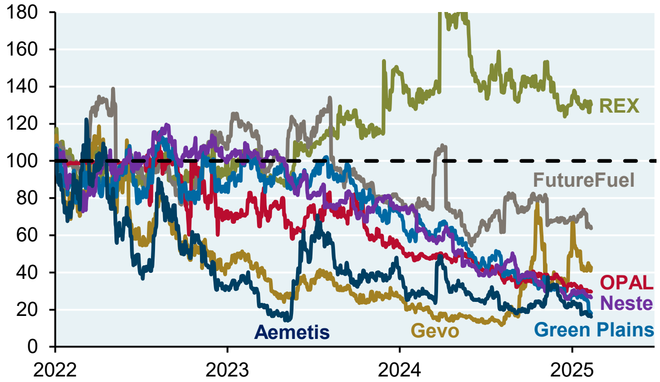
Renewable jet fuel cost estimates
US$ per gallon



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

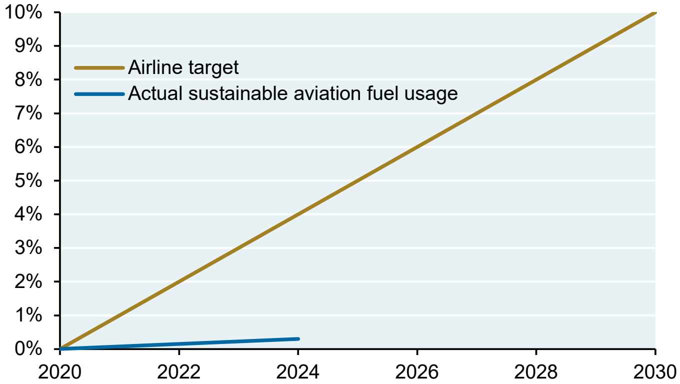
Additional evidence of the biofuel challenge can be seen in the poor performance of related company stock prices. Separately, Chevron, BP and Shell are scaling back projects to make biofuels from cooking fats, oils, greases and plant material. Fulcrum BioEnergy, a start-up backed by United Airlines to convert trash into jet fuel, has filed for Chapter 11 bankruptcy protection.

Biofuel company returns
Index (100 = 1/1/2022)



Source: Bloomberg, JPMAM, February 12, 2025

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



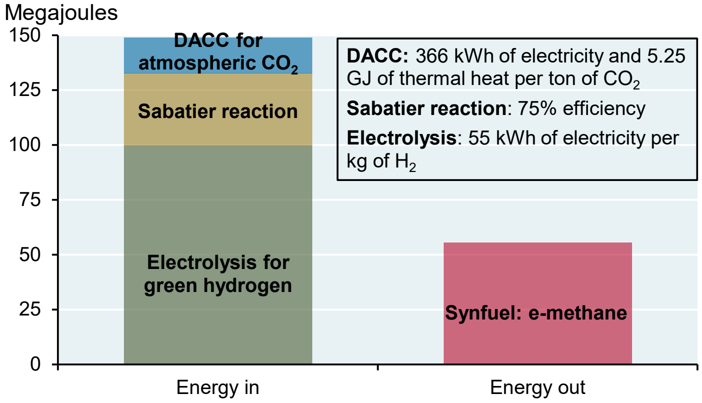
Source: International Air Transport Association, Bloomberg, February 2025

There are also debates about real-world emissions impacts of increased biofuel production. Some scientists and international regulatory bodies have concluded that growing crops to make aviation fuel does not reduce emissions on a full lifecycle basis[42]. The reason: biofuel crops often displace food crops, which drives the expansion of cropland into forests and grasslands to compensate for lost food production. Converting forest or grassland to cropland releases stored carbon and reduces carbon sequestration on that land in the future.

That's one reason why synthetic fuels have garnered interest: they don't have the same raw material supply, cropland displacement or upstream emissions issues of green biofuels. What they do frequently have however, is a large negative energy balance to overcome. As an example of a synthetic fuel, consider the process illustrated below. Synthetic methane (e-methane) can be produced by combining (i) CO_2 captured via direct air carbon capture with (ii) green hydrogen produced via electrolysis. So far, so good; this synthetic fuel could be used in applications such as heating, transportation and electricity generation. But…to produce 50 MJ of synthetic methane, you actually need 150 MJ of energy to start with. That's a very expensive loss of energy, and that's *before* including the capital cost of the equipment required to carry out the reaction itself.

In some theoretical world, the economic value of synthetic fuels could be high enough to offset the cost of the associated energy deficit. **But any effort to re-assemble CO_2 molecules into fuels will have to overcome a steep energy deficit of some kind due to the low thermodynamic potential and heating value of CO_2**, which is illustrated in the table. There are many synthetic fuel approaches being funded and tested. If any are successfully commercialized, I will enthusiastically report on them here. Until then, caveat emptor…and before you invest, try to understand the sustainable aviation fuel pathways explained on the following page.

Production of 1 kg of e-methane via Sabatier reaction



DACC: 366 kWh of electricity and 5.25 GJ of thermal heat per ton of CO_2
Sabatier reaction: 75% efficiency
Electrolysis: 55 kWh of electricity per kg of H_2

Source: Spitfire Research, Keith et al (DACC), JPMAM, 2024

Thermodynamic/heat potential of select molecules
CO_2 ranks at the bottom

	Molecule	Gibbs free energy (kJ per mole)	Heating value (kJ per mole)	Heating value (MJ per kg)
N_2	Nitrogen	0	0	0
NH_3	Ammonia	-17	383	23
H_2O	Water	-228	0	0
CH_4	Methane	-51	890	56
H_2	Hydrogen	0	286	142
CO_2	**Carbon Dioxide**	**-394**	**0**	**0**
CO	Carbon Monoxide	-137	283	10
O_2	Oxygen	0	572	0
C_2H_6	Ethane	-33	1560	52
CH_3OH	Methanol	-159	726	23
C_8H_{18}	Octane	17	5074	44
$C_{10}H_{22}$	Decane	34	6294	44
C_3H_8	Propane	-24	2044	46

