J.P.Morgan

EYE ON THE MARKET | 14TH ANNUAL ENERGY PAPER

Electravision

Electravision. The predominant vision for the future involves the electrification of everything, powered by solar, wind, transmission and distributed energy storage. This vision primarily relies upon the greater efficiency of electric motors and heat pumps vs their fossil fuel counterparts. While the grid is getting greener, electrification is advancing at a much slower pace for reasons related to chemistry, physics, cost, politics and human behavior. Our 14th annual energy paper takes a closer look, and also includes sections on nuclear power, China, hydrogen, "net zero oil" and Gaza's energy future.

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

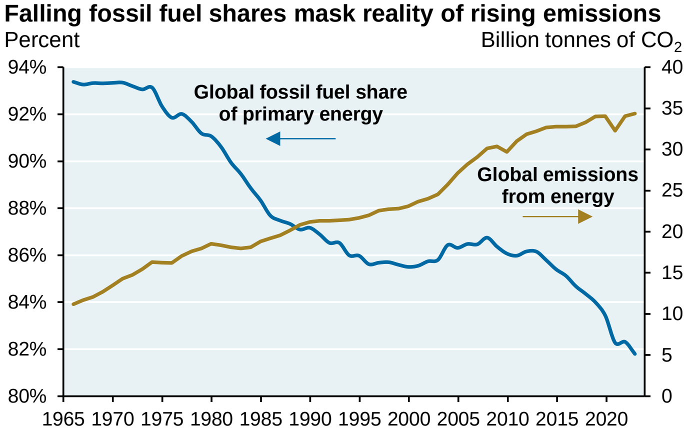
Electravision: 14th Annual Eye on the Market Energy Paper

The fossil fuel share of global energy use is falling at ~0.40% per year as the renewable transition progresses. That's almost exactly the same pace of decarbonization that occurred from 1973 to 1988 during the nuclear buildout. To be clear, global CO_2 emissions have not declined since energy consumption keeps rising; what's falling is the *share* of primary energy from fossil fuels, not their *level*.

The fossil-renewable gap in the second chart[1] should close at a faster pace given growing global initiatives to decarbonize; global transition spending has exceeded fossil fuel spending for the fourth year in a row and the gap is widening[2]. Looking ahead, the fiscal costs of the US energy bill could reach $900 bn by 2030 and $1.1 trillion by 2035[3]. But as things stand now, renewable energy is used almost exclusively to decarbonize the grid and its main purposes: space cooling, lighting, refrigeration, data centers, electronics and some space heating. The grid's use for industrial production and transport is still small.

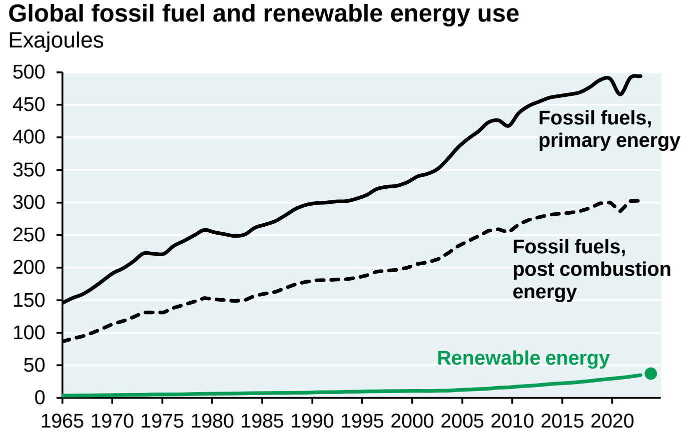
The consensus path forward is Electravision, the electrification of everything. The reason: if something can be electrified, it can eventually be decarbonized via wind, solar and energy storage. While this transition is underway, it will take time due to chemistry, physics, cost, human behavior and politics. As a result, current human prosperity is difficult to imagine without substantial contributions from natural gas. This gas ecosystem needs sufficient investment to avoid electricity and natural gas outages, and its methane footprint needs greater attention (a topic covered last year). This year's paper gets into the details of Electravision along with sections on nuclear power, China, "decarbonized oil", levelized costs, hydrogen, bio-oil, EV emissions, the latest from Vaclav Smil and concluding thoughts on solar power and Gaza's energy future. The appendices include data on global oil and LNG markets, and a travelogue of EV misadventures with Electrify America, Waymo and Jeep.

Falling fossil fuel shares mask reality of rising emissions



Source: EI Statistical Review of World Energy, JPMAM, 2023

Global fossil fuel and renewable energy use



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

[1] The standard convention in energy analysis (IEA, EI, EIA) is to show renewable and nuclear power on an "input-equivalent" or "thermal-equivalent" basis, grossing these electricity sources up to make their primary energy figures more comparable to fossil fuels which experience ~62% thermal losses during combustion. The EIA is moving to a new standard: they will show renewable and nuclear power without any gross-up, directly reflecting their electrical output whether in TWh, exajoules or BTUs.

The first chart uses the standard primary energy figures. The second chart shows primary energy of global fossil fuel use, and another series we compute on "post-combustion fossil fuel energy". This is derived based on the actual use of oil, natural gas and coal for transport, electricity generation and industrial/building heat and reflect their combustion efficiencies (30%, 38% and 90% respectively). This latter series is more comparable to renewable and nuclear energy since it gets closer to the amount of "work" that electrical energy can perform.

[2] "*Energy Transition Investment Trends 2024*", BNEF, January 2024, Page 7

[3] "*Economic Implications of the Climate Provisions of the Inflation Reduction Act*", Bistline et al, citing EPRI's REGEN model, March 30, 2023

The foundations of this piece are rooted in the science of the transition, rather than in the imaginary ways that the transition *might* work. Anyone who supports a clear-eyed analysis should be disturbed when science is distorted for political reasons:

- According to the "Silencing Science" tracker maintained by Columbia University, 346 anti-science actions were taken by the federal government during Trump's administration. Categories include gov't censorship, self-censorship, budget cuts, personnel changes, research hindrance and bias/misrepresentation
- Nearly 400 EPA scientists said they observed violations of the agency's scientific integrity policy in the second half of 2018 but did not report them due to "fear of retaliation, belief that reporting would make no difference, perceived suppression or interference by Agency leadership, and belief that politics and policy outweigh science"[4]
- Trump has pledged to revive a plan to reclassify thousands of federal employees[5]. These include scientists who are currently shielded from politics in permanent professional positions. The plan would allow his administration to more easily fire "rogue bureaucrats" that oppose his agenda. The administration could appoint replacements who are aligned with Trump politically regardless of scientific or technical expertise

Sorting out fact from fiction regarding the energy transition is hard enough without this kind of thing. There are legitimate debates about the right energy transition policies. As one example, the EPA will finalize standards this spring for existing coal and new natural gas plants that might require carbon capture as a precondition for approval to operate. One can debate the cost and technological readiness of this constraint. But the scientists that work on empirical analysis of energy and the environment should be left alone.

Michael Cembalest
JP Morgan Asset Management

Acronyms
BEV battery electric vehicle; **BNEF** Bloomberg New Energy Finance; **BTU** British thermal unit; **CHP** combined heat and power; **CCS** carbon capture and storage; **CF** capacity factor; **DACC** direct air carbon capture; **DOE** Department of Energy; **DRI** direct reduced iron; **EI** Energy Institute; **EIA** Energy Information Administration; **EOR** enhanced oil recovery; **EPA** Environmental Protection Agency; **EV** electric vehicle; **FERC** Federal Energy Regulatory Commission; **FF** fossil fuel; **GHG** greenhouse gas; **GW** gigawatt; **HGB** hydropower, geothermal and biomass; **HVAC** heating, ventilation and air conditioning; **ICE** internal combustion engine; **IEA** International Energy Agency; **IRENA** International Renewable Energy Agency; **kg** kilogram; **km** kilometer; **kW** kilowatt; **kWh** kilowatt-hour; **LBNL** Lawrence Berkeley National Laboratory; **LCOE** levelized cost of energy; **Li-Ion** lithium-ion; **LNG** liquefied natural gas; **MJ** megajoule; **MPG** miles per gallon; **mtpa** million tons per annum; **MW** megawatt; **MWh** megawatt-hour; **NERC** North American Electric Reliability Corporation; **NRC** Nuclear Regulatory Commission; **NREL** National Renewable Energy Laboratory; **PHEV** plug-in hybrid electric vehicle; **Quad** quadrillion BTU; **REE** rare-earth element; **SMR** small modular reactor; **TTF** Title Transfer Facility; **TWh** terawatt-hour; **UCS** Union of Concerned Scientists; **UNCTAD** United Nations Conference on Trade and Development; **USGS** US Geological Survey. [Version Mar 11].

[4] "*How President Trump's war on science impacted public health and environmental regulation*", Webb and Kurtz, in "*Progress in Molecular Biology and Translational Science*", 2020

[5] "*Trump's presidential push renews fears for US science*", Nature, Jeff Tollefson, January 2024

Table of contents

Prior year energy topics

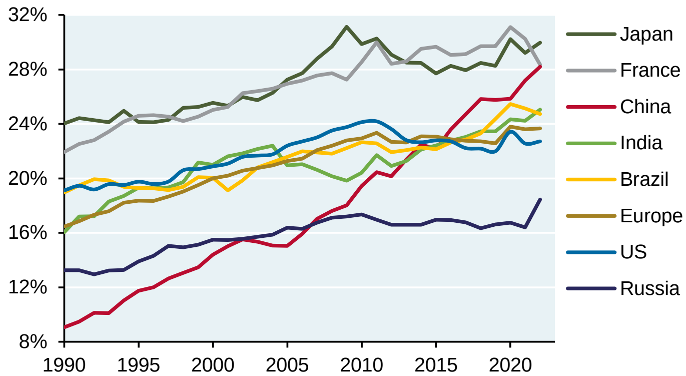
On our **Eye on the Market energy archive page**, you can read about topics we covered last year:

- the US electricity transmission quagmire and the growing interconnection queue of wind/solar projects
- the flawed concept of Levelized Cost when applied to renewable energy
- a deep dive on critical minerals, geological abundance and China's role in energy supply chains
- the high cost of biofuel replacements for traditional jet fuel
- benefits and limitations of municipal solid waste, and the controversy in Europe over solid biomass
- the slow pace of carbon sequestration and the related issue of flue gas CO_2 concentrations
- the dreamlike reveries of electric planes, nuclear fusion, space-based solar power, direct air carbon capture and fully autonomous passenger car networks
- field studies on US methane emissions showing higher levels than those reported to the EPA

Electravision: the contours of an electrified future

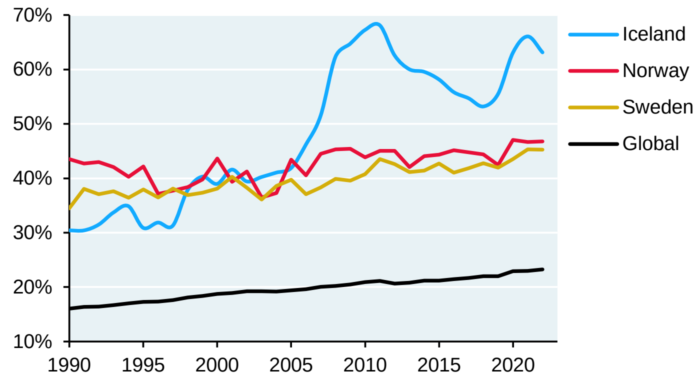
There are two main reasons for electrification: (a) if you can electrify it, you can decarbonize it; and (b) electric motors and electric heat pumps are more efficient than their fossil fuel counterparts. **In most countries, electrification accounts for 20%-30% of total energy consumption**. There's a lot of press coverage on countries with higher shares; but more people talk about Norway than there are people living in Norway, and the three countries shown on the right are not good proxies for the rest of the world. If there's something notable going on, it's rising electrification in China.

Major countries: electricity share of final energy consumption
Percent



Source: EI Statistical Review of World Energy, JPMAM, 2023

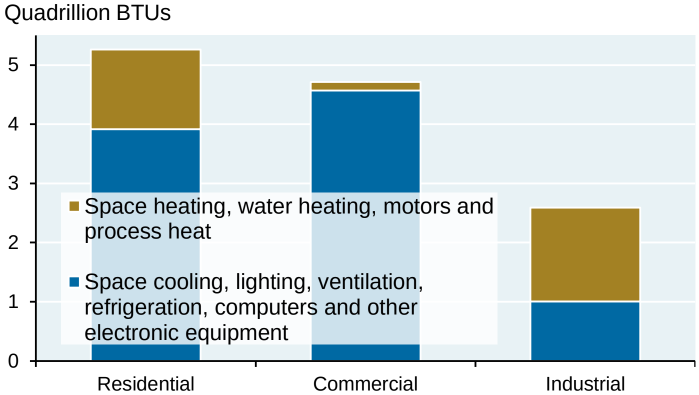
Most electrified: electricity share of final energy consumption
Percent



Source: EI Statistical Review of World Energy, JPMAM, 2023

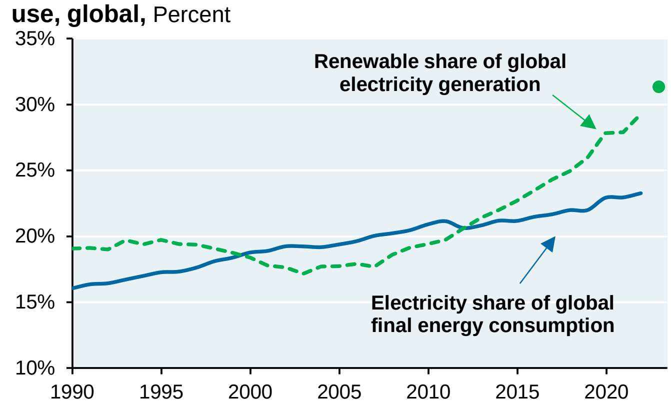
What is electricity used for? Mostly for residential-commercial-industrial space cooling, lighting, data centers, computer equipment, ventilation and some space heating. The use of electricity in transportation and industrial sectors is generally very small, and thermal heat is still the dominant form of space heating. That explains the chart on the right: **grid decarbonization (green line) is happening faster than electrification (blue line).** In other words, the grid is getting greener but the purposes for which it's used are expanding much more slowly.

US electricity uses: primarily HVAC
Quadrillion BTUs



Source: EIA, JPMAM. 2023. Transport too small to plot at 0.06 quads.

Grid decarbonization outpaces electrification of energy use, global, Percent



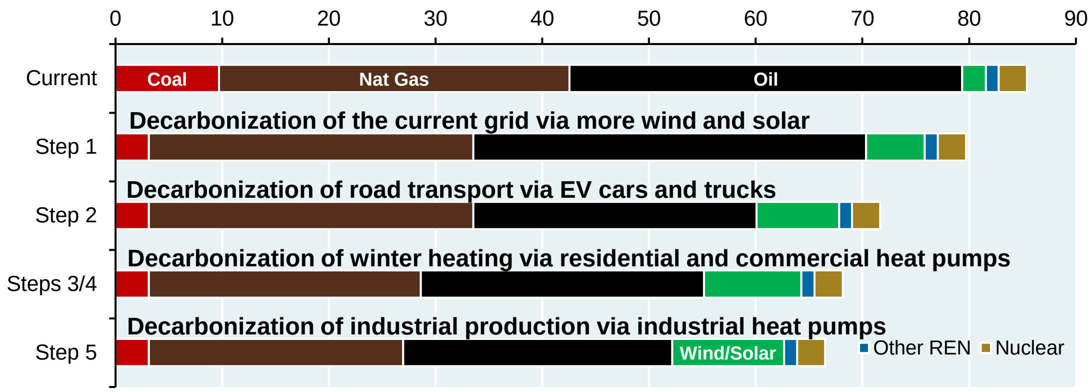
Source: EI Statistical Review of World Energy, IEA, JPMAM, 2023

How Electravision would work. Each country has a different roadmap but many details are similar to the US version outlined below[6]: **the grid is decarbonized further while at the same time, electrification of road transport, winter heating and industrial production increase as well**. The big picture: after accounting for efficiency of electric motors and electric heat pumps, only 8-9 quads of electrical energy would be needed to replace 27 quads of fossil fuel energy, with the latter decreasing by 34% from current levels.

The challenges: this would require a ~34% increase in US electricity generation (i.e., the same % increase in power generation that took place from 1993 to 2022, a period of 30 years), a ~400% increase in wind and solar power and enough backup thermal power and battery storage to handle 53% of a much larger grid coming from intermittent renewables. The next few pages walk through each step; all increases in electrification are assumed to be powered by new wind and solar. Electrification makes less sense from a decarbonization perspective if powered by additional natural gas.

How much would Electravision cost? I have no idea; a thorough assessment would have to include increased costs to both ratepayers and taxpayers. For example, it would need to incorporate the impact on US power prices (since 2019, power prices have been rising faster than core inflation, food prices and gasoline prices) **and** the incremental costs of subsidies to taxpayers (e.g., the $800 bn to $1.1 trillion cited on page 1).

Electravision roadmap for the US, Quadrillion BTUs of primary energy, new EIA convention
(primary energy for fossil fuels, delivered energy for renewables and nuclear)



Source: EIA data, JPMAM assumptions, 2024. Other renewables is primarily hydropower

	Current	Electravision	Change
Primary energy delivered (quads)	85.4	66.5	-22%
Fossil fuel primary energy use (quads)	79.4	52.2	-34%
Wind+solar generation (quads)	2.2	10.5	376%
Wind+solar generation (TWh)	645	3,069	376%
Total electricity generation (quads)	14.7	19.7	34%
Total electricity generation (TWh)	4,321	5,775	34%
Wind+solar share of electricity generation	15%	53%	38%
Renewable share of electricity generation	23%	59%	36%

Source: JPMAM, 2024. Using new EIA conventions for primary energy.

[6] **Electrification assumptions differ**. One example: "*Electrify: An optimist's playbook for our clean energy future*" by Saul Griffith from MIT. In an October 2023 article, Griffith cites possibilities for electrification of short haul aviation which is outside the scope of our analysis. We do not assume any electrification of shipping or aviation. In last year's paper we explained how short haul aviation trips (less than 200 miles) account for less than 5% of total aviation emissions, so even if we had included it, it would not have made much of an impact.

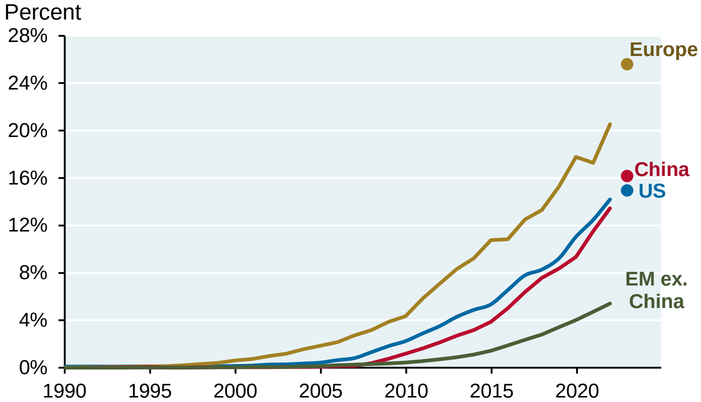
 # 1: Decarbonization of the US grid via more wind and solar power, before increased electrification

- Current: wind = 10% of generation, solar = 5% of generation
- Electravision: wind share increases to 19%, solar share increases to 18%; curtailment of 5%
- Coal share of generation falls from 20% to 5% with remainder coming from reduction in natural gas

The first stage of Electravision would be more wind and solar on the existing grid. Keep in mind that this may not result in widespread reductions of natural gas capacity. "Capacity credits" estimate the MW of gas capacity that can be disconnected for every MW of wind and solar added to the grid, and are just 10%-25% in the US (see page 18). In other words, the total cost of Electravision includes redundancy of generation capacity in addition to the cost of new generation capacity, transmission and storage. Note how Germany's thermal power has not declined despite large additions of wind and solar capacity since 2002. German CO_2 emissions and thermal capacity factors have declined, but its thermal plants still must be built and maintained.

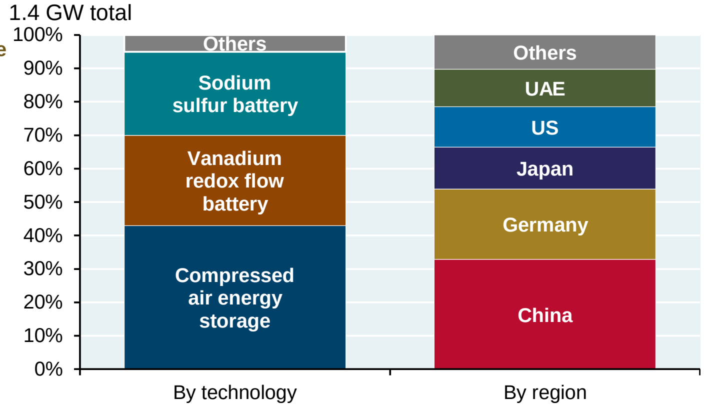
In the US, pumped storage accounts for 70% of utility-scale energy storage while chemical batteries account for another 28%. Within chemical batteries, almost the entire amount is 4-6 hour li-Ion capacity. If wind/solar buildouts increase and natural gas peaker plants are decommissioned, long duration energy storage (LDES) will be a critical part of Electravision since 4-6 hour li-ion battery storage will not be enough. New chemical LDES battery approaches such as vanadium redox and sodium sulfur are just beginning to be deployed alongside compressed air storage. But to be clear, global LDES capacity is still very small, just ~0.5% of all forms of energy storage. Low LDES capacity is due to high costs, low technological readiness and the need for improved round-trip efficiencies (i.e., compressed air 40%-60%, flow batteries 65%-80% vs li-Ion at ~90%).

Wind and solar share of electricity consumption
Percent



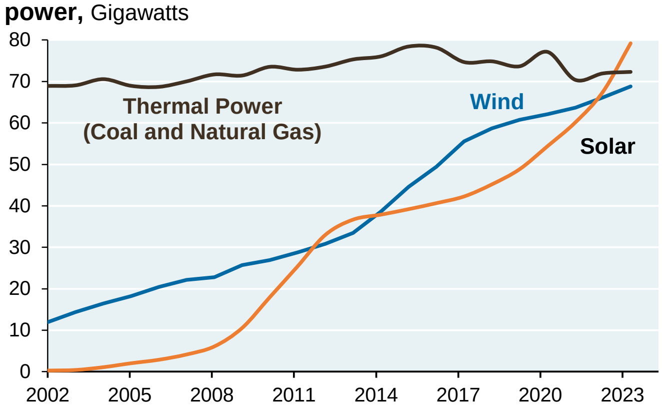
Source: EI Statistical Review of World Energy, IEA, JPMAM, 2023

Long duration energy storage by technology and by region
1.4 GW total



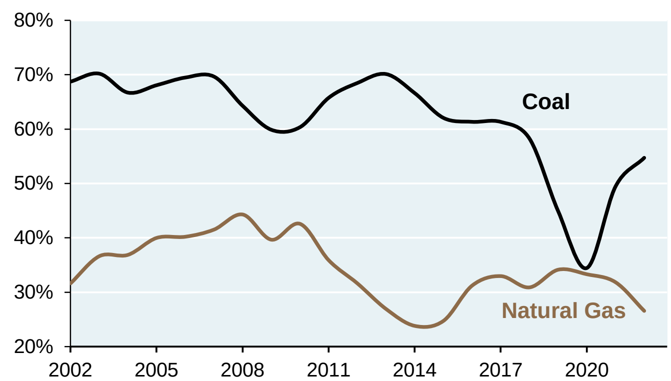
Source: *"2023 Global Long-Duration Energy Storage Update"*, BNEF, Sept 2023

Germany installed capacity of wind, solar and thermal power, Gigawatts



Source: Fraunhofer Institute, JPMAM, 2024

Germany thermal capacity factors
Percent



Source: EI Statistical Review, Fraunhofer Institute, JPMAM, 2023

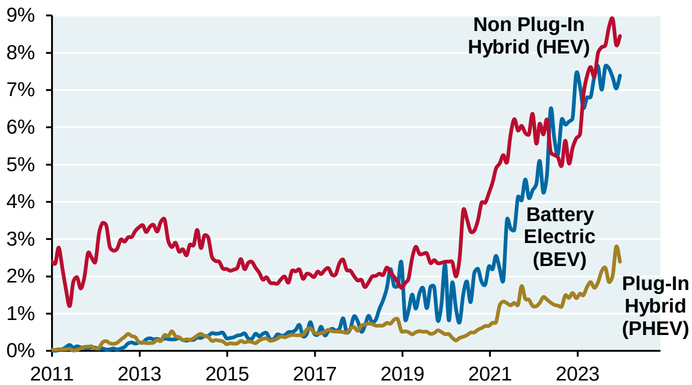
Step 2: Decarbonization of US passenger cars, light trucks and Class 8 trucks: growing but still in its infancy

- Current fleet: EVs represent 1.5% of passenger cars and light duty vehicles, and 0.6% of Class 8 trucks
- Electravision: 50% of passenger car energy petroleum use displaced by EVs, assuming 23 MPG for ICE cars/ light trucks and 0.33 kWh per mile for EVs; 50% of freight and commercial light truck energy petroleum use displaced by EVs assuming 6.5 MPG for ICE trucks and 1.7 kWh per mile for EVs[7]

US EV sales are now ~10% when including BEVs and PHEVs[8], but they're just 1.5% of the car fleet and even less as a share of the Class 8 truck fleet; it takes time to change the fleet when vehicles last for 12 years or more. More states are following California's lead to phase out internal combustion engine cars; states comprising one third of the existing car fleet plan to do so. EV capital commitments by manufacturers also suggest that the future of road vehicle transport is electric, but I wonder how long it will take.

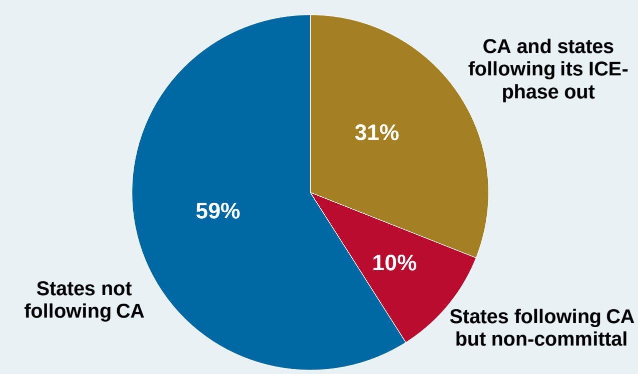
BNEF estimates that the US fleet will be 50% EVs by 2037, but that requires accelerated adoption from current levels. I wonder what BNEF would say about the following: US EV inventories on dealer lots reached an all-time high at 114 days in December 2023, double the figure from the prior year (these figures exclude Tesla and Rivian which sell direct to consumers). Ford and GM are cutting back on EV production, GM and Honda abandoned a plan to build lower-priced EVs, and a consortium of 4,000 auto dealers asked Biden to "tap the brakes" on EV mandates. In other words, Electravision EV forecasts are very optimistic and could take a LONG time.

US EV sales as a percent of total light-duty vehicle sales
Percent



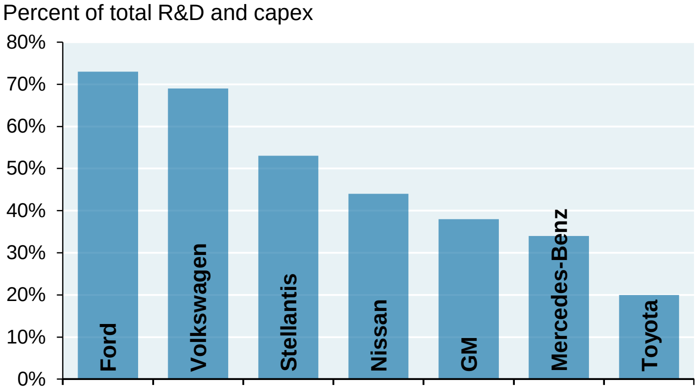
Source: ANL, JPMAM, January 2024

Share of US car fleet following California's fuel economy standards, Percent



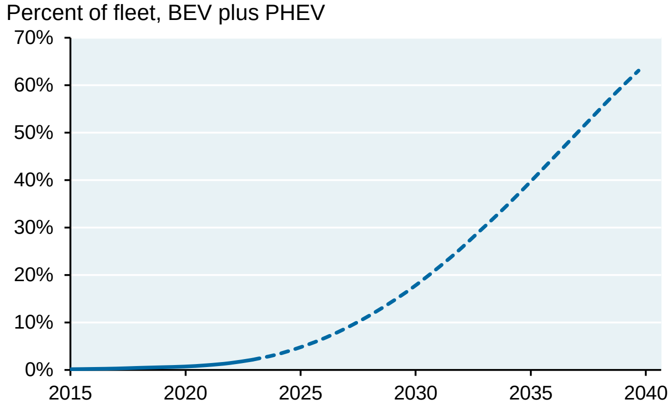
Source: BloombergNEF, December 2023

R&D and capex commitments for EVs and digital tech
Percent of total R&D and capex



Source: BloombergNEF, December 2023

EV share of US vehicle fleet as per BNEF projections
Percent of fleet, BEV plus PHEV



Source: BloombergNEF, JPMAM, June 2023

[7] **ICE vehicles**: 23 mpg for US vehicle fleet (DoT); 6.5 mpg for semi-truck (Phoenix Truck Driving Institute); **EVs**: 0.33 kWh per mile for Tesla Model X (DoE); 1.7 kWh per mile for Tesla Semi Class 8 all-electric semi-truck (Tesla)

[8] Non plug-in HEVs like the Toyota Prius are generally not included in broad EV totals since they only achieve ~20% reduction in emissions per mile compared to ICE cars, with battery ranges of just 1-3 miles

Electravision
Executive Summary

Steps 3 and 4: Decarbonization of winter heating via residential and commercial air-sourced heat pumps

	Current share of heating use					
	Heat pump	Fossil fuels	Resistance heating	Future heat pump share	Coefficient of performance	Furnace efficiency
Residential	6%	74%	20%	50%	3.0	90%
Commercial	11%	75%	14%	65%	3.0	80%

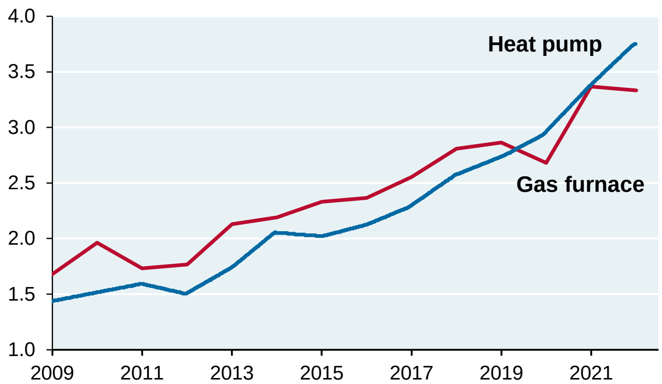
Source: "*Transitioning to Heat Pump Rooftop Units for US Commercial Buildings*", NREL; JPMAM May 2023

In an Electravision scenario, 50%-65% of winter heating energy is met via electric heat pumps, up from 6%-11% today. Heat pumps are the marginal source of winter heating in Europe and the US, but the challenge is the same as with vehicles: the time required to replace the stock of combustion devices with electrical ones. New home sales in the US and Europe are less than 1% of the existing housing stock. So, if heat pump sales are mostly confined to new homes or to replace furnaces when they stop working (their operating lives are 20+ years), this transition will take a *really* long time. Also: the Ninth Circuit overruled Berkeley's natural gas ban in new buildings after concluding that it conflicts with Federal law; the impact of this decision could be material.

The fourth chart shows another hurdle: **cost**. Natural gas is cheaper than electricity per unit of energy, offsetting heat pump efficiency benefits for homeowners. In other words, if a heat pump coefficient of performance[9] is 3x but electricity costs 3x more than natural gas, there might be limited economic benefits to heat pump adoption. Heat pump switching incentives are greater for heating oil and propane users (gold dot).

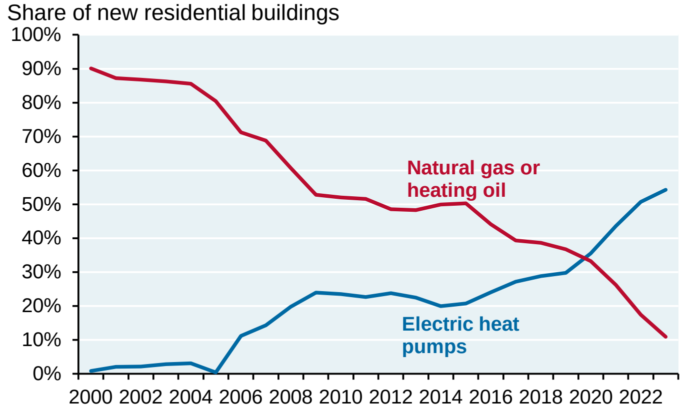
On Europe: heat pump adoption means that many buildings will have air conditioning for the first time, which could reduce Europe's net energy and emissions gains (see page 33) from heating electrification.

US heat pump sales exceed gas furnace sales
Annual sales, millions



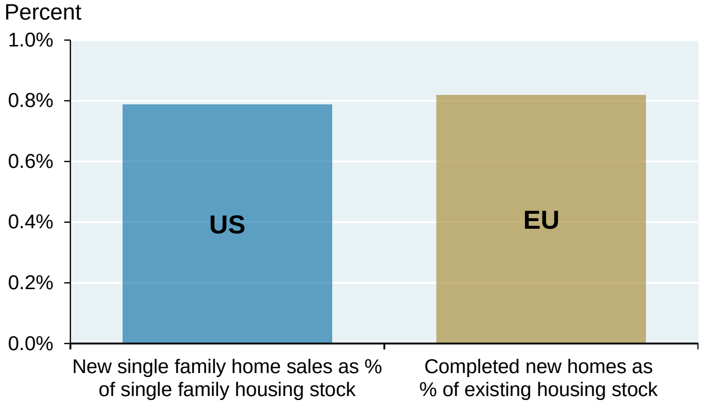
Source: Air Conditioning, Heating and Refrigeration Institute, 2023

Germany heating structure in new residential buildings
Share of new residential buildings



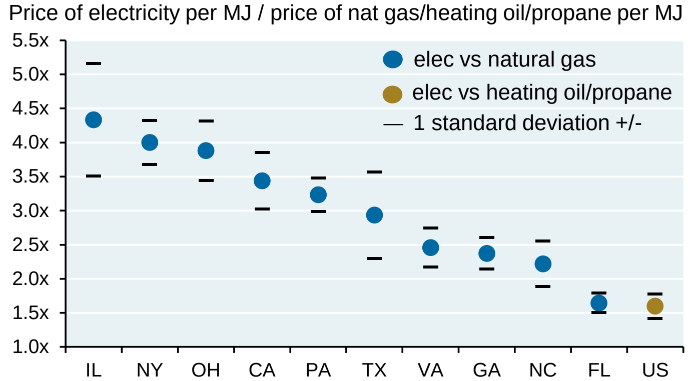
Source: AG EnergieBilanzen, JPMAM, Q2 2023

The slow pace of housing turnover
Percent



Source: Census, OECD, JPMAM, 2023

Winter price for electricity vs fossil fuels for heating
Price of electricity per MJ / price of nat gas/heating oil/propane per MJ



Source: EIA, JPMAM, 2023. Top 10 states by electricity consumption; assuming 90% gas furnace efficiency. Residential pricing.

[9] For more information on heat pump coefficient of performance, see **this page** from our 2022 energy paper

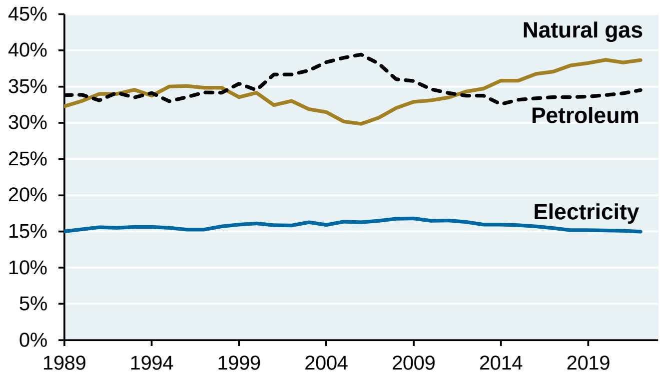
Step 5: Decarbonization of industrial production via industrial air- or ground-sourced heat pumps

- Current: 14% of industrial sector energy use is sourced from electricity
- Electravision: 30% sourced from electricity, assuming industrial heat pump coefficient of performance = 2.0

The electricity share of US industrial energy use has been stable for over 30 years, stuck at ~15%. According to NREL, at least half of all industrial process heat requires temperatures of 200°C or less. If that's the case, **why doesn't the industrial sector take more advantage of industrial heat pumps** that require less energy than furnaces? In other words, why isn't electrification's share of industrial energy use rising? Optimists believe we're on the cusp of a major transition to industrial heat pumps. Perhaps, but in the absence of any signs of change, a doubling of industrial electrification is a very optimistic Electravision scenario.

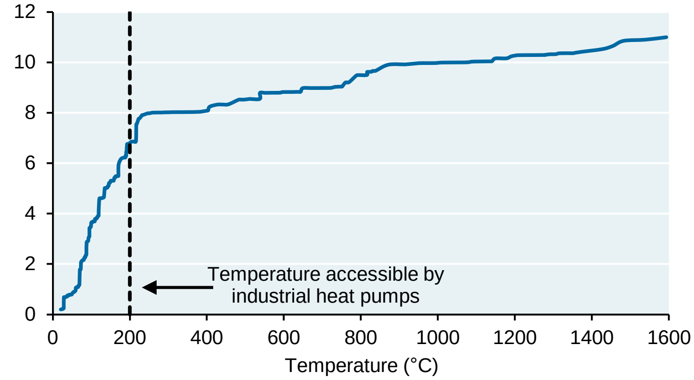
One explanation for the slow pace of change: **electricity is more expensive per unit of energy than natural gas for industrial users**, as shown in the third chart. In other words, you need fewer BTUs due to efficiency of heat pumps but you pay more for them. Furthermore, a lot of industrial equipment is fully amortized, so companies might be slow to replace it at high upfront cost without the certainty of much lower operating expenses.

Electricity share of US industrial energy use unchanged for decades, Share of industrial energy use



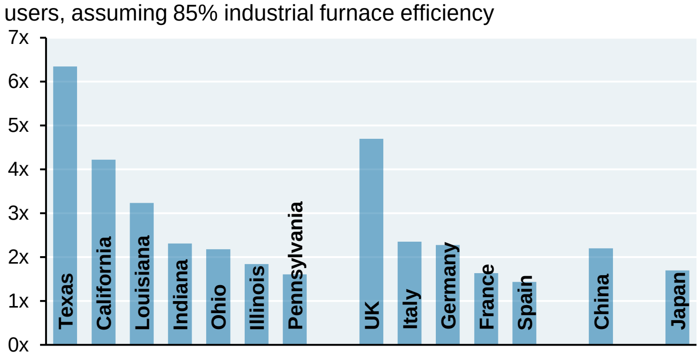
Source: EIA, JPMAM. 2023.