Source: Peter Edwards (Oxford, 2010), Engineering Toolbox

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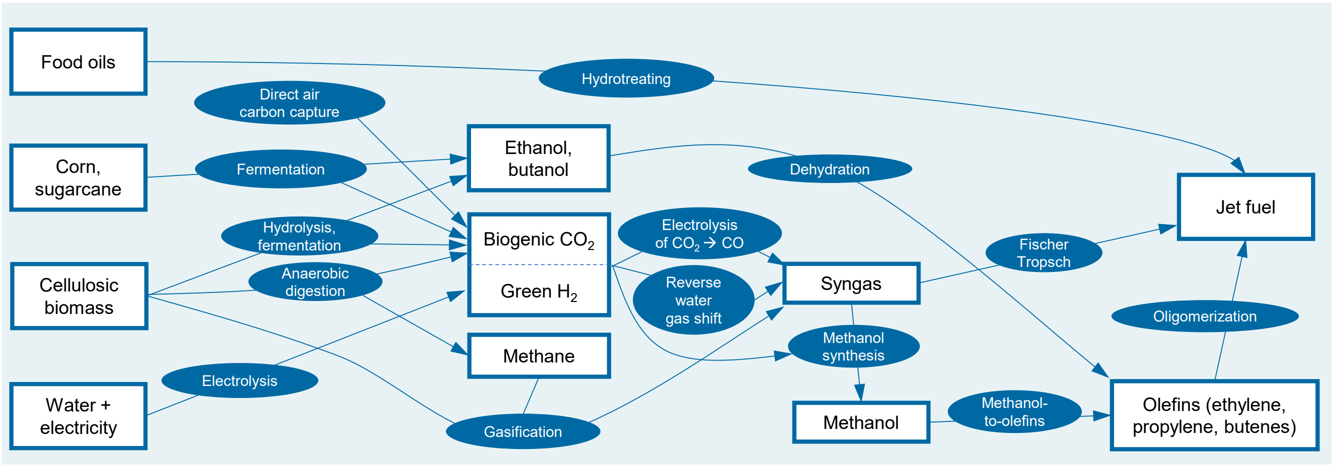
[42] Examples: reports from the International Council on Clean Transport, the International Civil Aviation Association and the Union for Concerned Scientists

Extra credit: understanding sustainable aviation fuel pathways

We show below the pathways most often attempted by green aviation fuel start-ups and those analyzed in industry literature. **These pathways all work fine in the lab; the questions revolve around their real-world energy deficits, all-in costs and technological readiness at scale**.

Sustainable jet fuel pathways



Source: Spitfire Research, JPMAM, 2025

Hydrotreating of food oils ("HEFA"). Hydrotreating and refining of triglyceride feedstocks like palm oil, soybean oil and used cooking oil is the most mature pathway, currently deployed at commercial scale. **Major challenge**: costs could skyrocket if utilization rises due to limited feedstock supply.

Alcohol-to-jet fuel. After fermentation of feedstocks like corn and sugarcane (or hydrolyzed and fermented cellulosic biomass), ethanol and isobutanol are converted into jet fuel via dehydration to create olefins, after which the olefins are transformed into jet fuel. **Major challenge**: feedstock costs and complexity.

Syngas conversion to jet fuel via Fischer Tropsch process, using power-to-liquid hydrogen feedstocks. The process begins with a combination of biogenically sourced CO_2 (see below) and green hydrogen created via electrolysis. These two gases are converted to syngas (which is a mixture of carbon monoxide and hydrogen) using a "reverse water gas shift" process that requires the addition of heat, or a solid oxide electrolyzer to convert CO_2 into CO. The syngas is then converted into jet fuel via the Fischer Tropsch process. **Major challenges**: this is thermodynamics in reverse, since you start with the byproducts of combustion (CO_2 and water) and add energy to make fuel. Also: the energy-intensive Fischer Tropsch process does not just create jet fuel but also results in lower-value biogenic byproducts that are either too light (methane, ethane, propane, naphtha) or too heavy (waxes) to be used as jet fuel. As a result, to create more jet fuel from the reaction, additional energy and equipment would be needed to either hydrocrack the heavy waxes or recycle the light byproducts which can be as much as 50% of the FT output.

Sources of biogenic CO_2 could include captured CO_2 byproducts from (a) corn fermentation, (b) fermentation of biomass such as woody pulp, agricultural residue and municipal waste, or (c) anaerobic digestion of biomass; or CO_2 from very expensive direct air carbon capture plants (CO_2 is only 0.04% of the earth's atmosphere).

Syngas conversion into jet fuel via methanol synthesis. The syngas created in the prior approach could be converted into methanol via methanol synthesis, followed by an intermediate conversion into olefins before becoming jet fuel. The reverse water gas shift and electrolysis steps could also be skipped by applying methanol synthesis directly to green hydrogen and biogenic CO_2, but a substantial heat penalty would be incurred. **Major challenge**: numerous steps, each with losses and capital costs.

Gasification of biomass/methane to create syngas. An alternative approach for creating syngas that does not require biogenic CO_2 and green hydrogen involves direct gasification of biomass, or methane created via anaerobic digestion of biomass. Gasification is also referred to as pyrolysis, which is the burning of biomass in an oxygen deficient environment. **Major challenge**: equipment costs and complexity, transport of low energy-intensity feedstock.

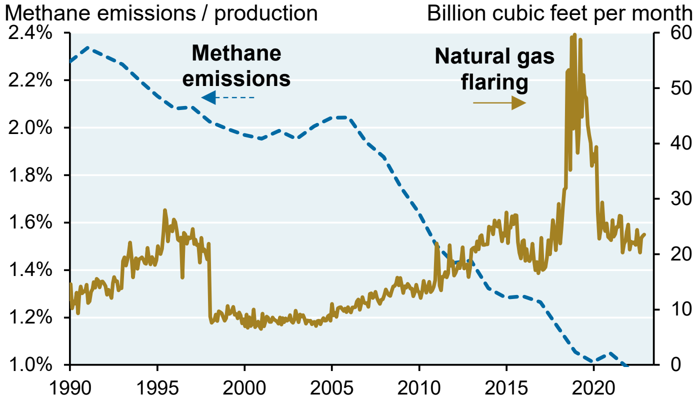
Space Mountain: tracking methane accumulation from US gas basins via satellites

Cornell's Robert Howarth started a firestorm with a paper asserting that US LNG exports shipped via steam turbine tankers have a higher GHG footprint than coal[43]. Around half of Howarth's estimated LNG emissions are due to assumed fugitive methane emissions. A Breakthrough Institute rebuttal[44] asserted that Howarth made a unit conversion error when calculating CO_2 per kilogram of LNG (although the impact would only reduce the result by 8%); that Howarth's assumed leakage rate of 0.32% for gas delivered to local distribution systems was too high; that the amount of tanker inventory required for the return trip was double the proper figure; and that Howarth over-attributes methane emissions to gas and under-attributes to oil and NGLs.