Cumulative industrial process heat use by temperature
Quadrillion BTU



Source: *"Manufacturing Thermal Energy Use in 2014"*, McMillan (NREL), 2019

Electricity: 2x-6x 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. September 2023. States shown are largest industrial users of US primary energy.

Industrial energy consumption by sector and type, trillion BTUs

	Fuel	Feedstock	Total
Chemicals	2,815	4,326	7,141
Petroleum/coke	3,342	903	4,245
Paper	2,488	3	2,491
Primary metals	1,734	307	2,041
Food	1,511	-	1,511
Non-metallic minerals	1,161	-	1,161
All others	247	599	846
Total	13,298	6,138	19,436

Source: EIA, 2018

An alternative to electric heat pumps: **co-located solar power with thermal energy storage**, in which the energy is used for heat and is stored *without* the use of electrochemical batteries. One example: long-term energy storage in bricks inside an insulated steel container; fans flow air over the bricks to access the heat. Very 20th century but potentially cheaper and more scalable than electrochemical alternatives.

The second explanation has to do with the chemistry of industrial energy use, which Lawrence Berkeley National Laboratory examined in a piece on high and low potential for electrification.

LBNL cited primary metals (ex-steel), secondary steel[10], machinery, wood products, plastics and rubber as sectors with **high electrification potential** since fossil fuels are mostly used for process heat which could be replaced by electric heat. Electrification potential is also high for certain mining activities related to transport, excavation, pit crushing and belt conveying systems. That's the table on the left.

On the right: **low/medium electrification potential sectors**. Chemicals, pulp/paper and food take advantage of integrated systems in which fuel combustion waste heat (CHP) powers related processes. CHP-intensive sectors are harder to electrify since producers would need to purchase energy previously obtained at little to no cost, and/or redesign the entire process. Other hard to electrify sectors include non-metallic minerals such as glass, brick and cement which require temperatures in excess of 1400°C, and which are non-conductive solids (i.e., harder to electrify production of things that do not conduct electricity). Finally, oil/coal refining exploits "own-use" fuel consumption, a source of energy lost when switching to electricity.

As shown in the pie chart, sectors with high electrification potential use roughly 23% of US industrial energy; medium potential sectors use 33%, and low potential sectors use 28%; the remainder was not analyzed.

Industrial sectors with high electrification potential

Sector	Heat requirement	Fuel consumption shares: HVAC	Process Heat	CHP
Primary metals ex. steel	1200°C	6%	75%	7%
Fabricated metal	430°C-680°C	20%	61%	7%
Machinery	730°C	46%	39%	4%
Secondary steel	1425°C-1540°C	4%	87%	0%
Wood products	180°C	10%	50%	14%
Vehicle parts (drying)	150°C	31%	33%	12%
Plastics and rubber	260°C	20%	33%	24%

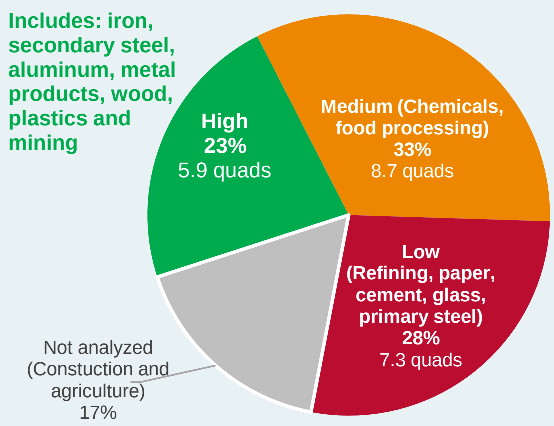
Source: LBNL, "*Electrification of buildings and industry*", March 2018.

Industrial sectors with medium/low electrification potential

Sector	Heat requirement	Fuel consumption shares: HVAC	Process Heat	CHP
Food/beverages	120°C-500°C	4%	25%	40%
Chemicals	100°C-850°C	1%	32%	43%
Pulp and paper	650°C	2%	21%	63%
Non-metallic minerals	870°C-1600°C	3%	90%	1%
Oil/coal products	220°C-540°C	0%	58%	22%

Source: LBNL, "*Electrification of buildings and industry*", March 2018.

US industrial energy use by electrification potential



Source: EIA (2020), LBNL, *"Electrification of buildings and industry", 2018.*

Steel production

	Primary: Blast oxygen furnace	Secondary: Electric arc furnace	Share of global steel production
Global	72%	28%	
China	> 90%	< 10%	53.7%
India	55%	45%	7.5%
Japan	75%	25%	4.7%
US	30%	70%	4.3%
Russia	66%	34%	4.0%
Korea	68%	32%	3.7%

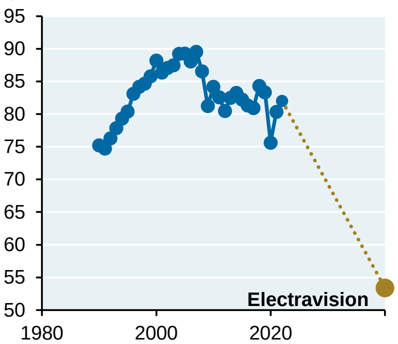
Source: Steel climate impact benchmarking report, USGS, April 2022

[10] **Secondary steel** refers to recycled steel which is melted down and regenerated in electric arc furnaces. Around 85% of all steel is already recycled globally, which is why primary steel production (producing it from cast iron made from iron and coke) is the predominant production method. Pilot projects using green hydrogen as a reducing agent to strip oxygen from iron oxide (instead of using carbon) are still in their infancy.

Electravision summary: the transmission buildout might be the hardest part

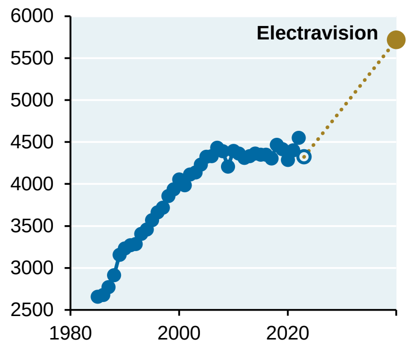
The charts show what Electravision would entail in the US: a 34% decline in fossil fuel consumption, a similar increase in electricity generation and a ~400% increase in wind/solar generation; after which intermittent renewable energy would represent 53% of the power coming from a much larger grid. I did not put an end date on the charts since I have no idea how long this would take to accomplish.

US fossil fuel consumption
Quad BTUs



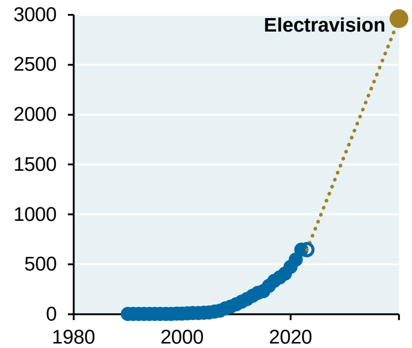
Source: Energy Institute, JPMAM, 2023

US electricity generation
TWh



Source: Energy Institute, IEA, JPMAM, 2023

US wind & solar electricty generation
TWh



Source: Energy Institute, IEA, JPMAM, 2023

Building wind/solar capacity and convincing owners of vehicles, furnaces and other devices to electrify might not be the hardest part. **Building more transmission might be.** Utilities spend almost as much on transmission and distribution as they do on power generation. In October 2023, the Department of Energy released a report on transmission needed by 2035 in a scenario that sounds like Electravision: "higher load and high clean energy growth". The DoE's estimate of required growth in transmission and interregional transfer capacity is very large (see box/table), particularly compared to *declining* growth in new transmission shown on the next page. Notably, the DoE does not believe that more distributed storage necessarily results in lower transmission needs.

Without legislative and cultural changes allowing transmission to replicate the growth of the interstate highway system, fiber optic cables, national rail, civil aviation, waterways and other infrastructure, **Electravision will remain just that: a vision**.

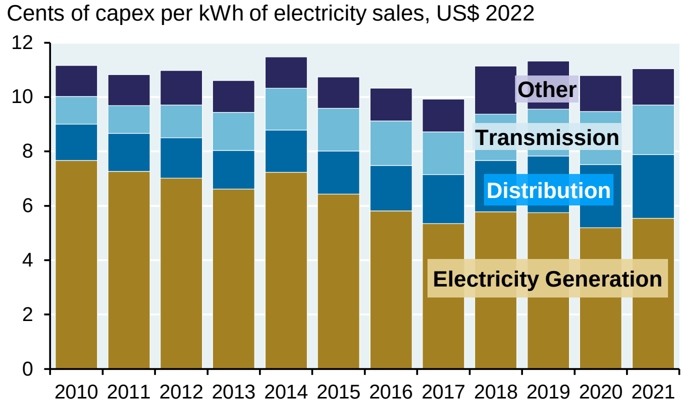
Transmission growth needed by 2035
Median growth vs 2020, high load & high clean energy scenario

Region	Growth	Interconnection	Growth
Plains (PL)	408%	PL-TX	3519%
Delta (DE)	231%	PL-SW	3238%
Midwest (MW)	174%	MO-PL	2102%
Mountain (MO)	173%	DE-PL	1019%
New England (NE)	126%	NE-NY	835%
Southwest (SW)	118%	MW-PL	730%
Texas (TX)	113%	DE-SE	572%
Southeast (SE)	102%	MA-MW	474%
Mid-Atlantic (MA)	61%	MW-SE	416%
New York (NY)	46%	MA-NY	412%
Northwest (NW)	31%	FL-SE	295%
Florida (FL)	24%	MO-NW	202%
California (CA)	4%	MA-SE	140%
		CA-MO	130%
		MO-SW	129%
		CA-SW	102%
		DE-MW	30%
		CA-NW	25%

Source: "*National transmission needs study*", DOE, October 2023

US transmission grid, from the DoE October 2023 report
Current within-region transmission: 85,000 GW-miles
New transmission req. by 2030: 33,000 GW-miles (+39%)
New transmission req. by 2035: 108,000 GW-miles (+128%)

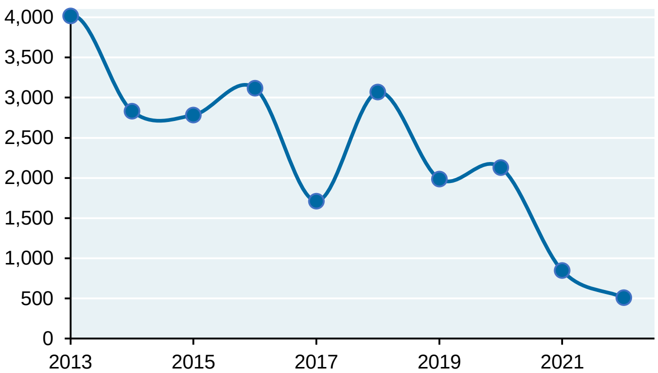
US utility annual spending by category
Cents of capex per kWh of electricity sales, US$ 2022



Source: EIA, February 2023

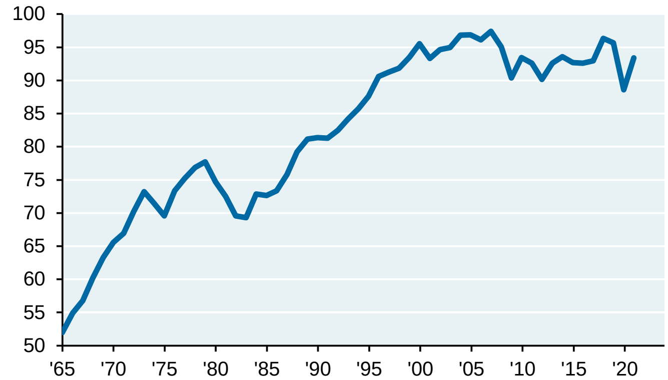
Last year we covered the difficult and time-consuming process of building high voltage transmission lines. While projects less than 150 miles have been completed in 5-10 years, projects more than 400 miles (e.g., from Wichita to St Louis) can require 15-20 years to complete. Another issue: rising costs. Of all 47 categories of core goods in the US producer price inflation report, **the highest increase since 2019: transformer equipment**, at 71% (see p. 21). Wood Mackenzie reports lead times of two years for buyers of generator transformers and power transformers, and Electravision has barely begun.

US transmission line growth
Miles added per year



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

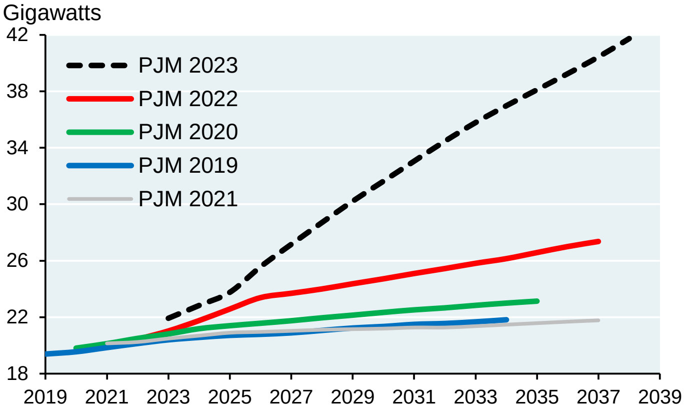
US primary energy consumption
Quadrillion BTUs



Source: EI Statistical Review of World Energy, JPMAM, 2023

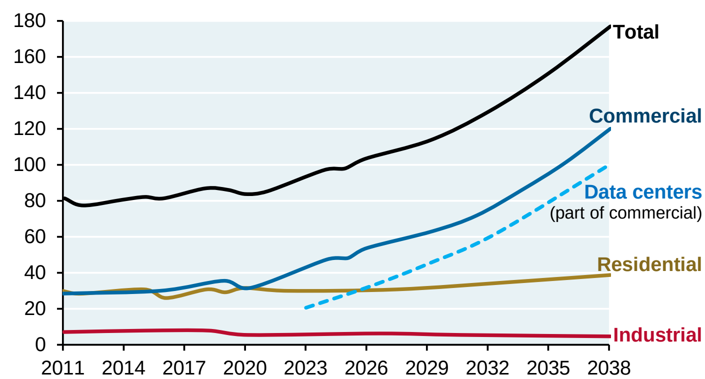
An important caveat: our Electravision scenario assumes that total US energy needs will not change much over the next two decades. Unchanged US energy demand is consistent with the last couple of decades; the energy needs of a growing US population have been offset by improving energy efficiency. However, **the rise of AI might change that.** One illustrative example: the PJM (mid-Atlantic) region has made sharp increases to projections of future power demand. These increases are **entirely due to an increase in data centers** which serve advanced computing/AI needs[11]. Constellation Energy estimates that the AI revolution could require more power in the US than the future electric vehicle fleet[12]. If that's the case, the productivity benefits from AI better be large enough to offset the increase power load. **Bottom line: the rise of AI could make the journey to Electravision longer, harder and most costly.**

PJM progression of power demand forecasts
Gigawatts



Source: PJM 2023 Power Demand Outlook, January 28, 2024

PJM demand forecasts by type
TWh



Source: Dominion Resources Integrated Resource Plan, January 28, 2024

[11] Power-hungry **Microsoft** plans to use AI to accelerate development of dedicated nuclear fission plants and has invested in nuclear fusion startups. It's unclear if either of these efforts will succeed, and I am skeptical on both. A more likely savior: sub-quadratic scaling methods and other techniques which eventually reduce the computational intensity of large language models and other forms of AI.

[12] "*AI is ravenous for energy. Can it be satisfied?*", WSJ, December 23, 2023; Constellation Energy

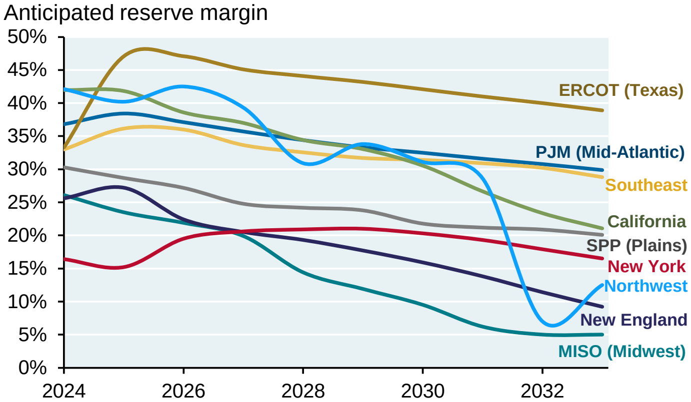
Meanwhile, in the trenches: the North American Electricity Reliability Corporation (NERC) and the Federal Energy Regulatory Commission (FERC) are raising red flags on the grid even before Electravision happens. If you think electricity outages are bad, wait until you read about near-misses of natural gas outages.

The electricity grid, outage risk and EPA proposals

Due to retirement of nuclear and dispatchable thermal generation and addition of intermittent solar and wind resources, US cities face rising risks of electricity outages. The MISO region which stretches from Minnesota to Louisiana is cited by NERC as having the greatest risk of power outages, even in normal conditions. Outage risk in more extreme weather conditions is cited for New York, New England and the entire Western US. NERC cites peak loads rising at "an alarming rate" due to electrification, coinciding with more intermittent generation and 80-110 GW of nuclear and fossil fuel retirements by 2033 (~7% of current installed capacity). "Reserve margins" indicate buffers to deal with a spike in summer demand and are shown in the chart on the left[13].

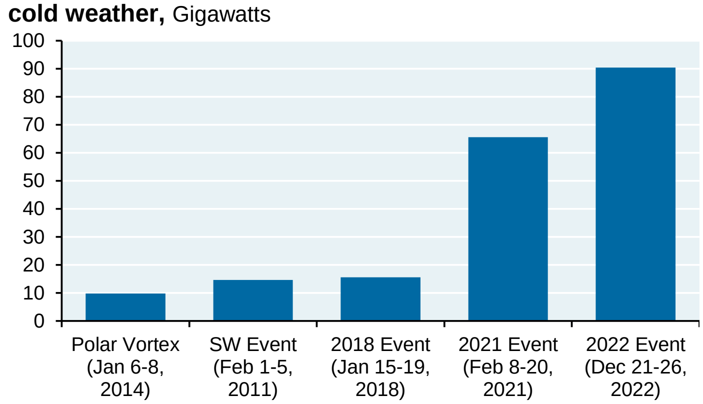
As shown on the right, unanticipated generation losses have been increasing during storms. In 2022, 90 GW of sidelined generation capacity represented ~13% of anticipated generation resources in the Eastern US. For everyone upset about wind outages during storms, look at the pie chart: **it's the natural gas system that led to the majority of *unplanned* electricity outages during the December 2022 winter storm, not renewables whose winter output is *expected* to be low**. To be clear, NERC is not arguing in favor of more renewables here; they argue for more investment in equipment winterization, gas storage and transmission.

Generation capacity buffer during peak summer demand
Anticipated reserve margin



Source: *"2023 Long-Term Reliability Assessment"*, NERC, December 2023

Peak unavailable national electricity generation due to cold weather, Gigawatts



Source: *"Winter Storm Elliott Report"*, FERC, NERC, October 2023

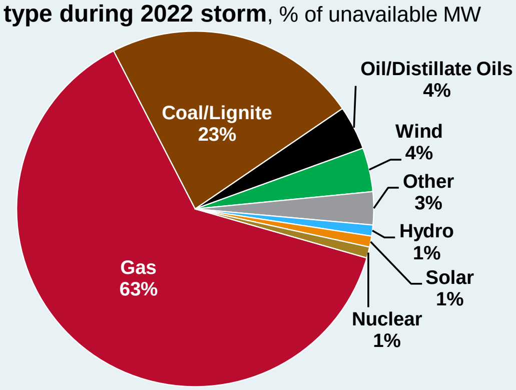
A cry for help from MISO regarding EPA proposals

MISO now warns of "immediate and serious challenges" to grid reliability due to wind/solar intermittency, and disclosed that it averted a capacity shortfall in 2023 only due to postponement of planned generation retirements. Demand continues to grow due to electrification while new projects are delayed due to supply chain and regulatory issues.

MISO's report warned of adverse consequences from current EPA proposals which would effectively require all coal plants, some existing natural gas plants and all new gas plants to (a) retire by a certain date, (b) retrofit with carbon capture and storage or (c) co-fire with green hydrogen. MISO cites cost and technological readiness as constraints to implementation of EPA proposals.

"*MISO's Response to the Reliability Imperative*", Feb 2024

Unplanned generation outages, derates and failures to start by fuel type during 2022 storm, % of unavailable MW



Source: *"Winter Storm Elliott Report"*, FERC, NERC, October 2023

[13] **A note on NERC anticipated reserve margins**. Variable resources such as wind and solar are "derated" by NERC to their expected peak value. For summer wind, expected peak capacity is often only 10%-20% of nameplate capacity. For summer solar, expected values are closer to 60% of nameplate. In winter, wind is derated to 5%-15% of nameplate while solar is derated close to zero. Source: NERC Reliability Assessment Director

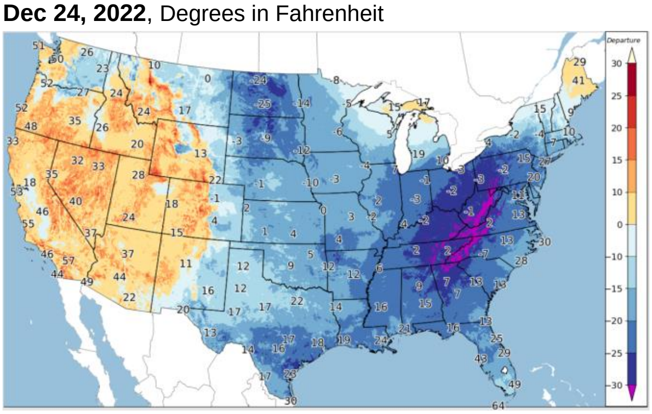
Local gas distribution systems

As bad as electricity outages are, widespread natural gas outages in large cities would be worse. This is what happened and what almost happened in December 2022[14]:

- Temperatures 20-30 degrees below normal (see map) resulted in the failure of gas production wellheads, pipelines and distribution systems. Dry gas production in the lower 48 states fell by 16%, with Marcellus and Utica production falling by 23%-54%
- On Christmas Eve morning 2022, interstate natural gas pipelines serving Con Edison experienced drops in pressure due to production losses and operational issues. By noon the pipelines informed Con Edison that pressure would not improve unless demand decreased
- Con Edison was close to having to cut gas service to customers, leaving them unable to heat buildings while outside temperatures were in the single digits. Con Ed supplemented its gas supply by drawing on its backup LNG facility until systemwide pressure was normalized, and ended up narrowly avoiding a gas system outage
- If a gas outage occurred, local gas distribution companies would need to go **building-by-building** and shut off gas valves to ensure that residual gas does not seep through units whose pilot lights are out. During the system restoration process, the main distribution system would be purged; then workers would have to ensure at each point of service that heating and cooking gas lines are safely purged and operational before restoring service and relighting pilot lights. Homes or buildings with safety issues would need remediation before any gas restoration. **Even losing service to 130,000 customers could have taken five to seven weeks (!!) to restore**. A large outage could also cause extensive property damage due to burst water pipes within homes and buildings since water expands when it freezes

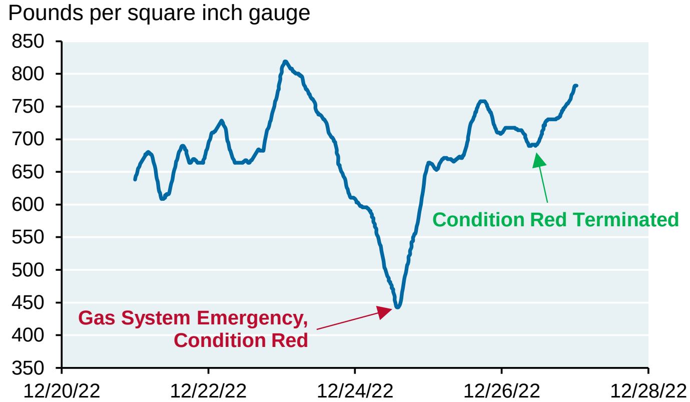
FERC/NERC solutions include winterization of gas equipment, more LNG backup supply and more fixed non-interruptible gas contracts[15] which in turn would require more gas production and distribution. Reinvestment in the natural gas industry is not popular at a time when all eyes are focused on the renewable transition. **But if the transition to Electravision takes more time than expected, such investment may be inevitable.**

Departure from Average Daily Minimum temperature, Dec 24, 2022, Degrees in Fahrenheit



Source: "*Winter Storm Elliott Report*", FERC, NERC, October 2023

Con Edison average meter station inlet pressure
Pounds per square inch gauge



Source: *"Winter Storm Elliott Report"*, FERC, NERC, October 2023

[14] *"Winter Storm Elliott Report: Inquiry into Bulk-Power System Operations During December 2022",* FERC, NERC and Regional Entity Staff Report, October 2023

[15] When gas customers sign firm contracts, both pipelines and supply are designed to meet customer demand at all times. In contrast, **interruptible customers pay a much lower price than firm rates since they do not have pipeline capacity set aside for them**. Even so, customers with interruptible contracts sometimes draw when not permitted, particularly during severe storms. While there are financial penalties involved, that doesn't solve the real-time problem of customers situated upstream consuming more than their designated amounts, causing severe problems for customers downstream. This is what happened to Con Ed during Winter Storm Elliott.

The latest from Vaclav Smil

For many years, Vaclav served as our technical science advisor on this paper. His insights and suggestions were invaluable and the opportunity to learn from him is one of the highlights of my 36 years at JP Morgan. Vaclav turned 80 last year and we still correspond on a variety of topics. He sent me an essay he just completed which he has allowed me to share, which you can read **here**. Some passages from its introduction (bolding is mine):

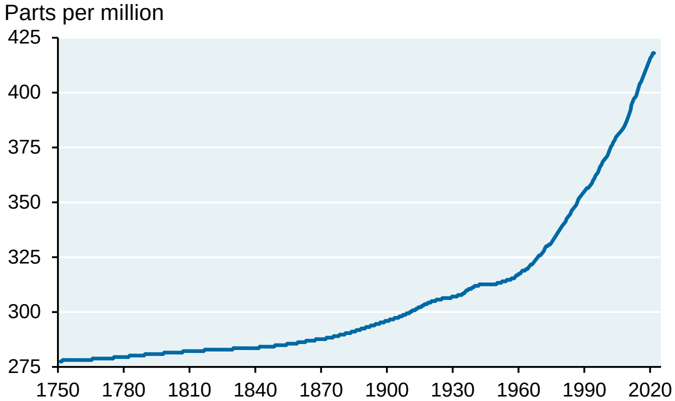
> "In mass terms, we will never run out of fossil fuels: enormous quantities of coal and hydrocarbons will remain in the ground after we end their use because it would be too expensive to extract them. Although the world of the early 2020s is in no imminent danger of running out of fossil fuels, **in 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 CO, nitrogen (NO, NO_2) and sulfur (SO_2 and SO_3) 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 CH_4 (from rice fields, landfills, cattle, and natural gas production), and N_2O (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 CH_4 and N_2O, has translated to about 1^{o}C of global warming compared to the 19th-century mean. 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"

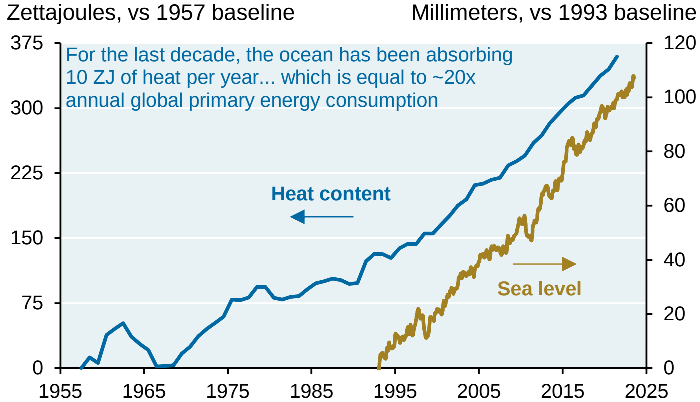
The remainder of Vaclav's essay walks through accomplishments and setbacks in the transition to date, future energy demand, green hydrogen for steel production, materials required per MW for wind vs natural gas, the energy intensity of new transmission capacity, transition costs and a lot of other topics. Vaclav's essay is a great read for anyone looking to learn more about the transition from one of the world's preeminent energy scientists.

Atmospheric CO_2 concentrations
Parts per million



Source: National Oceanic and Atmospheric Administration, May 2023

Ocean heat content and sea level
Zettajoules, vs 1957 baseline Millimeters, vs 1993 baseline

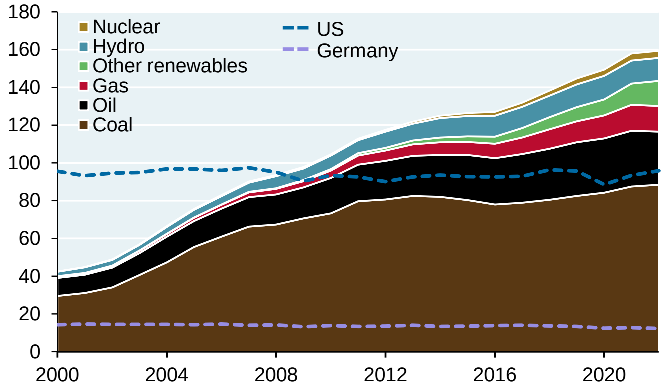


Source: NASA/NOAA, JPMAM, 2023. 1 ZJ = 10^{21} joules.

All Eyes on China: the world's largest energy user is building a lot of everything

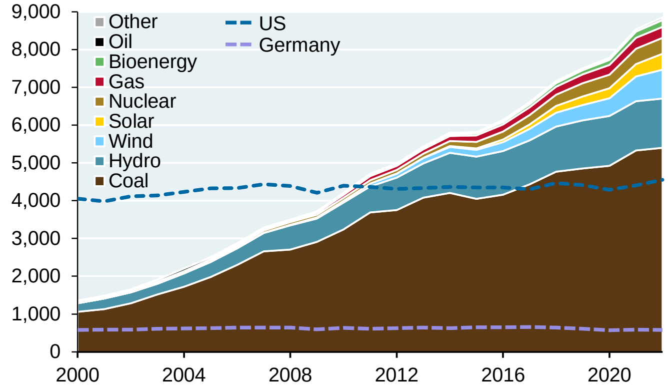
Twenty years ago, Chinese energy consumption was a fraction of US levels and not much higher than Germany. Today, China's primary energy and power consumption are larger than the US and Germany combined. That's why there's so much attention paid to China's progress on decarbonization.

China primary energy consumption by type
Exajoules



Source: EI Statistical Review of World Energy, JPMAM, 2023

China electricity generation by source
TWh



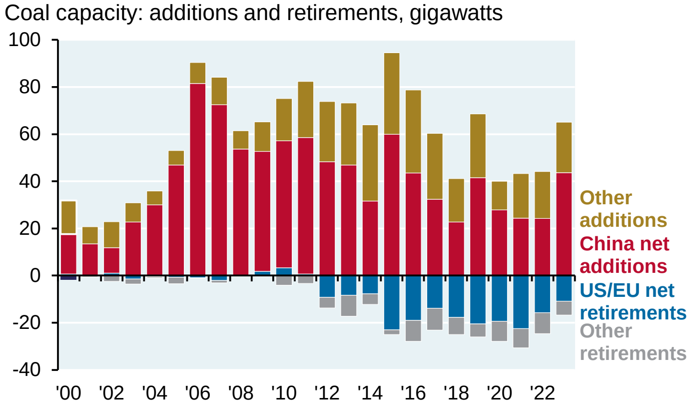
Source: EI Statistical Review of World Energy, JPMAM, 2023

A lot of attention is paid to China's continued construction of new coal plants, and we have shown the chart below for many years. China approved 106 GW of new coal plants in 2023, increasing its total coal pipeline to 200 GW. China and India coal consumption rose by 5% and 8% in 2023, offsetting a 20% decline in the US/EU and driving global coal consumption up by 1.4% in 2023 to a new record level.

That said, China is also building out large amounts of renewables and nuclear as well:

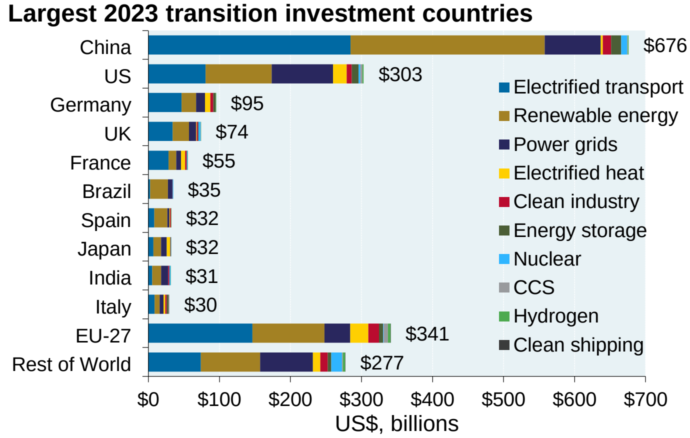
- China installed ~230 GW of new wind and solar power in 2023 with growth rates of ~100% y/y
- As shown on p.4, China's electrification of energy use has surpassed the US and Europe and is still rising
- China's BEV share of vehicle sales is now ~25% with another 10% from PHEVs, much higher than the US
- As of February 2023, China had 57 GW of nuclear in operation, 30 GW under construction, 46 GW of proposed plants and 175 GW in the distant planning stage
- The coal share of China's primary energy consumption has fallen by ~1.3% per year since 2011, declining from 70% to 55%
- China's investments in the grid have reduced its solar curtailment to just 2%, down from 10% in 2020[16]
- The chart at the bottom right shows how **China is the primary global driver of energy transition investment**

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



Source: Global Energy Monitor, JPMAM, January 2024

Largest 2023 transition investment countries

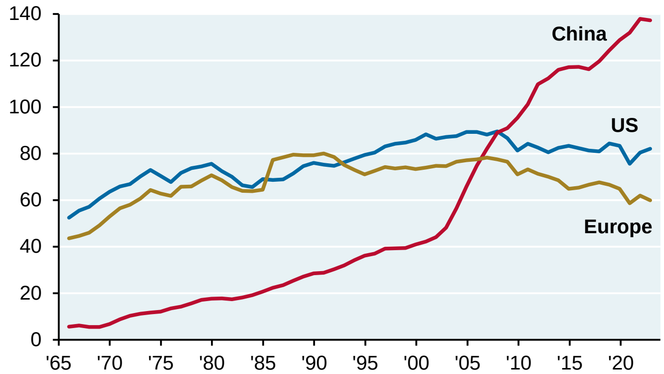


Source: BloombergNEF, JPMAM, 2024

16 *"How China became the global renewables leader"*, Wood Mackenzie, November 20, 2023

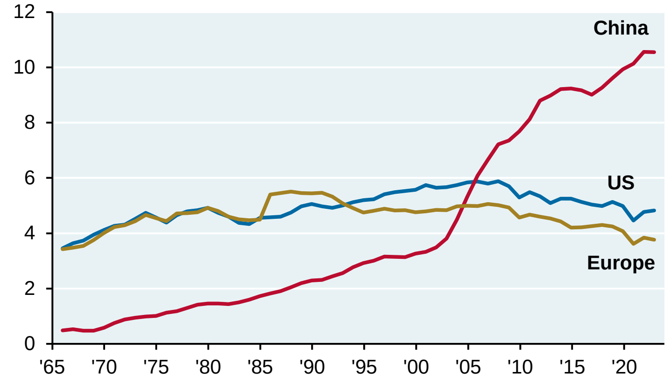
That's good news but China's energy demand has been growing, unlike stagnant energy consumption in the West. As a result, renewable *shares* of China's energy and electricity use are not as indicative of emissions declines as they are in developed countries. The charts below show *absolute* levels of emissions and fossil fuel consumption. Is China close to an emissions plateau? It's tempting to think it might be given China's ongoing investments in renewable energy and nuclear power. The next 3-4 years will tell us what we need to know; keep in mind that the prior plateau from 2013-2017 ended up being a head fake.

Fossil fuel consumption
Quadrillion BTUs



Source: EI Statistical Review of World Energy, JPMAM, 2023

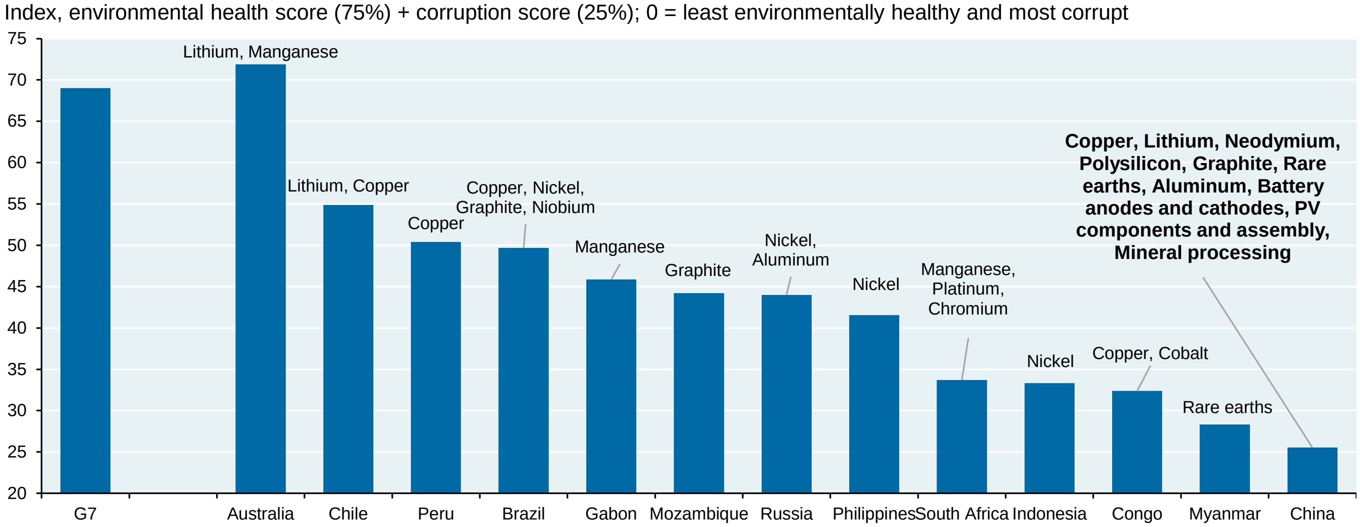
CO_2 emissions from energy
Billion tonnes of carbon dioxide



Source: EI Statistical Review of World Energy, JPMAM, 2023

In last year's paper we included a long section on renewable supply chains and China. The challenge for the G7 is illustrated below. The Y axis shows an index of environmental health and corruption by country (the lower the value, the more environmentally unhealthy and corrupt each country is), along with descriptions of each country's presence in renewable supply chains. Other than Australia, most of these countries score poorly, particularly China. **As a result, while the G7 can try and develop its own natural resource and processing supply chains for renewables, they will be competing with countries like China that can almost always do so more cheaply and with much less regulatory oversight.** Two examples from prior Eye on the Market pieces: China's unregulated rare earth element industry reportedly accounts for 40%+ of its total REE output, and Chinese polysilicon plants (which dominate global solar supply chains) routinely dump toxic waste into rivers and lakes, which is one reason why 70% of China's rivers and lakes are unfit for human use.