While Breakthrough's rebuttal may make good points, it's not worth sorting out the details since it's clear that methane venting and leakage needs to be addressed[45]. Over the last few years, empirically observed methane measurements[46] have exceeded the ~1% methane leakage figures reported to the EPA and which are shown on the left. Potential fixes include more on-site gas gathering rather than flaring; requiring that vents on atmospheric pressure tanks be connected to flares; electrification of pneumatic gas venting pumps and controllers; more frequent leak detection/quicker remediation; and more capture of biogenic methane emissions from food waste in landfills, which could then be used for electricity generation.

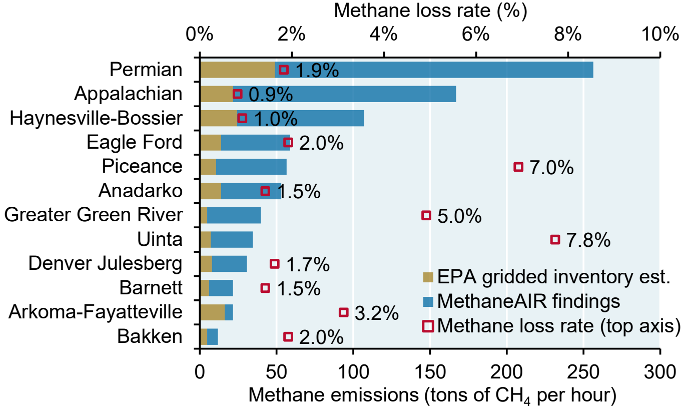
A new era of methane measurement has arrived with MethaneAIR and MethaneSAT, high-frequency and high-accuracy aerial and satellite-based measurements. As shown on the right, MethaneAIR detected methane emissions flows from the largest US basins in 2023 that were consistently 4x-5x greater than the gridded inventory estimates published by the EPA in 2020[47]. MethaneAIR's analysis covered 70% of US onshore gas production. As for estimated methane loss rates, MethaneAIR's results by basin were usually higher than the EPA 1% national average. By the end of 2025, MethaneSAT data will be made widely available as well.

Methane emissions and natural gas flaring



Source: EPA, EIA, JPMAM, 2024

Major US basin methane emissions and intensity



Source: MethaneSAT, JPMAM, 2024

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[43] *"The greenhouse gas footprint of LNG exported from the US"*, Robert Howarth (Cornell), 2024

[44] *"Major Paper on Liquified Natural Gas Emissions Is Riddled with Errors"*, Breakthrough Institute, July 2024

[45] **"It is difficult to get a man to understand something when his salary depends on his not understanding it"** [Upton Sinclair]. Twice in the last few years, a specific individual in the legal department of one of the largest public company operators in the Marcellus Shale contacted me to complain about references to methane studies in my energy paper. I won't go into detail but he was highly unprofessional and confrontational about it, which was a reflection of his inability to accept basic facts.

[46] Examples: Zavala-Araiza (2015), Alvarez (2018), Zhang (2020), Barkley (2021), Rutherford (2021), Plant (2022), IEA (2022), Chen (2022) and Hmiel (2023)

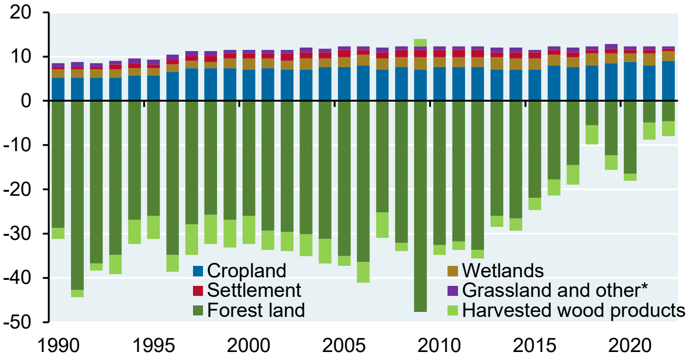
[47] As a reminder, EPA methane emissions data are self-reported by the oil & gas industry and are almost always estimated based on a number of assumed production factors, rather than being empirically obtained through field measurements. The 150+ participants in OGMP 2.0 (the Oil & Gas Methane Partnership) have pledged to converge to higher-quality empirical measurements over time.

On a related GHG topic, something strange is happening in Finland. As shown below, Finland's land sink which absorbs CO_2 from the atmosphere has been shrinking. Reasons reportedly include[48]:

- Aggressive logging and unsustainable forestry management practices. However, Finland's finance ministry estimates that decreasing forest harvesting by 1/3 would reduce GDP by ~2%. Even if Finland's gov't were willing to limit harvesting, the state has limited control owning only 35% of all forests
- Higher temperatures and more frequent droughts increase the rate at which trees die
- Tree-damaging species like invasive beetles and moths thrive in warmer temperatures
- Burning of peatland (decayed plant material) for energy, which can be more GHG-emissive than coal depending on the timeframe and equipment used

Emissions from land use in Finland

Million tons of CO_2 equivalent



Source: Natural Resources Institute Finland, October 2024. *Includes indirect nitrous oxide emissions

In other words, if carbon sinks elsewhere erode like they are in Finland, it would further increase the importance of reducing fugitive methane emissions, *whatever* their levels happen to be. **The good news is that there are an increasing number of companies developing methane detection tools, as shown in the table**. This in turn could enable large AI hyperscalers to ensure lower methane-intensity of the gas that powers their data centers.

Select methane emissions monitoring companies

Type of monitoring technology	Select companies	Company descriptions
Satellite operators	MethaneSAT	Designed and built by EDF, Harvard and Ball Aerospace to publicly disclose global, high-res coverage of methane emissions from oil and gas facilities. Measures regions at intervals under seven days, regularly monitoring ~50 major regions accounting for +80% of global oil and gas production
	GHGSat	Developed first sensor for small satellites that can detect methane emissions and locate individual sources of methane from around 500km above the earth. 6 satellites in orbit and 6 more being developed. Detected 143 $MTCO_2E$ of methane emissions in 2021
Satellite data analytics	Orbio Earth	Uses satellite images captured every 4 days to identify methane leaks at any site on earth; reconciles data with other emission factor datasets to provide accurate benchmarks. Able to capture high spatial resolutions, which allows Orbio to attribute emissions to specific assets as opposed to regions
	Kayrros	Models public satellite data to monitor and measure methane emissions. 'Carbon Watch' product provides a daily assessment of methane at the asset level
Aerial	Bridger Photonics	Leverages LiDAR (Light Detection and Ranging), for aerial methane leak detection; core LiDAR sensors are mounted on small aircrafts and transmit continuous wave lasers at a frequency that is known to be absorbed by methane; catches 9/10 leaks. Clients: Exxon, Chevron, Cheniere, SoCalGas; have around 100 clients at the moment, mostly in the oil and gas sector
	InsightM	Uses spectrometers, mounted on small planes, which measure the absorption of reflected sunlight by methane molecules; cover up to 100 square miles per plane per day. High detection limits mean small leaks are often missed, but a good solution for super-emitters; backed by Blackrock
	SeekOps	Founded by NASA Jet Propulsion Lab alums to detect and measure methane leaks using autonomous drones. Can inspect a well-pad in 15 minutes, a third the time of many competitors, but known as a higher cost provider
Ground-based (including continuous/ stationary)	Teledyne Flir	Detects hydrocarbon and volatile organic compound (VOC) emissions from natural gas production and use. Embedded GPS data helps in identifying the precise location of faults and leaks, for faster repairs
	Longpath	Obtained a $162mm DOE loan to build over 1,000 emissions monitoring towers across all key US oil and gas production regions. These towers will monitor 24,000 square miles and are estimated to prevent emissions equivalent to 1.3mm cars
	Qube	Point-based metal oxide sensors, which are low cost, accurate and reliable; business model is to offer the most cost-effective measurement option; Clients: ConocoPhillips, Oxy, Devon, Chesapeake, EQT

Source: J.P. Morgan Global Corporate Advisory - Sustainable Solutions Team, October 2024

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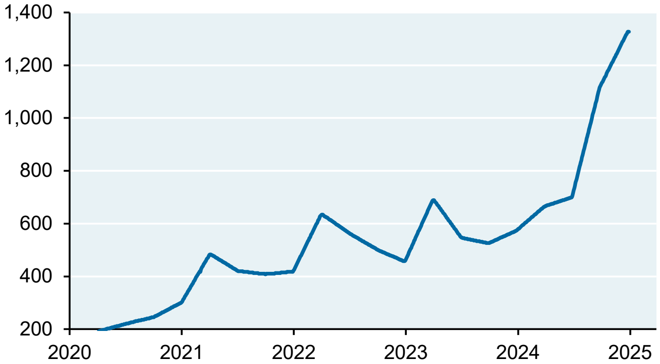
[48] "*What happens to the world if forests stop absorbing carbon? Ask Finland*", Guardian, October 2024

Frydrogen: the cancellation of green hydrogen projects when exposed to the sunlight of energy math

I started referring to green hydrogen as "whydrogen" in 2022 since many claimed pathways for green hydrogen production, transmission and consumption have large cost and logistical problems. Here we are three years later, and many hydrogen projects are being fried (terminated) since the energy math didn't work.

Quarterly mentions of hydrogen project delays or cancellations in news or company disclosures



Source: Sustainable Market Strategies, Q4 2024

Hydrogen and electric mining trucks

At our Sustainability Summit last year, Fortescue presented plans for a green hydrogen ecosystem. According to public sources, the company has now shelved or delayed certain green hydrogen projects in Northern Australia (Darwin), Eastern Australia (Gibson Island), Tasmania and Canada (British Columbia) and ended its partnership with Plug Power.

Fortescue announced partnerships with Liebherr which produces 200-ton diesel-electric mining trucks that connect to overhead pantograph lines (with diesel used on either end of the journey), and which reportedly reduce emissions by 29%-54% vs diesel only; and all-electric versions with 3200 kWh batteries charged with a 6 MW charger, and which reportedly charge in just 30 minutes. See box below for sources

My favorite quote on the subject comes from Hanns Neubert in the June 2024 German MIT Technology Review:

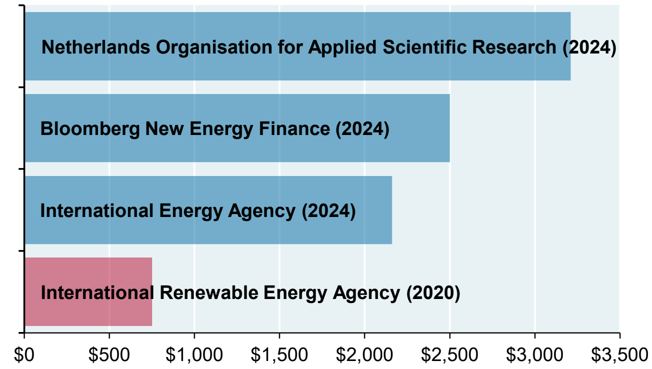
> "Electrolyzers, which do not exist, are supposed to use surplus electricity, which does not exist, to feed hydrogen into a network that does not exist in order to operate power plants that do not exist. Alternatively, the hydrogen is to be transported via ships and harbors, which do not exist, from supplier countries, which - you guessed it - also do not exist"

This exaggerates how barren the green hydrogen landscape is; there are *some* green hydrogen gigaprojects projects under development with offtake agreements and government support, such as Neom in Saudi Arabia and Kakinada in India. That said, it's not far off. Here are some hydrogen facts and figures to keep in mind[49].

Misunderstanding of electrolyzer costs

Hydrogen has an "original sin" problem: early estimates of electrolyer costs were too low. It started with an influential IRENA paper in 2020 estimating electrolyzer costs at $750 per kW. The European Energy Transitions Commission now concedes that costs are far higher, at least when sourced from Western manufacturers; the latest estimates for 2024 range from $2,100 to $3,200 per kW. This revised assessment had led to a 5x increase in Western 2030 electrolyzer cost projections from BNEF and the Hydrogen Council relative to initial projections.