Transition minerals are generally sourced and processed in countries with poor environmental protections and a lot of corruption
Index, environmental health score (75%) + corruption score (25%); 0 = least environmentally healthy and most corrupt

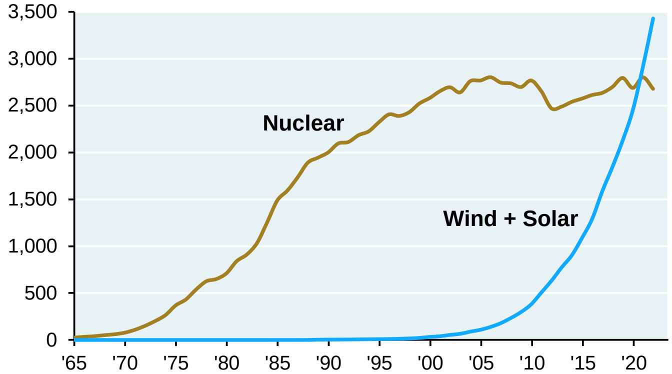


Environmental health: PM 2.5, NO_x, SO_2, CO, heavy metals, ozone, lead, drinking water, biodiversity, etc
Source: Yale EPI Environmental Index, Transparency International, JPMAM. 2023.

Essential energy transition charts

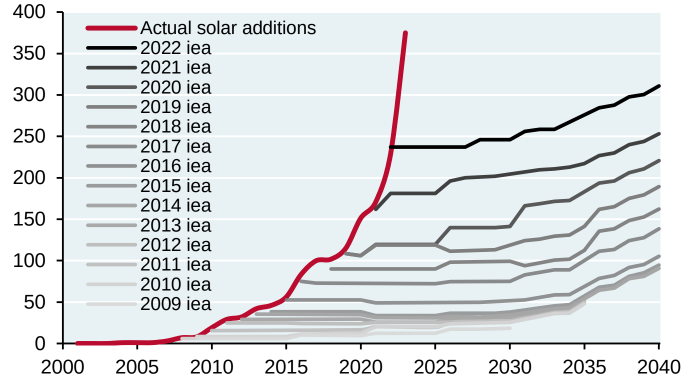
Every year we include charts that track the progress, costs and challenges of the energy transition. This page: global wind/solar generation soar past nuclear; the IEA consistently underestimates solar capacity additions; ISO capacity credits show that when 1 MW of wind/solar is added to the grid, thermal gas/coal requirements only fall by 10%-25% of that amount due to wind/solar intermittency; fossil fuel shares of primary energy are falling faster in China and Europe than in the US; global hydropower capacity factors have been declining; and coal shares of primary energy have been flat or falling with the exception of Vietnam and Indonesia.

Global nuclear vs wind + solar electricity generation
Terawatt-hours



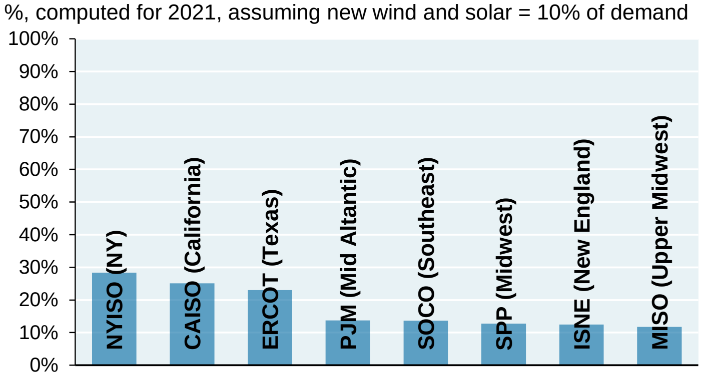
Source: EI Statistical Review of World Energy, JPMAM, 2023

IEA consistently underestimated solar capacity growth
GW of global annual solar additions vs IEA 10-year forecasts



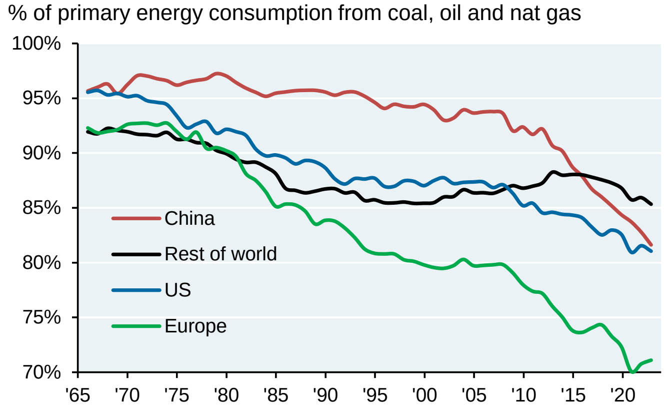
Source: Carbon Brief, BNEF. 2023. IEA = International Energy Agency.

How much natural gas capacity can be reduced per MW of new wind and solar power?
%, computed for 2021, assuming new wind and solar = 10% of demand



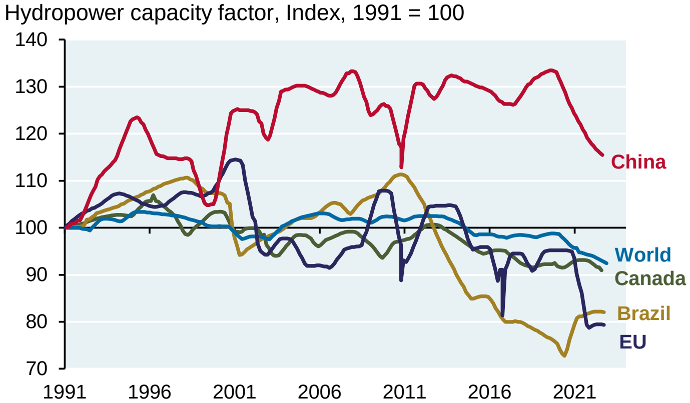
Source: EIA data, JPMAM computations, 2022

Fossil fuel share of primary energy since 1965
% of primary energy consumption from coal, oil and nat gas



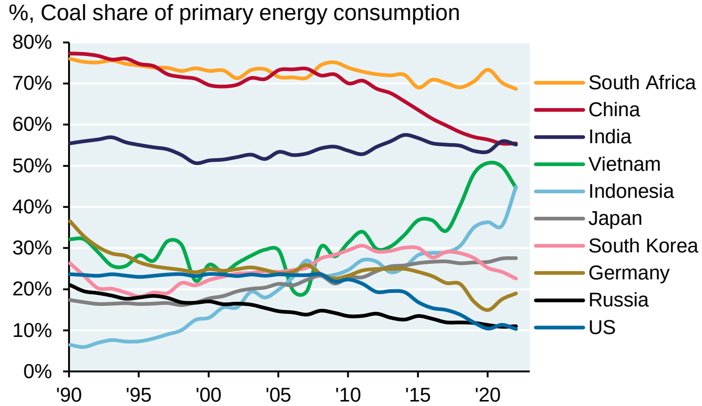
Source: EI Statistical Review of World Energy, JPMAM, 2023

Falling water
Hydropower capacity factor, Index, 1991 = 100



Source: IEA, JPMAM, 2023

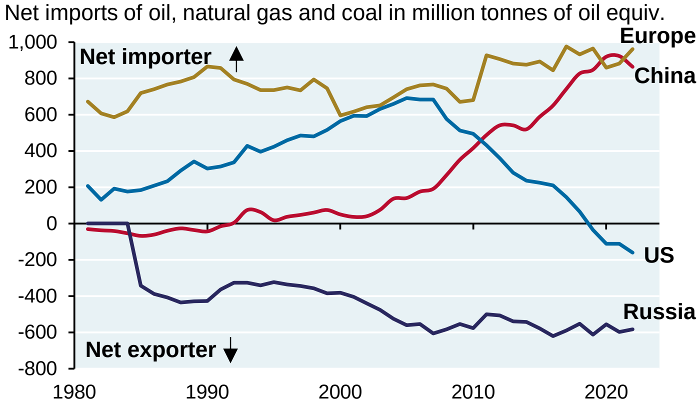
Top Ten consumers of coal by energy content
%, Coal share of primary energy consumption



Source: EI Statistical Review of World Energy, JPMAM. 2023.

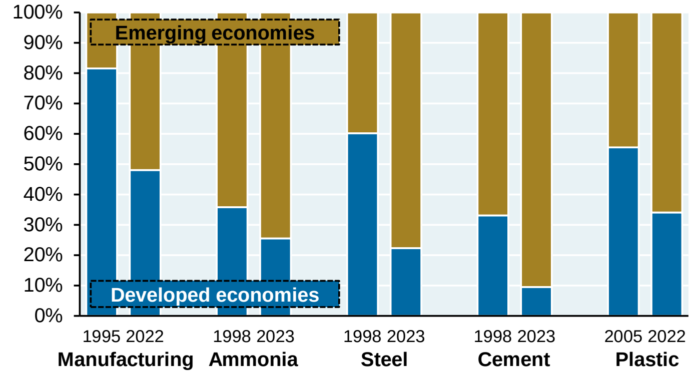
On this page: the US has achieved US energy independence for the first time in 40 years while Europe and China compete for global energy resources; energy intensive manufacturing has been shifting to the developing world for reasons related to developed world outsourcing and the developing world's own consumption; renewable jet fuel alternatives are very expensive, resulting in cost and supply challenges if the US military attempts to decarbonize energy use for aviation[17]. As per the last two charts, CCS faces a fundamental physical challenge: while coal and gas plants account for the bulk of industrial emissions, they have among the lowest flue gas concentrations of CO_2, which increases the cost and complexity of capturing and sequestering it.

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



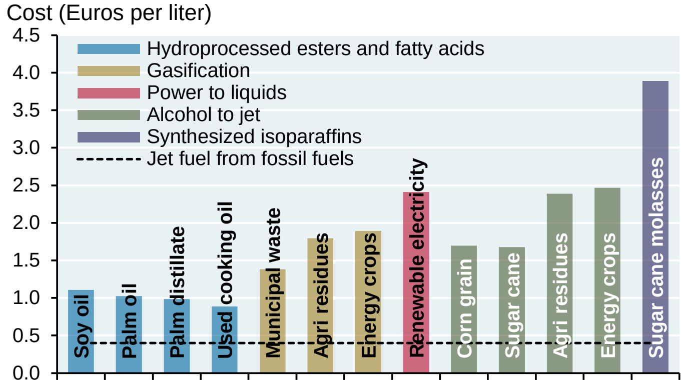
Source: EI Statistical Review of World Energy, JPMAM, 2023

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



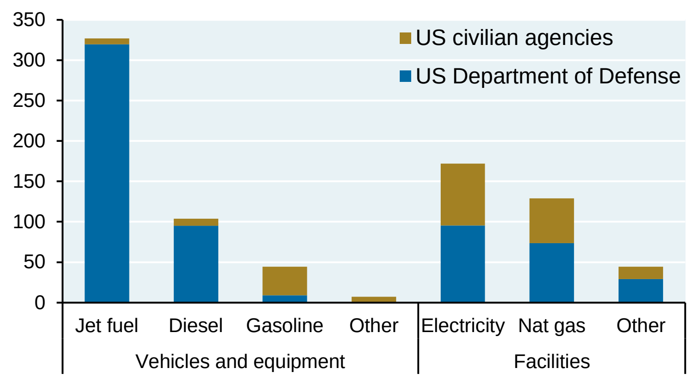
Source: UN DESA, Worldsteel, Plastics*Europe*, USGS, JPMAM, 2024

Renewable jet fuel cost estimates
Cost (Euros per liter)



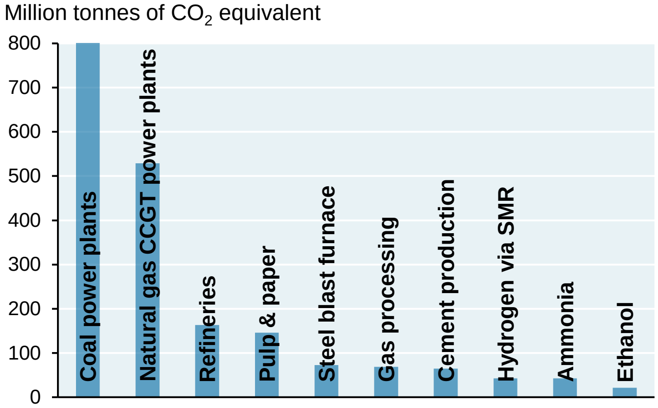
Source: Royal Society Policy Briefing, February 2023. Energy crops include oilseed, miscanthus and poplar.

Federal gov't energy consumption
Trillion BTUs



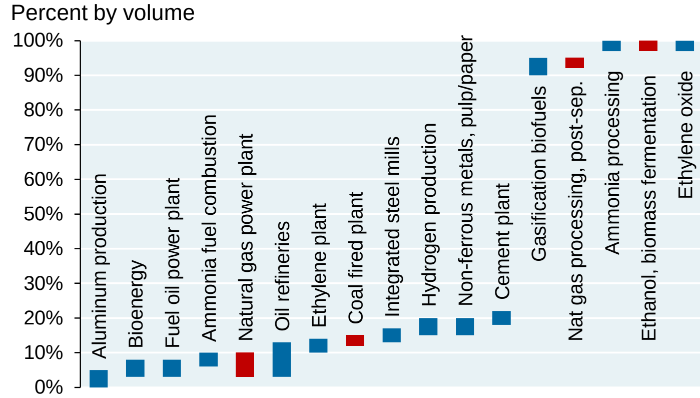
Source: DOE, JPMAM, 2022

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.

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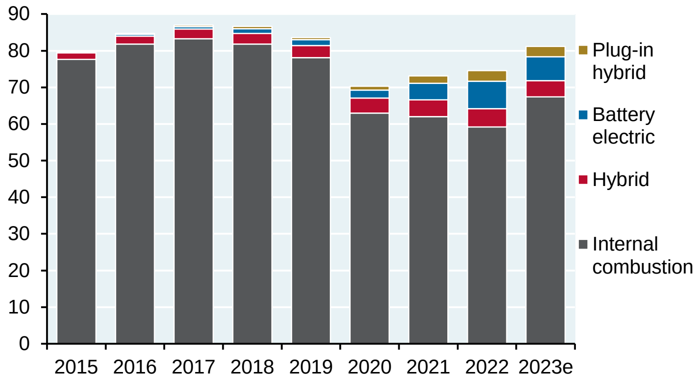
[17] And to be clear, an EV version of the 60-tonne M1 Abrams tank is absurd; it would require a battery that weighs 2/3 of the tank itself to match its 250 mile range

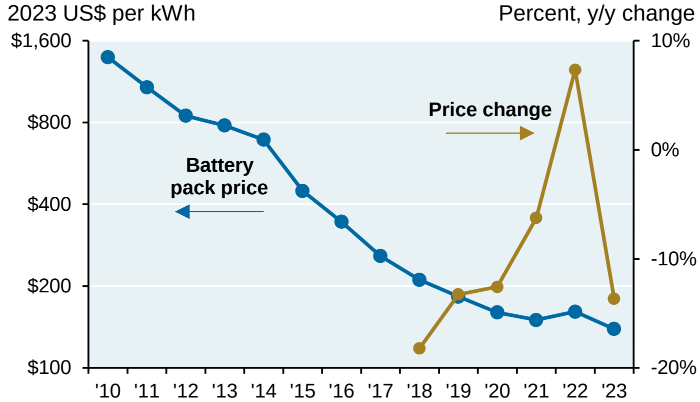
On this page: global ICE passenger car sales rebounded in 2023; lithium ion battery pack prices continue to decline after a temporary spike in 2022; EV metals costs per battery type explain why LFP batteries are preferred by automakers (i.e., no cobalt or nickel); China and Europe rank at the top of EVs as a share of car sales; US gasoline demand appears to have peaked since miles traveled have reached pre-COVID levels while gasoline demand has not; and the mileage of internal combustion engine cars by model year continues to rise. Notes: global gasoline demand has risen above its 2019 peak, in contrast to the US data; and Germany EV sales have declined in share terms due to the expiration of certain purchase subsidies.