Electrolyzer system costs
US$/kW



Source: Visa Siekkinen (Seinäjoki University), JPMAM, 2024

Fortescue sources: on hydrogen and electric mining trucks

Capital Brief (Sep 7 2024, Nov 25 2024)
Hydrogen Insight (Jul 11 2024, Oct 18 2024, Nov 12 2024)
The Australian (Mar 5, 2025)
Stone World (Dec 8 2024)
Leibherr specs for T264 mining truck, pages 12-13

According to company spokespeople, Fortescue remains committed to building out a green hydrogen ecosystem although its timelines have changed

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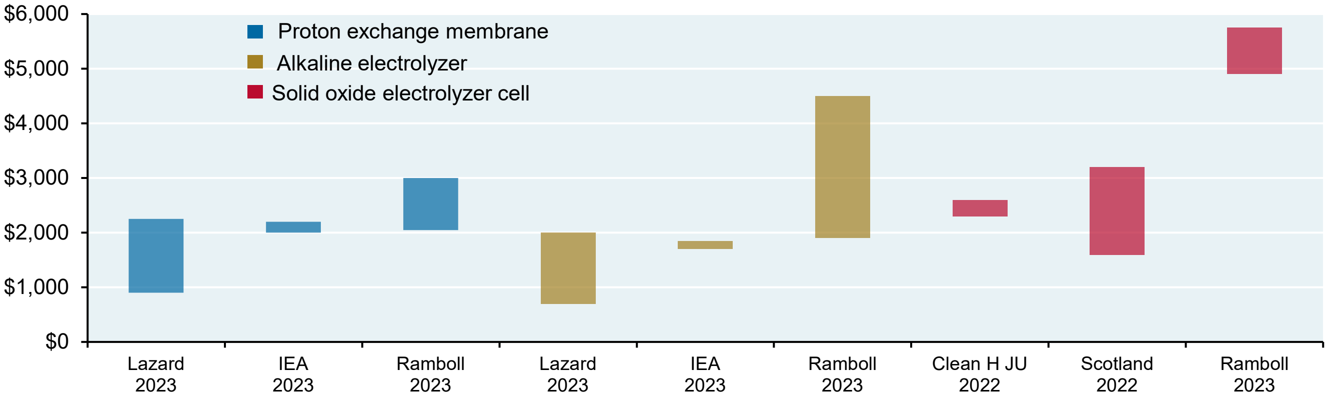
[49] Sources include the BNEF H1 2024 Hydrogen Update; BNEF 2025 Hydrogen Levelized Cost Report; a June 2024 lecture by Michael Liebrich at Imperial Energy Futures Lab; "*Green Hydrogen: A Multibillion-Dollar Energy Boondoggle*" by the Manhattan Institute, Feb 2024; and our research from prior energy papers

Scale and subsidies have resulted in lower pressurized alkaline electrolyzer costs in China, while Chinese PEM electrolyzers are priced similarly to European models[50]. In Europe, projects cannot qualify for green hydrogen subsidies if Chinese electrolyzers make up more than 25% of the total stack. There's still plenty of uncertainty regarding what electrolyzer costs actually are, as shown below.

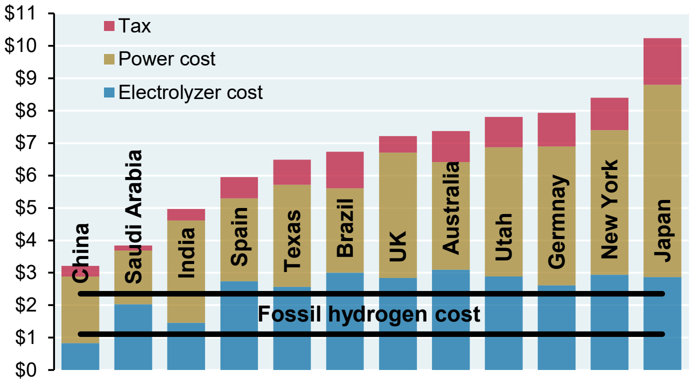
Electrolyzer costs by type
US$ per kW



Source: "Achieving affordable green hydrogen production plants", Ramboll, JPMAM, November 2023

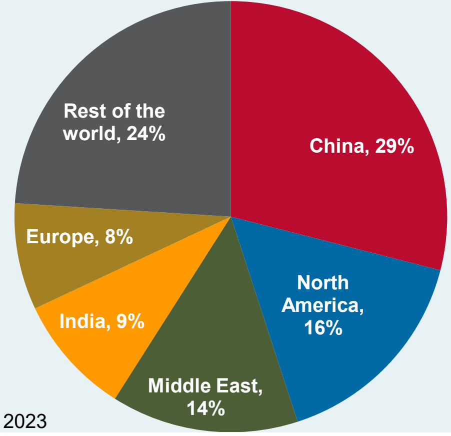
All-in green hydrogen costs in most countries are not competitive with brown (fossil fuel) hydrogen. China is the exception, and also the largest consumer of hydrogen for ammonia production and fuel refining

Levelized cost of green hydrogen, 2025
$ per kg, assuming optimal electrolyzer utilization rate



Source: BNEF 2025 Hydrogen Levelized Cost Report

Hydrogen use by region



Source: IEA, 2023

Bad energy math

- More energy is required to manufacture hydrogen than that hydrogen itself contains[51]
- The so-called "wind-to-wheel efficiency" of converting MWh of wind into electricity and then powering a BEV is 80%, compared to 30% for fuel cell vehicles
- When used for residential heating, electric heat pumps are 4x-5x more efficient than combusting green hydrogen in residential boilers

Lack of hydrogen demand

- Only 12% of green hydrogen projects scheduled for completion by 2030 have identified offtake agreements, and only 5% of projects scheduled for completion by 2030 have reached the final investment decision stage
- It gets worse: of the projects that have offtake agreements, only 11% of that amount represents **binding** contracts. So…just 1% of all projected green hydrogen production has a binding offtake agreement

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[50] "*Cost of electrolysers for green hydrogen production is rising instead of falling*", BNEF, March 4, 2024

[51] https://www.eia.gov/energyexplained/hydrogen/

- Only Korea and the EU have explicit hydrogen consumption quotas, and I suspect that the EU will not end up sticking to its 2030 targets

Overinvestment in electrolyzers

- Electrolyzer manufacturers are expanding capacity much faster than demand. BNEF estimates that by the end of 2024, there could be over 50 GW of assembly capacity vs just 4.4 GW of electrolyzer demand

Transportation and leakage problems

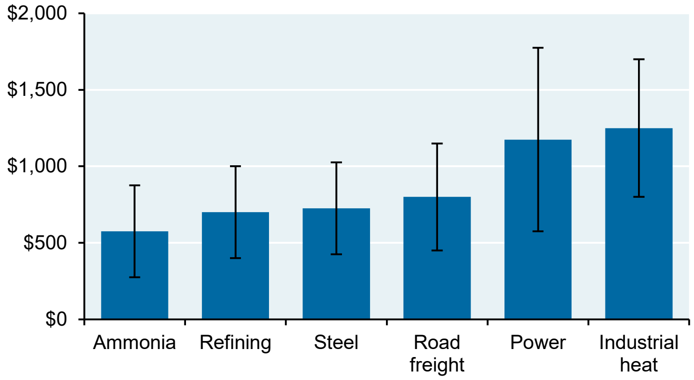
- Less than 1% of announced hydrogen pipeline capacity has reached the final investment decision stage
- Transporting hydrogen as ammonia is energetically costly with a round trip electricity-to-electricity efficiency of 20%-25% due to energy conversions and losses
- Dutch scientists found a ~4% leakage rate when assessing hydrogen emissions across the industrial hydrogen value chain[52]. Why this is important: hydrogen's estimated GHG impact is 13x-40x higher than CO_2, depending on the timeframe used

Absurdly high subsidies and carbon abatement costs

- The green hydrogen economy barely exists despite mountains of taxpayer subsidies promoting supply. In the US, for example: a production tax credit of $3 per kg is equivalent to $91 per MWh based on the energy content of hydrogen (i.e., greater than wholesale electricity prices which averaged between $30 and $50 per MWh in 2024) and also implies a carbon abatement cost of $375 per tonne (!!)
- A Harvard study[53] found that green hydrogen entails carbon abatement costs of $500 to $1,250 per ton of CO_2, in some cases exceeding the cost of direct air carbon capture

Carbon abatement cost of green hydrogen by sector

US$ per ton of CO_2



Source: Shafiee and Schrag (Harvard), Joule, 2024

The bottom line on green hydrogen

Green direct electrification of transport, heating and industrial production is usually much cheaper than green hydrogen for the same uses. As a result, green hydrogen may only be a useful decarbonization strategy if a) it's made where electricity is 100% green and inexpensive, b) green electricity is not needed to displace coal and (c) green hydrogen replaces brown hydrogen. This might be true in Western Australia, Namibia and Chile but these conditions generally don't apply in the US, Europe or other large countries.

What about blue hydrogen (natural gas reformation combined with carbon sequestration)?

Wood MacKenzie estimates that at least three US blue hydrogen projects will reach Final Investment Decision stages in 2025, amounting to 1.5+ Mtpa of production. If completed, the US would be the world leader in blue hydrogen. Blue hydrogen plants generally remove only 50%–60% of the overall plant-wide CO_2 emissions produced. The reason: most blue hydrogen plants only capture CO_2 from syngas which is more pressurized/ concentrated and cheaper to capture, and not from more diffuse CO_2 emitted by natural gas combustion (which would include flue gas from the reformer furnace, from gas combustion used in the gas purification train and from any heat/electricity used to run the CCS equipment).

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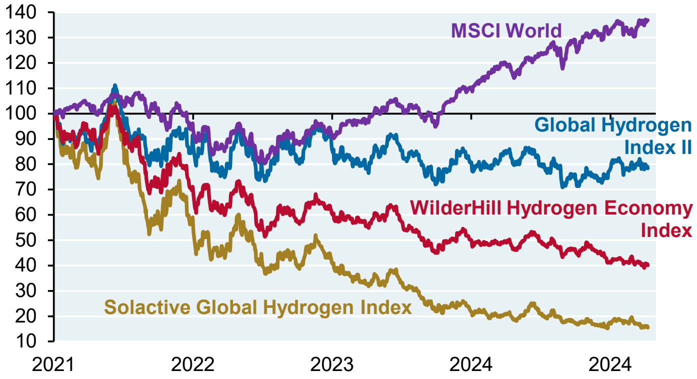
[52] "*First detection of industrial hydrogen emissions using high precision mobile measurements in ambient air*", Westra et al, Nature Portfolio, 2024

[53] "*Carbon abatement costs of green hydrogen across end-use sectors*", Roxana Shafiee (Harvard Center for the Environment) and Daniel Schrag (Harvard Dep't of Earth Sciences), *Joule*, December 2024

As for investors in hydrogen companies, they have been completely fried as well.

Hydrogen indices total return
Index (100 = June 2021)



Source: Bloomberg, JPMAM, February 11, 2025

Notable hydrogen casualties

Hydrogen project restructuring: Better Energy, Shell, BP, Air Products, Orsted, Accelera, Thysenkrupp, Green Hydrogen Systems, Syzygy Plasmonics, Airbus ZEROe, Plug Power, Ballard, Nikola

Insolvency: HH2E, Fusion Fuel, Universal Hydrogen, Hyzon, First Mode, Hyvia, Quantrun, TECO 2030

Source: Umagine/H2C0

What about alternatives to electrolysis for green hydrogen production? They exist, but they each have their own challenges and are heavily dependent on subsidies. Most technologies are still in the development stage.

Companies	Description	Byproducts	Challenges
Monolith, Hazer, CZero, Modern Hydrogen, Ekona, Hydrogen Utopia	Methane pyrolysis/ splitting	Carbon-rich products (e.g. graphite, acetylene)	These companies see hydrogen as a valuable byproduct of making a carbon-rich product, but many of these companies have not demonstrated that they make carbon products of great value. Without value from the carbon, they are throwing away 3/4 of the mass and 1/2 the energy of their methane feedstock, requiring the hydrogen alone to finance it. Even if it were feasible, graphite and carbon black demand is ~18 million tonnes per year which would be accompanied by 4.5 million tonnes of hydrogen per year, less than 5% of world current hydrogen demand
Starfire	Green ammonia decomposition	Nitrogen	Cracking ammonia into hydrogen is not difficult technically, but is energetically wasteful: heat is released to make ammonia earlier in the food chain; therefore heat must be added back to decompose ammonia back into its hydrogen and other components. Moreover, green ammonia is rare since 99% of hydrogen is still made from fossil fuels without carbon capture. Also: all residual ammonia traces must be removed from any hydrogen used for fuel cells
SGH2, Plagazi, Mote, Waste2H2	Gasification/ reformation of waste	Biogenic CO_2	Gasification of waste biomass is a good source of syngas from which to make things like transportable liquid methanol. Making pure hydrogen gas from it actually reduces its value and usefulness, although it still might be cheaper than green hydrogen from electrolysis. Also: most of the energy produced by combusted municipal waste originates from fossil origin materials (plastics and other synthetic materials which would have remained inert in the landfill) rather than the organic materials
GTI	Sorption-enhanced reforming of methane	Carbon dioxide (mostly captured by the sorbent)	Processes involving "sorption enhanced reforming" of methane have been worked on for decades. They might be of use to "blue" hydrogen production, but past schemes have failed due to problems with the limited cycle life of the sorbent (the material that absorbs the carbon dioxide emissions which are produced by the reaction)
QD-SOL	Sunlight nanoparticles	Oxygen	Photochemical water splitting has been worked on since the 1970s. Such complex schemes suffer from the poor energy density of the hydrogen, the cost of keeping the apparatus sealed against hydrogen diffusion outward and oxygen diffusion inward and degradation of the photocatalysts by UV. It is doubtful that it makes sense to replace PV, which continues to get more efficient and cheaper and which produces a product which is easy to move, just to avoid doing electrolysis