Global passenger vehicle sales by drivetrain
Vehicles, millions



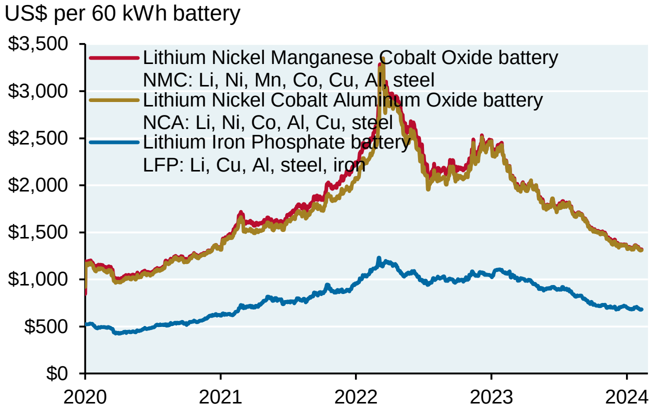
Source: BloombergNEF, December 2023

Volume-weighted average lithium-ion battery pack price
2023 US$ per kWh — Percent, y/y change



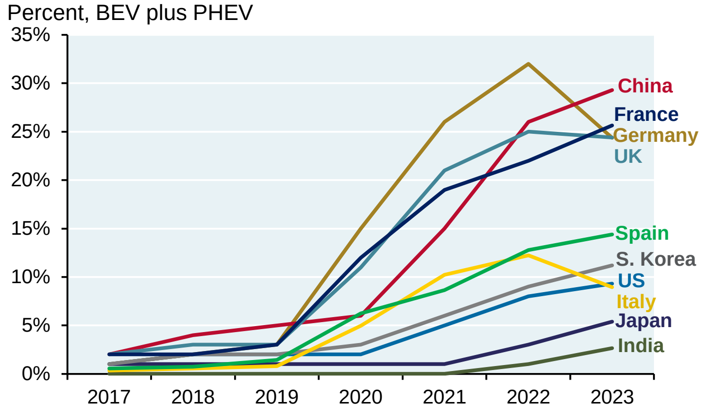
Source: BloombergNEF, December 2023

Estimated metals cost per EV battery type
US$ per 60 kWh battery



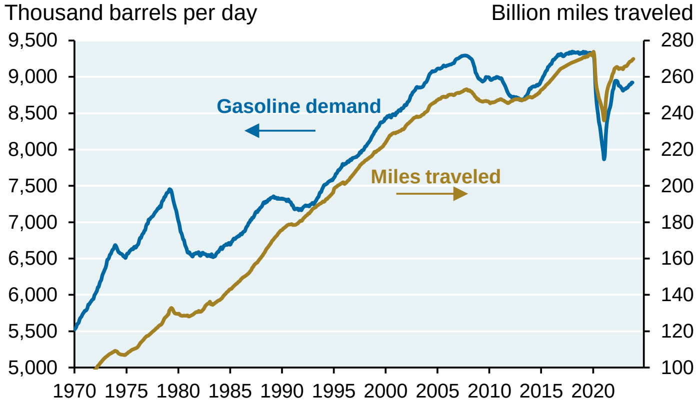
Source: Uni. of Birmingham (UK), ANL, Bloomberg, JPMAM, Feb 13, 2024

EV share of passenger vehicle sales, largest car markets
Percent, BEV plus PHEV



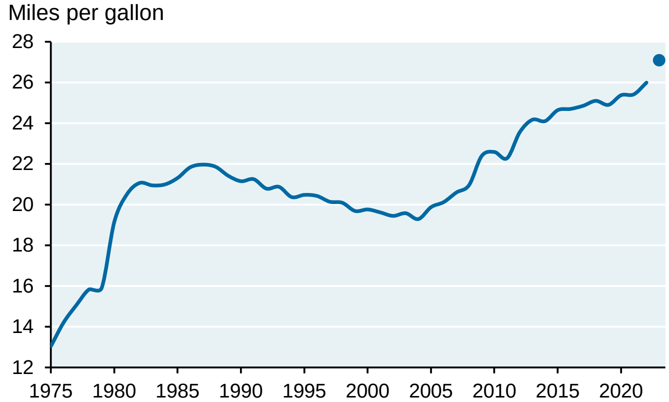
Source: BloombergNEF, Bloomberg, JPMAM, Q3 2023

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



Source: Bloomberg, JPMAM, December 2023

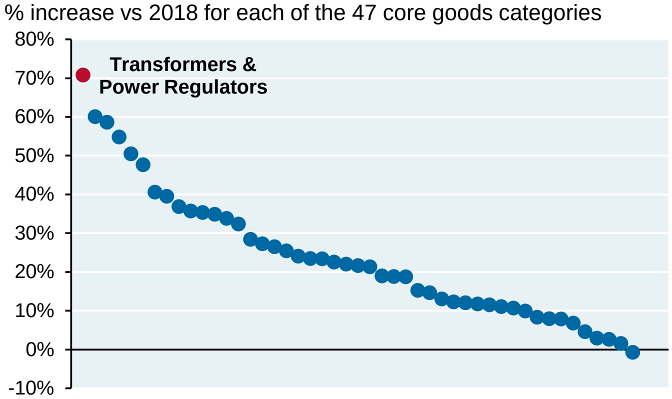
US real-world average fuel economy by model year
Miles per gallon



Source: EPA, JPMAM, 2023

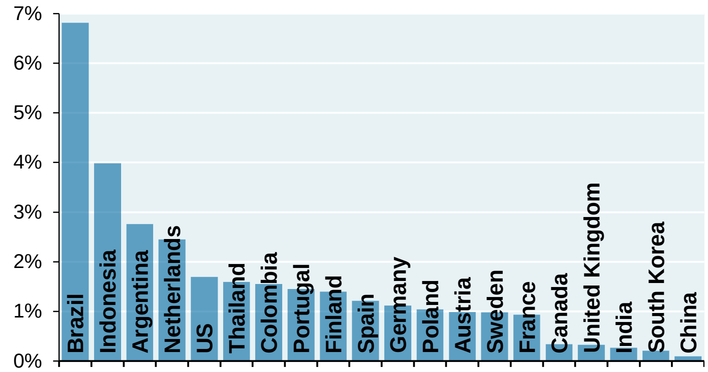
On this page: transformer and other transmission equipment have seen the highest inflation of all producer goods since 2019; biofuels produced from corn, sugarcane and palm oil are generally small at 1% of primary energy, with the exception of Brazil and Indonesia; hydraulically fractured oil and gas production has been a growing part of US energy supplies, now accounting for >50% of primary energy consumption; planned CCS capacity is 6%-7% of current emissions in the US and Europe but CCS project completion rates have historically been low, so the projections are speculative. Last chart: the large energy deficit resulting from production of synthetic fuels, using the example of a Sabatier reactor to produce green methane from atmospheric CO_2 and green hydrogen. In addition to the energy deficit, there's also the cost of carbon capture equipment and electrolyzers to consider. We will discuss synthetic fuels in greater detail next year.

Core goods PPI component inflation
% increase vs 2018 for each of the 47 core goods categories



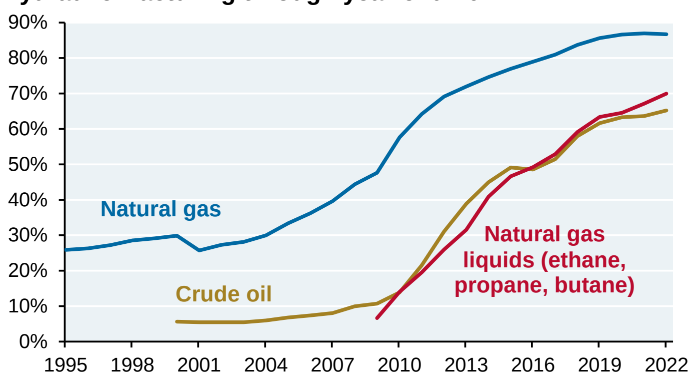
Source: Bloomberg, JPMAM, February 2024

Biofuel production as a percent of primary energy
Percent



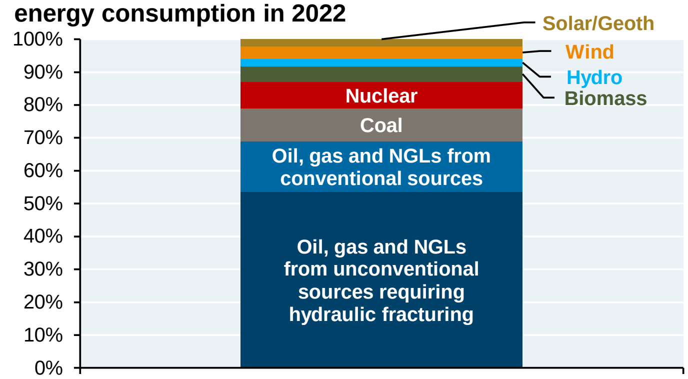
Source: EI Statistical Review of World Energy, JPMAM, 2023

Percentage of US oil and gas production derived from hydraulic fracturing through year-end 2022



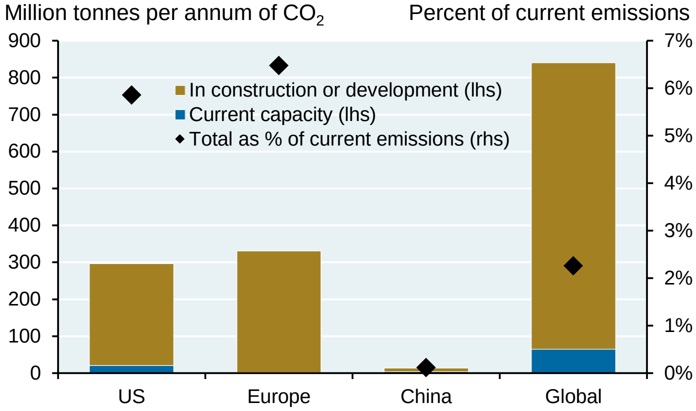
Source: EIA, US Department of Energy, JPMAM, 2022

Hydraulic fracturing accounted for 53% of all US primary energy consumption in 2022



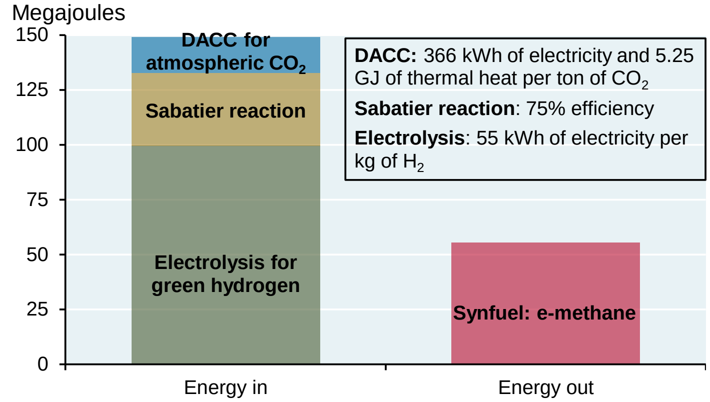
Source: EIA, BP, Society of Petroleum Engineers, S&P Platts, JPMAM. 2022.

Current vs planned carbon sequestration by 2030
Million tonnes per annum of CO_2 Percent of current emissions



Source: Global CCS Institute, OWID, JPMAM. 2024.

Production of 1 kg of e-methane via Sabatier reaction
Megajoules

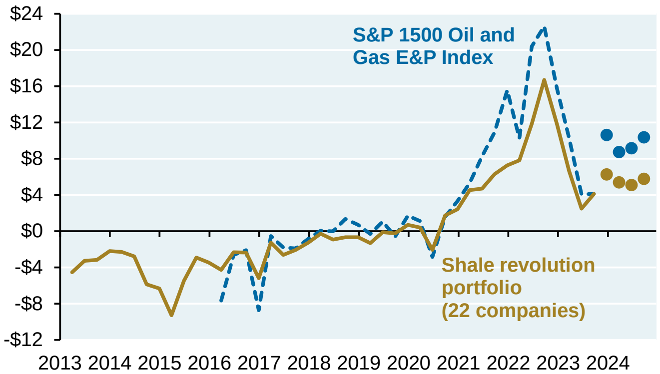


Source: Spitfire Research, Keith et al (DACC), JPMAM, 2024

Investment returns in oil & gas, renewable energy and nuclear-exposed shares

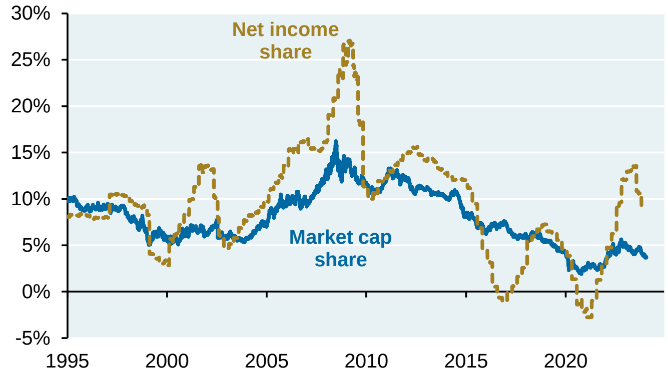
The profitability of the traditional energy sector improved substantially after the profitless period from 2013-2020. However, energy sector valuation multiples remain low due to concerns about stranded asset risk, and the degree to which some institutional investors either cannot or will not invest in the sector. From 2021 to November 2023, the best energy trade was to be long traditional (legacy) energy sectors and be short renewable energy. The Fed pivot in November 2023 revived renewable valuations; I don't think there's a clear cut winner for 2024 now that most of the damage has been done to unprofitable energy business models. Note at the bottom how US oil and gas production is soaring.

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



Source: Bloomberg, JPMAM, Q3 2023

S&P 500 energy share of market cap and net income
Percent



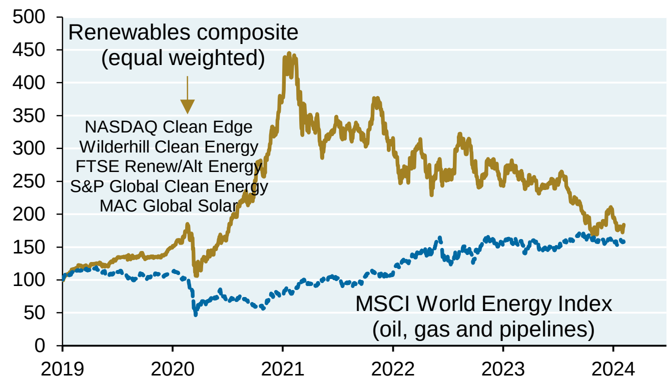
Source: Factset, JPMAM, February 12, 2024

Percentile rank of energy sector valuations relative to S&P 1500, start of available data to Jan 2024

	Enterprise value to cash flow (EBITDA)		Free cash flow yield	
	Last 12 M	Next 12 M	Last 12 M	Next 12 M
Oil & Gas Drilling	0	3	73	95
Oil & Gas Equipment & Services	1	0	96	98
Integrated Oil & Gas	4	2	87	84
Oil & Gas Exploration & Production	4	8	85	83
Oil & Gas Refining & Marketing	6	17	91	90
Oil & Gas Storage & Transport	8	5	81	82
Energy	2	4	87	85

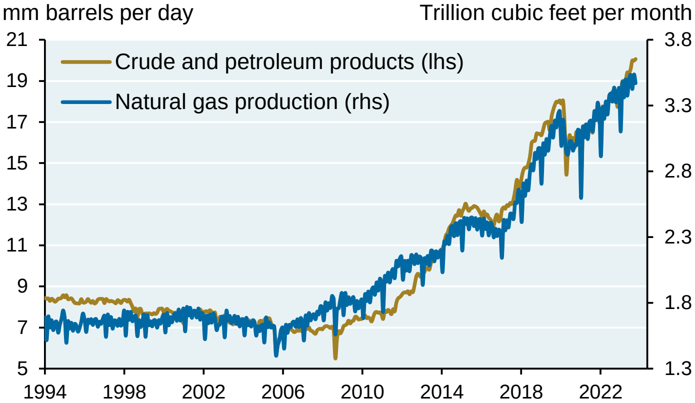
Source: FactSet, JPMAM, January 2024

Investment returns: renewables vs traditional energy
Index (100 = Jan 2019)



Source: Bloomberg, JPMAM, February 9, 2024

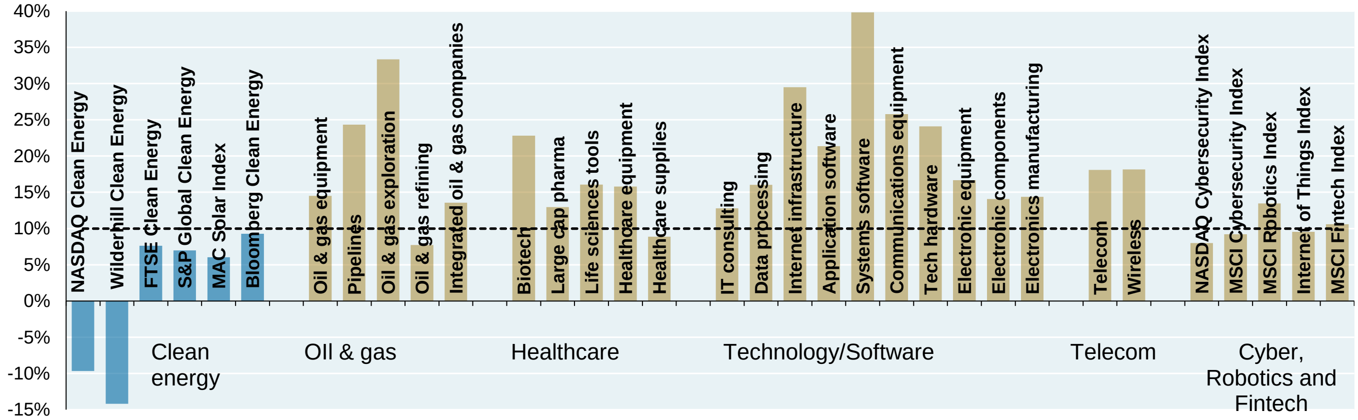
US oil and gas production soaring
mm barrels per day
Trillion cubic feet per month



Source: Bloomberg, JPMAM, November 2023

A primary reason why renewable energy indexes have not performed as well as many investors expected: **despite being seen as growth stocks, their operating margins are generally below a variety of growth sectors and traditional oil & gas sectors as well**.

Operating margins by sector and index

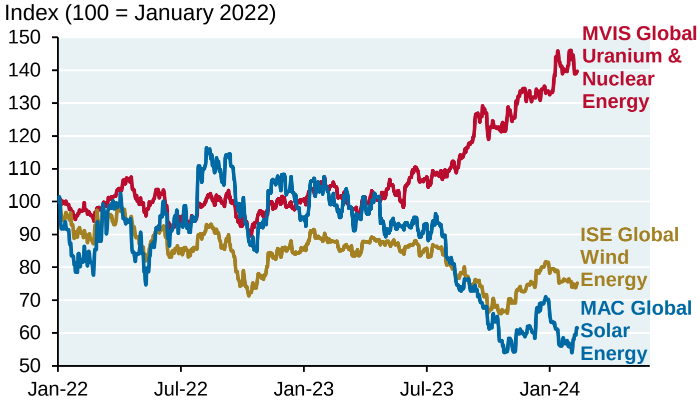


Source: Bloomberg, JPMAM, March 1, 2024

The other notable trend: a 2023 rally in companies linked to nuclear energy. As we discuss in the next section, there's a lot of talk of a nuclear renaissance in the West. So far there's little evidence of this, but China, India and Russia have a lot of MW either under construction or in the planning phase (see table). The MVIS Global Uranium & Nuclear Energy Index tracks performance of companies in the uranium and nuclear energy industries with at least 50% of revenues from nuclear. The spot price of uranium has reached a post-Fukushima high, a level which may spur more mining projects. The top 3 performers in the table are uranium producers.

Global energy ETF prices

Index (100 = January 2022)



Source: Bloomberg, JPMAM, February 13, 2024

Largest 10 positions in Global Uranium & Nuclear Energy ETF

Name	Country	Return in USD since 1/1/2023
Global Uranium & Nuclear Energy ETF	**-**	**43%**
Cameco Corp	Canada	93%
Nexgen Energy	Canada	73%
NAC Kazatomprom	Kazakhstan	60%
Constellation Energy	US	51%
China General Nuclear Power Co	China	37%
CEZ AS	Czech Republic	20%
Endesa Sa	Spain	10%
PG&E Corp	US	1%
Public SVC Enterprise	US	1%
Fortum Oyj	Finland	-22%

Source: Bloomberg, JPMAM, February 12, 2024

Nuclear power on the drawing board, gross GW

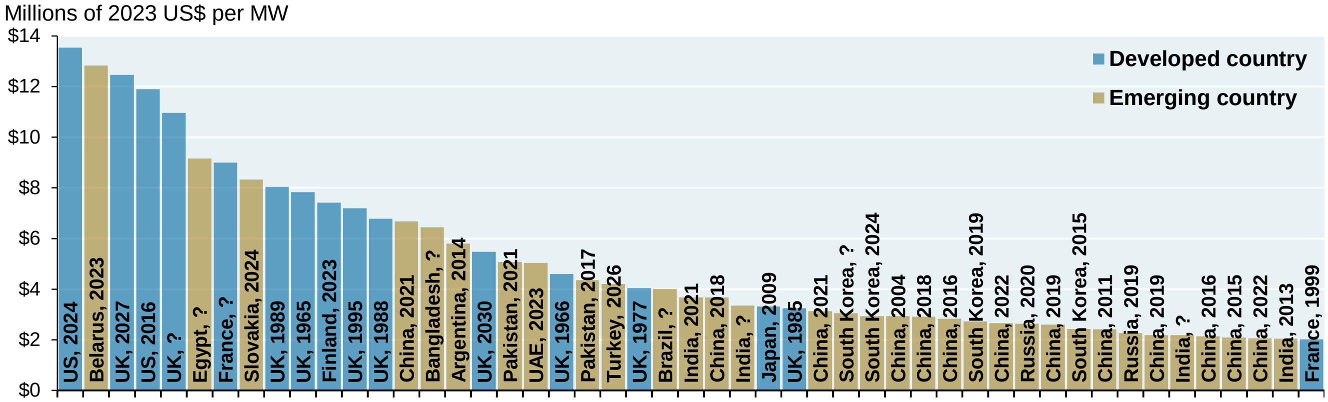
	Under construction	Proposed	Planned
Emerging countries	61	95	304
of which China	30	46	175
Developed countries	9	13	48

Source: World Nuclear Association, 2024

Nuclear power: Elusive measures of true cost, German decommissioning/deindustrialization and NY State

The most elusive questions in energy, other than those related to commercialized fusion[18], revolve around real-world costs of building nuclear fission plants. In December 2023, leaders from 22 countries announced plans to triple nuclear capacity by 2050 and extend the life of existing plants. How much will it cost to build new plants? It depends on which countries you look to as examples. Regional differences explain most of the variations below and these differences are unlikely to go away. The size of a fission plant and type (boiling or light water, pressurized water, fast breeder, etc) do not explain cost differences in any meaningful way. Recent large cost overruns in the US, UK, France and Finland are a logical starting point for any plant undertaken in the West[19].