Source: Spitfire Research, JPMAM, 2024

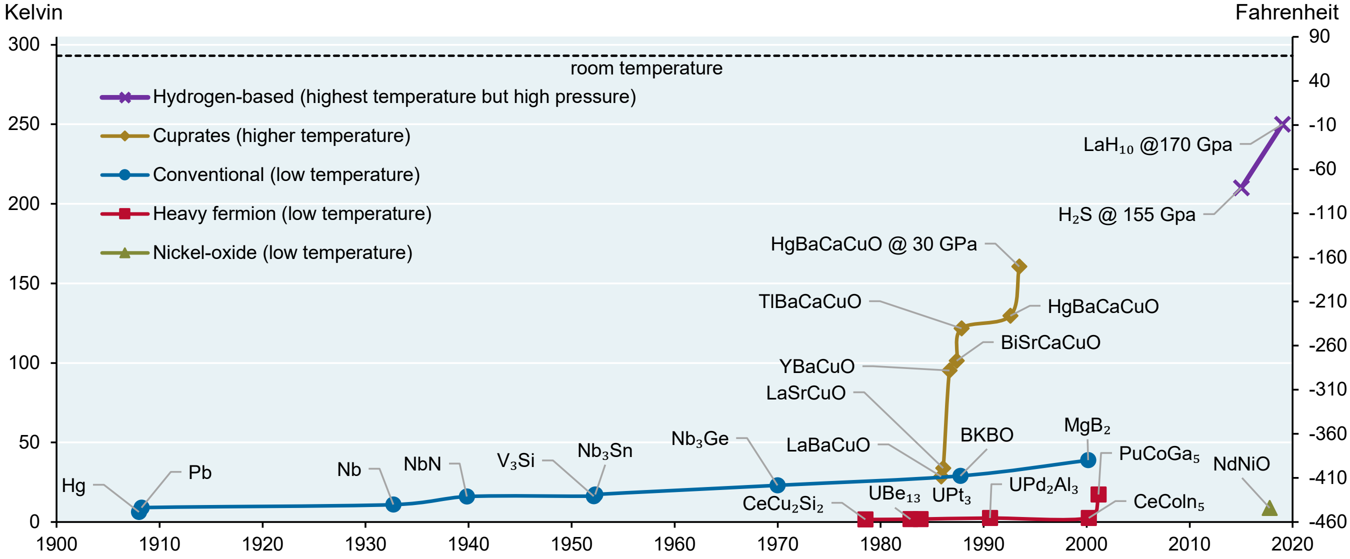
The superconductivity scandal at *Nature*: another one bites the dust

Whether it's nuclear fusion, carbon mineralization, geoengineering or other drawing board ideas, I generally don't write about them until they are commercialized. The reason: some ideas never make it out of the lab despite breakthroughs breathlessly reported by green tech media sites. Case in point: the superconductivity scandal at *Nature*, one of the most respected scientific journals. First, some background…

Superconducting cables experience little to no losses due to lack of electrical resistance. As a result, if such materials could be created in bulk at a reasonable cost with manageable physical properties, they could in theory more efficiently transmit power on high-capacity networks. For that reason, superconductors are sometimes mentioned as possible contributors in a world with greater green electrification of energy consumption[54].

Superconducting materials have existed for over 100 years but for most of that time, they only operated at extremely low temperatures such as -360°F rather than anywhere close to room temperature. The chart is a simplified depiction of superconductor materials advances over time, followed by category explanations.

The 120 year search for room temperature, ambient pressure superconductors



Source: University of Copenhagen, Brad Ramshaw (Cornell University), JPMAM, 2024

- **Conventional** superconductors are the most well understood but require *very* low temperatures. As a result, their use has generally been confined to cases where higher temperatures are less important since the superconducting components are very small parts of the overall project scope (e.g. quantum computing and research telescopes), or to cases where the benefits of having a superconductor outweigh the cost of cooling them such as magnetic resonance imaging (MRI). Totally impractical for bulk electricity transmission
- **Heavy fermion superconductors**, whose electrons are 100 times heavier than regular electrons, are less well understood but have been widely studied since the 1980's due of the belief that there could be a "topological" superconductor which would facilitate the creation of "fault-tolerant" quantum computers (i.e. quantum computers with such a low error-rate that they are able to continue with a given computation even after an error and still arrive at a correct answer). However, like conventional superconductors, their low temperatures are completely ill-suited for electricity transmission
- **High temperature cuprates** are at the forefront of superconductor research since they can function at temperatures as high as -**160°F** at ambient pressure. They can be cooled with liquid nitrogen at a cost of ~$0.60 per liter as opposed to liquid helium which cools most other superconductors at a cost of ~$20 per liter. Commercialization efforts have been held back by technical challenges unrelated to temperature such as difficulty in processing these materials into usable shapes. Cuprates have potential for applications in fusion reactors, levitating maglev trains and for the military/NASA but not the electricity grid

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[54] Two examples: "*What's so super about superconductivity*", World Economic Forum, October 2023, and "*Superconducting Cables for Europe's Clean Energy Future*", SINTEF, October 2022

- **Hydrogen-based superconductors** operate closer to room temperature, **but only when they are placed under enormous pressure**, equivalent to around half the pressure at the center of the earth (!!). As a result, they are practically unusable
- **Nickel-oxide superconductors** replace copper in high temperature cuprates with nickel; however, this approach has not yielded superconductivity at temperatures close to those of the other cuprates

Bottom line: the holy grail in superconductor research for the renewable transition would be a superconductor that functions at or above room temperature and at ambient pressure since it would not require large amounts of energy for cooling or pressurization. In 2020, Nature reported such a breakthrough but…

The rise and fall of a room temperature superconductivity claim

In 2020, the scientific community was excited by a groundbreaking claim: Ranga Dias (formerly) of the University of Rochester announced **the discovery of the world's first room-temperature superconductor.** Published in the prestigious journal *Nature*, the research described a material composed of hydrogen, carbon and sulfur that exhibited superconductivity at room temperature and under extreme pressure of ~267 GPa [compared to ambient pressure of 0.0001 GPa]. The superconductor Dias claimed to have discovered would have fallen into the category of hydrogen-based superconductors but at a higher temperature.

While higher-temperature superconductors had been developed before, they operate far below room temperature which limits their practical applications. Dias' claim of superconductivity at room temperature was hailed as a historic achievement given the implications for power grids with zero transmission losses, ultra-efficient energy storage, advances in magnetic levitation and quantum computing breakthroughs.

The Dias claim unraveled quickly. Brad Ramshaw, a physicist at Cornell University specializing in quantum materials, was among the first to publicly question the reproducibility of the results, particularly its magnetic susceptibility measurements. Ramshaw raised concerns about irregularities in the data and pushed for access to the raw experimental data files. The inability of other scientists to replicate the findings, coupled with inconsistencies in the data identified by Ramshaw and others, led *Nature* to retract the paper in 2022.

After *Nature* retracted this paper, Dias made another claim which was also (!!) published by *Nature* in 2023. Dias claimed he discovered another room-temperature superconductor (composed of lutetium and hydrogen) that could operate at more manageable pressures. **In other words, an even more astonishing breakthrough if true**. After Ramshaw submitted a complaint to *Nature*, Dias' own students questioned the work as well noting that the raw data looked like it had been altered to give the appearance of superconducting properties. The paper was soon retracted by *Nature* (again)[55].

More room temperature superconductivity claims that didn't pan out, this time in South Korea

In July 2023, Sukbae Lee and his team from Korea University claimed they had synthesized a room temperature superconductor (LK-99) at ambient pressure. Lee and his team described LK-99's modified lead-apatite structure in two papers posted on arXiv, a repository for scientific papers that does not require peer review. Lee's claims along with a video of LK-99 partially levitating (an indicator of superconductivity) went viral.

However, skepticism arose almost immediately within the scientific community. Within weeks, replication attempts by researchers showed no evidence of superconductivity in LK-99. Instead, the observed phenomena such as resistance drops and magnetic behavior were attributed to impurities in the sample. By late August 2023 most experts concluded that LK-99 was not a superconductor. Ramshaw believes that LK-99 is a case of sloppy science rather than outright fraud.

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[55] The decision to publish the second Dias paper has caused a lot of soul-searching within the *Nature* team. To their credit, *Nature* published a post-mortem of the entire mess: "*Superconductivity scandal: the inside story of deception in a rising star's physics lab*", Nature, March 8, 2024

Topics for 2026: demand response, shipping, geologic hydrogen, sodium ion batteries and fusion (maybe)

Demand response refers to industrial, commercial and residential users altering consumption based on the price of power. Some European aluminum smelters now vary power use depending on renewable energy on the grid; new EU laws require that dynamic price power contracts be made available to consumers. Similar efforts are underway in California. The big question: how much power will users be willing and able to shift in exchange for lower prices, and would this meaningfully reduce the amount of backup thermal power a grid might need?

Decarbonization of shipping. In 2022, 99%+ of global shipping fuels were sourced from oil-refined products. There's a lot of R&D on biofuels, ammonia, hydrogen, methanol and electricity for long and short haul shipping. Maersk announced 19 methanol dual-fuel containerships for delivery by 2025, and Clarksons reports that in 2022, 90 new orders were for ammonia-ready vessels, 43 for methanol vessels and 3 for hydrogen-ready vessels. However, ship engines can be "ready" for alternative fuels while operators use oil-refined fuels until alternative fuel prices decrease. This may be a long way off: to replace heavy fuel oil consumed by containerships and other general cargo vessels, production of green ammonia/hydrogen/methanol would require all electricity produced by the EU-27[56]. What would shippers pay for green fuel? According to a 2024 BCG survey, no more than a 5% premium. This is not going to be enough, even after subsidies. One silver lining: since a lot of shipping activity is the movement of fossil fuels, shipping energy consumption would fall in a more decarbonized future.

Geologic hydrogen. Scientists from the US Geologic Survey released a paper on naturally occurring hydrogen, estimating that massive amounts may exist. While most estimated hydrogen reservoirs would be impractical to recover, even a fraction could provide enough energy to support net zero emissions targets, and exceed energy in existing natural gas reserves. Over the next year, research is expected to focus on where hydrogen reservoirs are located, and what it would take to access them. That said, some reports are highly skeptical[57]:

- Current global geologic hydrogen extraction is roughly equal to the power in a single wind turbine
- Actual flows of hydrogen detected so far are small and not commercially exploitable
- Hydrogen seeps are diffuse and lack pressure support, further limiting their potential
- Hydrogen content in some areas is below 50% and is mixed with other gases
- Lifecycle assessments of geologic hydrogen production/processing indicate that hydrogen concentrations of 85%+ might be required to meet clean hydrogen definitions due to the presence of methane as well
- Geologic hydrogen deposits are likely to be very far from energy demand centers

Sodium ion batteries. Fluctuations in lithium prices and national security concerns have led to increased interest in sodium ion batteries which also require no cobalt or nickel, just aluminum and sodium. Lower energy density and fewer lifetime charge cycles may confine their use to stationary industrial applications like data centers and microgrids, although CATL claims that its sodium ion energy densities have improved to 200 Wh/kg compared to li-ion at a max of ~260 Wh/kg. US national labs have begun R&D efforts as well. Global 2024 production of sodium ion batteries was just 1% of lithium ion, so this technology is in its very early stages.

Nuclear fusion. It may take decades for fusion to be commercialized, but I might look at the 45 private fusion companies and at efforts in China. In January 2025, China's Experimental Advanced Superconducting Tokamak (EAST) fusion reactor maintained a steady, confined loop of plasma for 1,066 seconds, doubling its previous record (France has reportedly since eclipsed this figure by sustaining ultrahot plasma for 1,337 seconds). It's a step in the right direction but fusion reactors have never achieved "ignition", the point at which fusion creates self-sustaining energy. In addition to EAST, a prototype China fusion plant is in the planning stages and the China Burning Plasma Test Reactor is scheduled to be operational in 2027. **Contrarian point of view**: the Earth has access to a perfectly functional fusion reactor…which is the Sun. It has 1 billion years left on its warranty, a safe distance of 93 million miles away and is the simplest and cheapest form of fusion power available…as we illustrate in the Executive Summary in the beginning of this piece. See you next year.

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[56] "*A Study on the Limitations of Green Alternative Fuels in Global Shipping*", Jan Emblemsvag, Journal of Marine Science and Engineering, January 2025

[57] "*Everything you need to know about natural or geologic hydrogen*", March 2024, Hydrogen Science Coalition

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