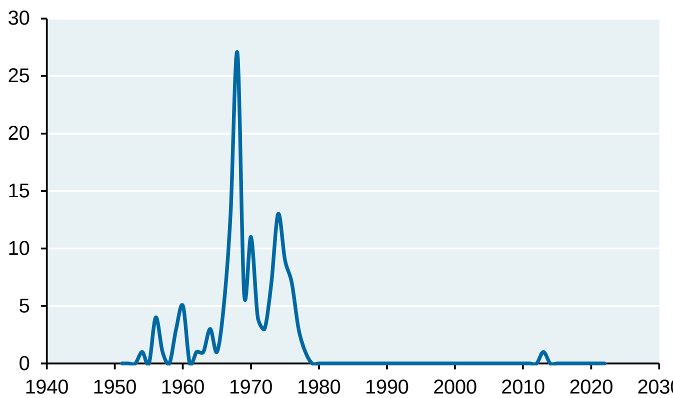
Nuclear capital costs by country and year of completion
Millions of 2023 US$ per MW



Source: Britain Remade, World Nuclear News, Reuters, Bloomberg, AP News, IEEFA, 2023

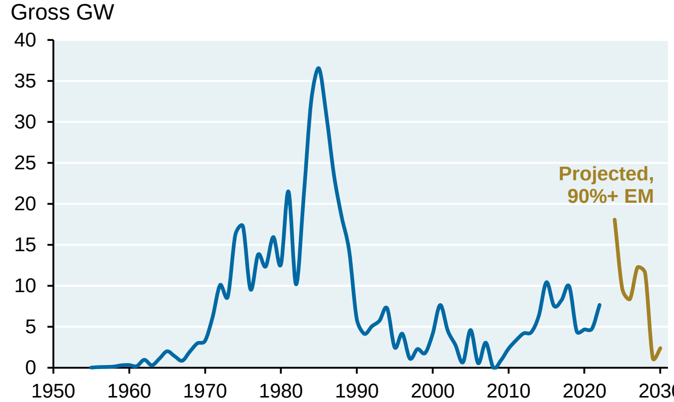
What about the "once we build more of them, the price will go down" argument? In the US, nuclear construction would have to really reignite for this effect to materialize. I'm not even sure that 5 plants a year would do it; a pace of 5-10 plants per year might be needed for such synergies to appear.

# of US nuclear plants built by year of construction start



Source: Power Reactor System Database, JPMAM, December 2023

Global nuclear power plants by year of completion
Gross GW



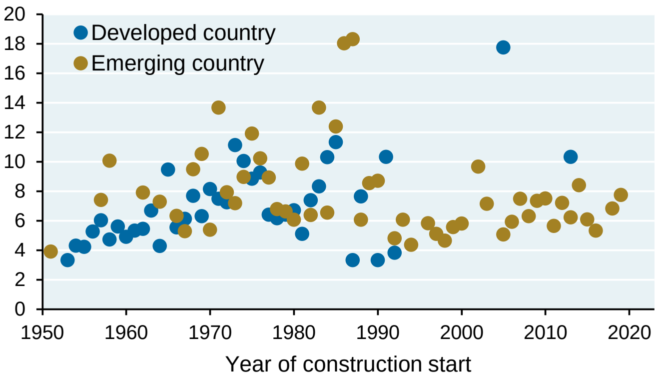
Source: Power Reactor System Database, JPMAM, December 2023

[18] Global investments in **private nuclear fusion companies** have now reached $6.2 billion. Four companies expect to deliver power in 2030, and another 19 expect to deliver power in 2035. Hope springs eternal.

[19] **Flamanville (France)** construction began in 2007; by 2020 it was 5x over budget. Project managers had to address structural anomalies, faulty cooling welds and fire/explosions onsite. Operation is scheduled for 2024 after more delays and cost overruns. **Hinkley Point (UK)** is $13 billion over budget and several years late after the 5th budget increase in 8 years. The total cost is now estimated at $46 billion, double original projections. **Vogtle 3 (Georgia, US)** came in 7 years late and $16 billion over its original $14 billion budget. **Olkiluoto (Finland)** was scheduled to be completed in 2009; it was completed in 2023 and cost $12 billion, three times its original estimate. As shown on the next page, the levelized cost of these plants is much higher than our estimate of a wind-solar-gas system with high renewable penetration and adequate thermal backup capacity.

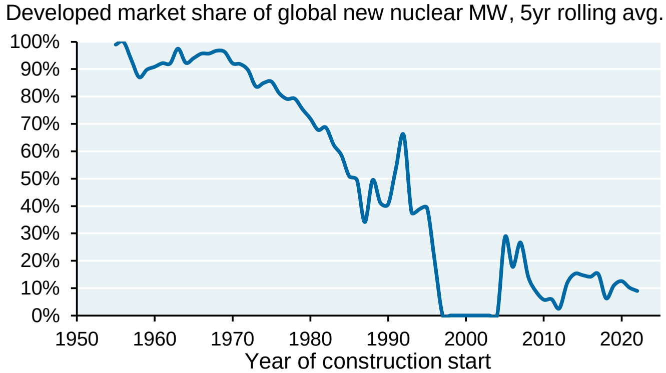
If a country is willing to build nuclear fission plants, how long would it take to complete them? The chart on the left shows how difficult a question is this to answer for the developed world. Average completion times[20] in developed countries ranged from 4 to 10 years for plants whose construction began from 1960 to 1990, but **there are so few observations for developed countries since 1990, it's impossible to know**. Plants have been completed in 6-8 years in *developing* countries such as China, India and Russia but this has nothing to do with what can be accomplished in the West.

Average nuclear plant completion time by year and region
Years



Source: Power Reactor System Database, JPMAM, December 2023

During the 1980's, global nuclear construction shifted from developed to developing countries
Developed market share of global new nuclear MW, 5yr rolling avg.



Source: Power Reactor System Database, JPMAM, December 2023

What happened to NuScale and its small modular reactor project?

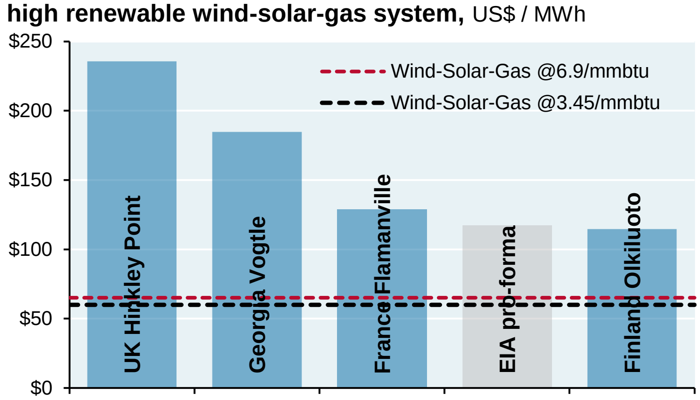
NuScale had a lot going for it: a $1.4 billion cost-sharing deal with the DoE, and design approval from the NRC that bypassed the typical lengthy site permitting process since its six small modular reactors were designed to be built on the DoE's Idaho National Lab site. NuScale claimed that construction costs would be below $3 mm per MW, that it would be built in ~5 years and that it would run at a 95% capacity factor.

Eventually, NuScale scrapped plans to build SMRs when cost estimates soared to $20 mm per MW due in part to rising reinforced concrete prices; its designs require more reinforced concrete per MW than conventional reactors. Even before cost overruns, electricity purchase commitments covered less than 25% of NuScale's output. Then as cost projections rose, electricity buyers gave NuScale an ultimatum: boost commitments to 80% or terminate the project. In November 2023, NuScale conceded the target was unachievable and all parties determined the project should end. SMR hyperbole was everywhere in 2021 but is quieter now. **As I wrote last year, I never understood the logic behind SMRs.** Nuclear power is one of the most capital intensive of all industrial projects, and a significant part of that capital cost is fixed per plant irrespective of its capacity. So why would shrinking the size of a nuclear fission plant be of any economic benefit?

NuScale Power share price
Price, SPAC merger date May 2022

Source: Bloomberg, JPMAM, February 16, 2024

Levelized cost of 4 specific nuclear plants vs cost of high renewable wind-solar-gas system, US$ / MWh



Source: EIA, JPMAM, 2024

[20] Average completion times can obscure massive delays on individual projects. Example: Watts Bar-2 Tennessee (1973, 43 years); Diablo Canyon California (1968, 17 years); and Hartlepool UK (1968, 20 years)

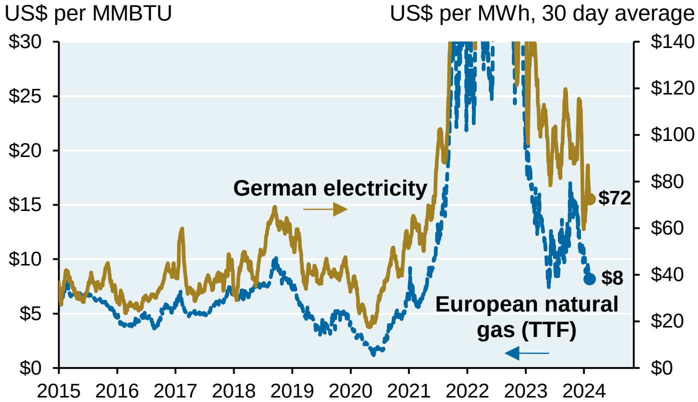
To sum up, there's reason to be cautious about the cost and timing required for the West to increase its baseload nuclear power. **That said, decommissioning *existing* nuclear fission plants is an entirely different matter.** That brings us to the case of Germany and its exposure to Russian energy: had it not decommissioned nuclear, **how exposed would Germany have been to Russia in 2022 when Russia invaded Ukraine?**

First let's look at what did happen. After Russia's invasion in 2022, European electricity and natural gas costs spiked as Russian pipeline imports were replaced by pipeline imports from Norway and expensive LNG imports. While power prices have now fallen from peak levels, they're still ~2x higher than pre-war levels.

A lot has been written on European de-industrialization due to higher energy costs. Impacts include declining German production of energy-intensive goods and German industrial companies negatively affected by high gas prices. Roughly one third of German industrial companies plan to or already did relocate[21], and its petrochemical plants run at just 75% of capacity. The IEA cites declines of ~6% per year in European industrial power demand in 2022/2023 (demand destruction in chemicals, steel and aluminum), which has been the main reason for European power demand falling to levels last seen two decades ago[22]. **There is some good news:** as power prices declined, some curtailed production has been restarted.

EU gas vs German electricity prices

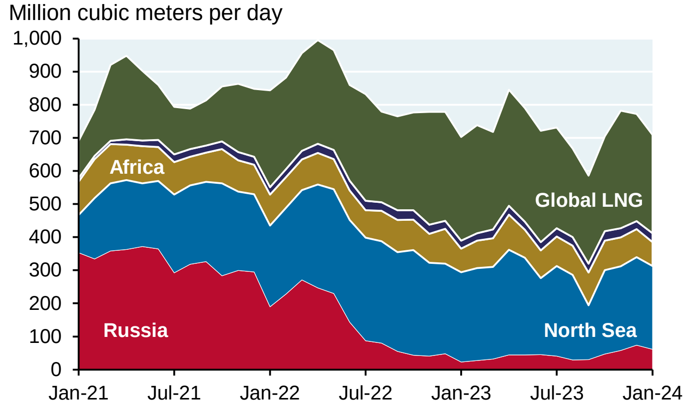
US$ per MMBTU — US$ per MWh, 30 day average



Source: Bloomberg, JPMAM, February 12, 2024

European imports of natural gas and LNG

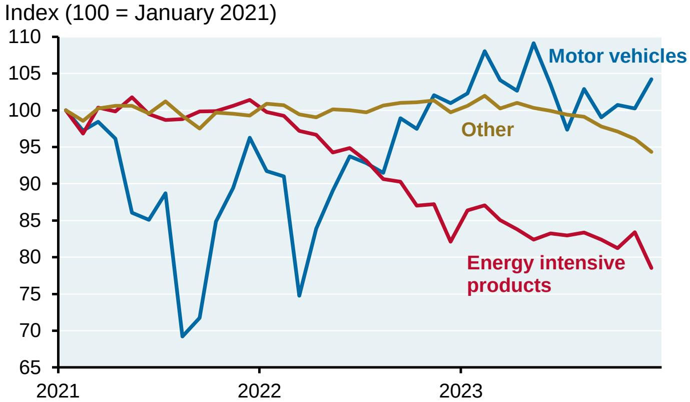
Million cubic meters per day



Source: J.P. Morgan Commodities Research, January 2024

German industrial production

Index (100 = January 2021)



Source: Greg Fuzesi, JP Morgan Economics, December 2023

German industrial plants impacted by high gas costs

Capacities impacted in '000 tonnes per year

Plant	Impact
BASF Ludwigshafen: Caprolactam (95), Cyclohexanone (279), Adipic Acid (270), Ammonia (880), Melarine (65), Toluene Diisocyanate (300), Soda Ash, Cyclohexanol	Shutdown on high production costs
Yara Brunsbuettel: Ammonia (750)	65% utilization
Dow Leuna, Schkopau: Polyethylene (385)	15% rate reduction
Oxxynova: Dimethylterephthalate (240)	Shutdown

Source: Mitsubishi UFJ Financial Group, December 2023

[21] MUFG Energy 2024 Outlook, December 2023

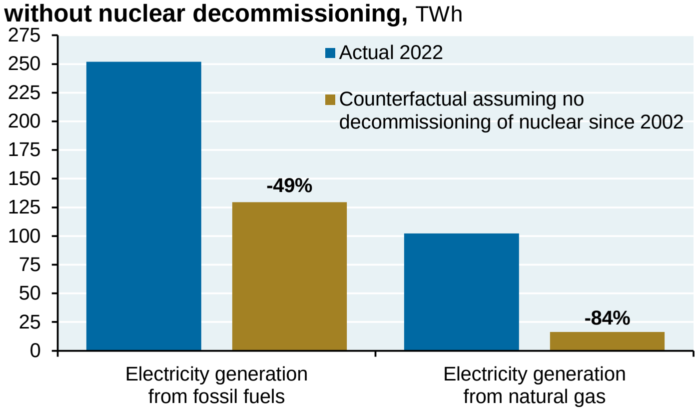
[22] "*Electricity Market Report Update: Outlook for 2023 and 2024*" and "*Electricity 2024*", IEA

Now let's look at what *might* have happened if Germany had not decommissioned nuclear. In 2002, Germany had 24 GW and 164 TWh of nuclear generation which provided 28% of its power needs. After Japan's Fukushima meltdown in 2011, Germany gradually decommissioned its nuclear fleet. By the end of 2021, Germany had only 4.1 GW of nuclear capacity still operating (it has since fallen to zero). Assuming that its nuclear plants were never decommissioned, we can estimate the capacity and generation Germany would have needed from fossil fuels in 2022. Since Germany produces its own coal, we can also estimate imported natural gas Germany would have needed for electricity generation.

Had Germany not decommissioned its nuclear, we estimate that Germany would have needed 50% less electricity generation from fossil fuels and 84% less generation from natural gas in 2022. Large declines are also seen in the counterfactual need for natural gas capacity on the right. Would more German nuclear power have made a difference in 2022? Germany was the largest European importer of gas in 2022; on the margin, its gas demand would have been much lower in this scenario. Would it have been enough of a decline in marginal demand to reduce regional gas and electricity prices? Unclear, but it does seem like Germany's political decisions, domestic subsidy expenses and economic adjustments could have been less painful[23].

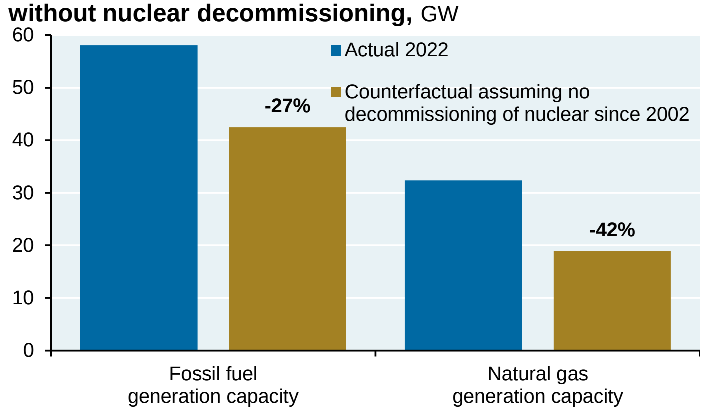
Charts: how exposed would Germany have been to Russia in 2022 had it not decommissioned nuclear power?

German fossil fuel GENERATION required in 2022 with and without nuclear decommissioning, TWh



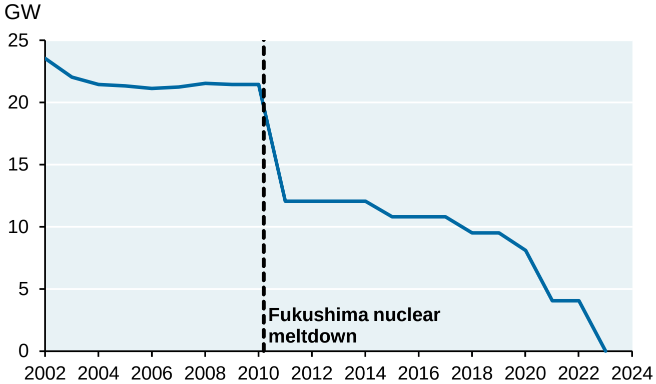
Source: Fraunhofer Institute, Energy Institute, JPMAM, 2023

German fossil fuel CAPACITY required in 2022 with and without nuclear decommissioning, GW



Source: Fraunhofer Institute, Energy Institute, JPMAM, 2023

Germany installed nuclear capacity
GW



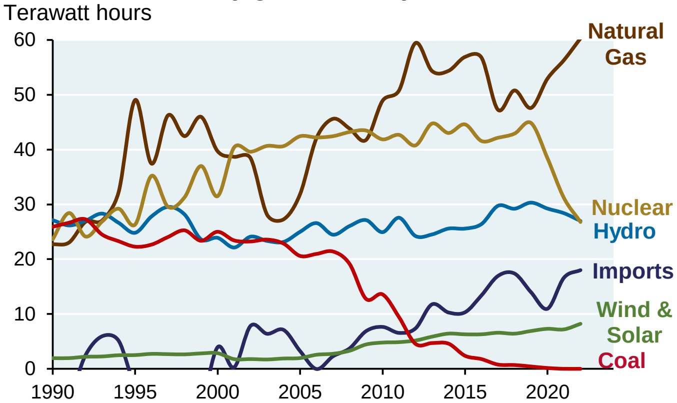
Source: Fraunhofer Institute, JPMAM, 2023

[23] Some analysts link Germany's decision to decommission nuclear power and increase natural gas reliance on Russia with Ostpolitik (a deliberate plan to increase economic links with Russia with the goal of integrating it into Europe). The "Putinverstehers" (Putin-admirers) were led by former German Chancellor Gerhard Schroder, who earned millions in fees from Russian energy companies for promoting its interests. In an April 2022 NYT interview after the apparent failure of Ostpolitik, Schroeder said "I don't do mea culpa. It's not my thing."

One final look at nuclear decommissioning, this time from New York. In 2020 and 2021, New York State shut down Indian Point's nuclear plants with the intention of replacing its generation with renewable energy. That's not what has happened so far: three new natural gas plants (Bayonne Energy Center, CPV Valley Energy Center and Cricket Valley Energy Center) have filled the gap along with mostly gas-fired electricity imports from states like Pennsylvania. The chart below on GHG emissions illustrates how the closure of Indian Point has temporarily pushed New York City regional emissions per MWh above the US average and above ERCOT. So, while Texas is more "red" than New York City, it's now more "green" as well.

The Champlain Hudson Power Express (Canadian hydropower) and the Clean Path project (upstate New York wind/solar) should replace Indian Point's lost generation. While Champlain Express is expected to start bringing power to New York City in 2025, Clean Path is not set to deliver power until 2027. As shown below, both new megaprojects are expected to exceed Indian Point's lost generation as long as Canadian hydropower capacity factors remain stable, and when assuming that CPNY wind/solar capacity factors are equal to those on existing NY projects. [Note: a prior version of this paper incorrectly estimated these figures and has been revised accordingly]. New York has an advantage over Massachusetts and other Eastern states that need new clean energy capacity since it shares a border with Canada and can decide unilaterally to approve projects like CHPE. As we have written in prior years, Massachusetts has seen two separate Canadian hydropower import projects fail due to objections from neighboring states regarding construction of high voltage direct current lines. These states are attempting to build offshore wind but are running into challenges there as well (see page 34).

New York: electricity generation by source
Terawatt hours



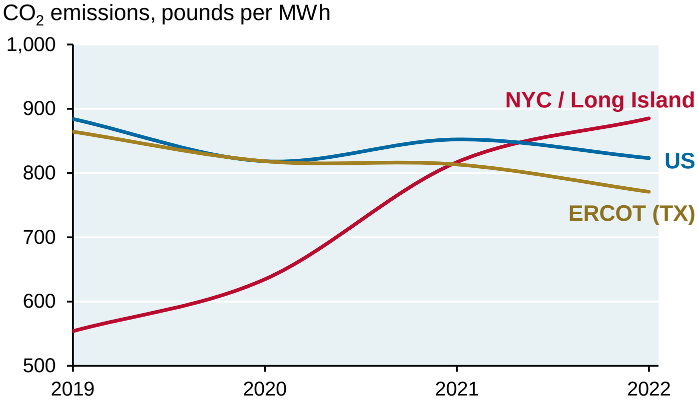
Source: EIA, JPMAM, 2023

Wind and solar capacity factors by state

	Wind				Solar			
	7 highest		7 lowest		7 highest		7 lowest	
	State	CF	State	CF	State	CF	State	CF
1	NE	46%	WV	27%	UT	29%	MA	18%
2	ND	43%	NH	26%	NV	28%	NY	17%
3	IA	43%	MA	25%	AZ	28%	PA	17%
4	SD	43%	NV	24%	NM	27%	WI	17%
5	KS	42%	NY	24%	CA	27%	VT	17%
6	MT	39%	OR	23%	TX	26%	RI	17%
7	IL	38%	UT	21%	AR	25%	NJ	17%

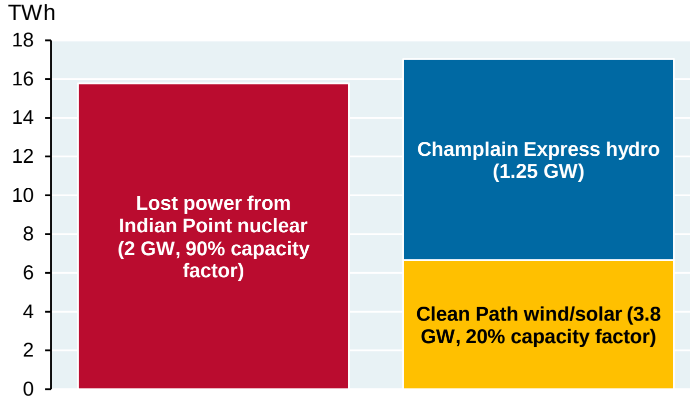
Source: EIA forms 860/923, JPMAM, 2023. All states with more than 50 MW of solar and more than 100 MW of wind

The GHG impact of shutting down Indian Point
CO_2 emissions, pounds per MWh



Source: EPA eGRID data, 2022

Planned replacement of Indian Point generation
TWh



Source: JPMAM, 2024

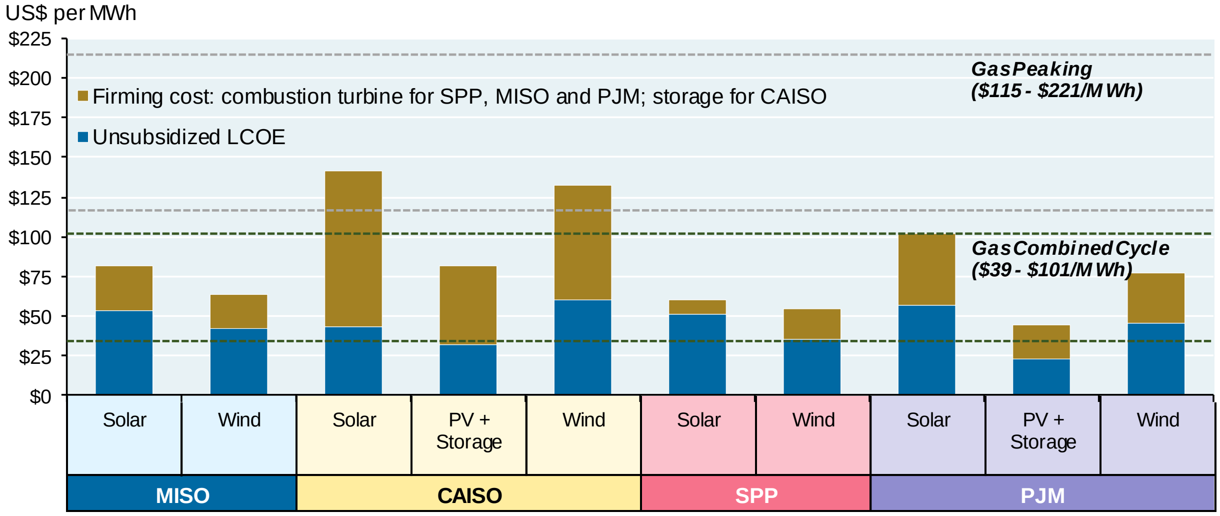
Lazard's epiphany does not go far enough: the inadequacies of levelized cost, Part 2

Last year, I wrote a long section on the problems with levelized costs of energy when applied to renewables. I described LCOE as the cocktail napkin of energy math[24] and cited Paul Joskow at MIT who began to write about this over a decade ago (see text box). Not much has changed, other than a gradual recognition by more analysts that LCOE is a mostly useless measure when comparing renewables to baseload power.

The most committed disciples of LCOE over the last two decades have been Lazard's energy team, propagators of their annual LCOE report. **After 16 years, the Lazard team has had an epiphany:** while it's not incorporated in their base case figures which are still of little practical use, Lazard now includes a new supplemental exhibit on the cost of "firming the intermittency" of wind and solar power. In other words, the costs required to provide power when there's not enough wind or sun to meet the load demand. For MISO, SPP and PJM regions, Lazard incorporates the cost of peaker combustion turbines into wind and solar costs; and for CAISO, they incorporate the cost of utility scale energy storage, presumably fueled by overbuilding solar power. In their new exhibit, some revised LCOE estimates for wind and solar power are at or above median costs for combined cycle natural gas plants (their firming costs are shown by the gold bars). To be clear, should storage and solar costs continue to decline, so would Lazard's respective firming costs in regions like CAISO.

There are still odd things in Lazard's report. Lazard assumes an operating life of only 20 years for new natural gas combined cycle and combustion turbine plants[25]. This is strange, particularly since the EIA reports the average age of *existing* natural gas plants at 22 years, and the EIA assumes 30-year cost recovery for new ones. Sargent & Lundy consults for the EIA on LCOE estimates and confirmed that they assume 30-40 years for natural gas plant operating lives. A longer assumed operating life would reduce natural gas LCOE estimates. This assumption is another sign of how Lazard sometimes tilts the playing field in their analysis, and explains why it took 16 years for firming costs to show up in their report.

Levelized costs of energy: Incorporating the cost of backup thermal power and energy storage
US$ per MWh



Source: *"Lazard's Levelized Cost of Energy Analysis - Version 16.0", Lazard, April 2023.*

Paul Joskow (MIT): LCOE is "inappropriate for comparing intermittent generating technologies like wind and solar with dispatchable generation…and also overvalues intermittent generating technologies compared to dispatchable baseload generation"…"LCOE comparisons of baseload and intermittent, non-dispatchable generation make little sense; what's needed instead is a system-wide model rather than simplistic LCOE calculations"

[24] "*Growing Pains*", 2023 Eye on the Market Energy Paper, pages 14-18

[25] "*LCOE Plus*", Lazard, April 2023, page 39

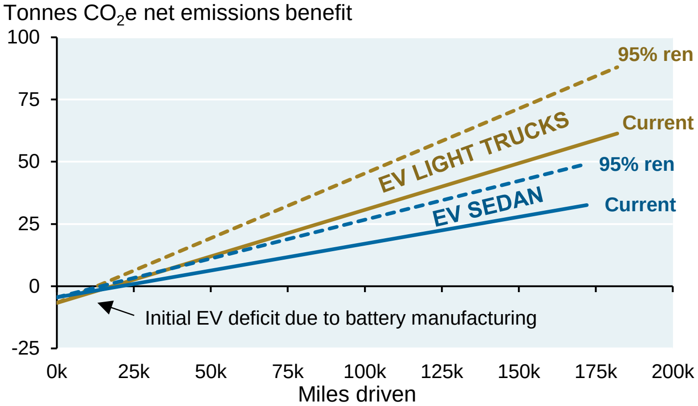
Advanced Electravision topics: timing, temperature, transmission and turbines

Electravision entails more than just building new renewable generation capacity and transmission lines. Consumers of electricity may have to adjust to new pricing models for power since the time of day when they consume it will be more important than it is today. Furthermore, estimating emissions benefits from Electravision EV and heat pump adoption will require more precise analysis than current models. This section gets into advanced topics: real-world EV emissions; capacity and transmission requirements as a function of driver and homeowner electricity use; and the challenges of offshore wind development in the US.

[a] Estimated emissions reductions from EV adoption may be too optimistic unless they reflect "marginal" emissions rates rather than "average" emissions rates

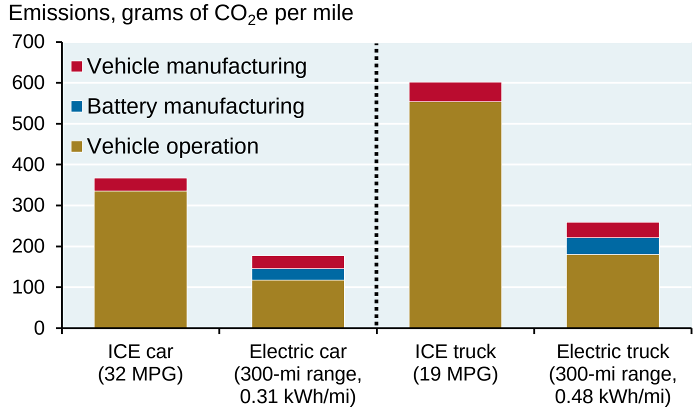
Many studies compare lifecycle emissions of EVs to internal combustion engine cars. The general conclusion: after around two years of operation, the average EV matches the carbon intensity of the average ICE car or light truck. After that, the EV accrues net carbon benefits through to the end of its life. The initial EV carbon deficit reflects the carbon intensity of battery manufacturing. One example: a 2022 piece from the Union of Concerned Scientists[26]. The first chart shows UCS estimated lifetime net emissions benefits for EV cars and light trucks assuming the emissions intensity of the current population-weighted electricity grid, and a future grid that is 95% renewable. Based on UCS estimates, after 15k-20k miles (around two years of driving), EV trucks and cars accrue net emissions benefits vs ICE vehicles. This is a consistent finding across many studies[27].

Cumulative emissions benefits from EVs vs ICE vehicles
Tonnes CO_2e net emissions benefit



Source: "*Driving Cleaner*", Union of Concerned Scientists, July 2022

Lifecycle emissions, EVs vs ICE cars and light trucks
Emissions, grams of CO_2e per mile



Source: *"Driving Cleaner"*, Union of Concerned Scientists, July 2022

However: there's an issue that needs to be further explored. UCS EV CO_2 estimates are based on the average emissions rate of the current grid: i.e., the sum of all CO_2 emissions from electricity generation divided by total MWh. But for the *next* EV added to the grid, **what matters is *marginal* emissions rates (i.e., what does the grid look like when EVs are actually charged)** and not average emissions rates. UCS is aware of this distinction but uses average emissions rates due to an inability to "make assumptions about charging behavior or the response of electricity generation units to an increase in demand". We agree that the former is hard to do, but some analysts have made progress on the latter. This is particularly important for the future when more EVs are anticipated as a share of the fleet.

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[26] "*Driving Cleaner: How Electric Cars and Pick-Ups Beat Gasoline on Lifetime Global Emissions*", Union of Concerned Scientists, Reichmuth et al, July 2022

[27] Similar findings to UCS results: "*Comparative lifecycle GHG emissions of a mid-sized BEV and ICE vehicle*" from the IEA; BNEF's Electric Vehicle Outlook; and a study from the European Federation for Transport & Environment

Researchers at Convergent Science estimated upper and lower bounds of marginal emissions rates by US region, calculated over every hour in a given year. Each estimate reflects the energy sources that are most correlated with changes in marginal demand. As shown, **estimated marginal emissions rates for the US are 1.5x – 1.8x higher than average emissions rates[28].**

Average vs marginal emissions rate, kg of CO_2 per MWh

Geographical region	AVERAGE emissions rate	Lower bound MARGINAL emissions rate (FF and renewables)	Upper bound MARGINAL emissions rate (FF only)	Ratio of marginal rates to average rates
Pacific Northwest	186	92	584	0.5 - 3.1
California	196	396	469	2.0 - 2.4
Texas	401	508	529	1.3 - 1.3
New England	216	408	433	1.9 - 2.0
Midwest/South	560	749	766	1.3 - 1.4
New York	174	478	520	2.7 - 3.0
Mid-Atlantic	395	690	724	1.7 - 1.8
South	454	687	704	1.5 - 1.5
Midwest	492	523	762	1.1 - 1.5

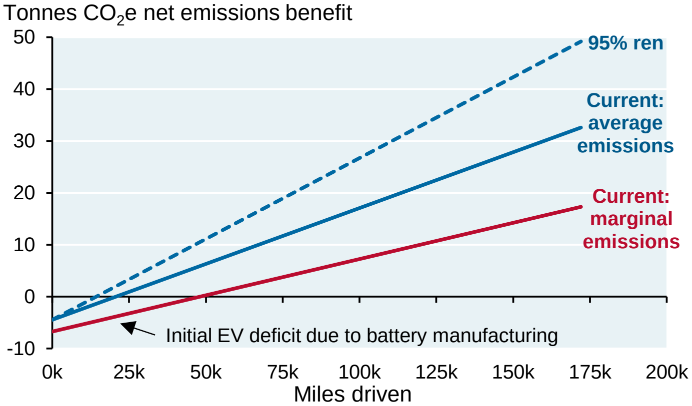
Source: Tristan Burton and Kelly Senecal (Convergent Science), April 13, 2022

How would marginal emission rates impact the UCS analysis? Let's assume that on a national population-weighted basis that marginal emissions rates are 1.5x higher than average rates (and that's before incorporating higher emissions rates of battery manufacturing in China). The next chart shows the revised net emissions benefits for EV vs ICE sedans assuming marginal emissions rates. The result: the lifetime net emissions benefit for the sedan falls roughly in half from 32 tonnes of CO_2 to 17 tonnes instead.

The red line is based on average marginal emissions rates over the entire year; as a result, it assumes no ability to influence the timing of EV charging through pricing incentives. Furthermore, it uses today's grid and does not account for the pace of wind and solar additions which are growing faster than EV adoption. **The bottom line on EV emissions: more wind and solar, time-of-use electricity pricing incentives, centralized charging programs (see box) and more public/private charging infrastructure whose use coincides with solar power peaks would increase EV net emissions benefits closer to UCS assumed levels.**

Cumulative emissions benefits from EVs vs ICE sedan

Tonnes CO_2e net emissions benefit



Source: UCS, Convergent Science, JPMAM, July 2022

Centralized EV charging optimization

Seven leading US utilities are conducting pilot programs to remotely control time-of-day charging of EVs to reduce peak load and transmission needs. The remote access takes place through the charging device or wirelessly with the vehicle. Many utilities are also piloting distributed energy resource management systems which remotely control behind-the-meter thermostats, water heaters and batteries

Source: Darcy Insights "*Benchmarking Study, Managed EV Charging Programs*", February 2024

[28] *"Data-Driven Greenhouse Gas Emission Rate Analysis for Vehicle Comparisons",* Burton and Senecal, 2022

[b] Clustering of charging behavior can substantially increase peak loads and the need for transmission

Researchers at the Technical University of Denmark analyzed what would happen to the grid if EVs, currently 10% of the fleet in Denmark (BEV+PHEV), reached 90%+ of the fleet[29]. For example, if all EV charging were evenly distributed throughout the day, incremental capacity needs would only be 1 GW and peak loads would only rise by 17%. At the other end of the extreme, if every EV owner charged at the highest possible power[30] at the same time of day, peak loads would increase by 550% with an additional 33 GW of capacity required. That is an absurdly pessimistic scenario, but so is the first one which is too optimistic.

Denmark: capacity and peak load increases at 100% EV penetration

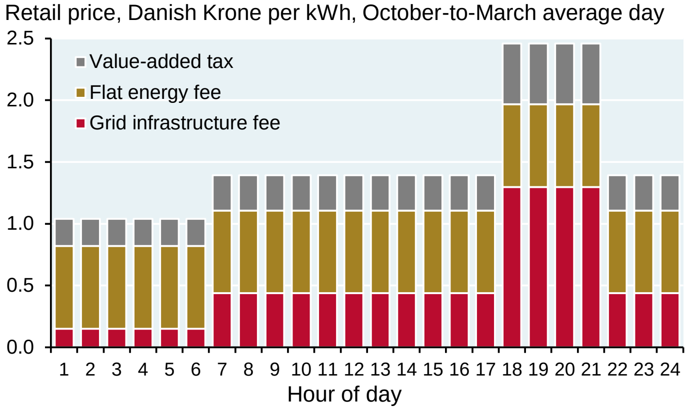
Confluence of EV charging	Additional power required	Increase in peak consumption
Evenly distributed charging	1.0 GW	17%
3.7 kW @ 30% coincidence factor	3.3 GW	55%
3.7 kW @ 100% coincidence factor	11.1 GW	185%
11 kW @ 100% coincidence factor	33.0 GW	550%

Source: Mattia Marinelli, Technical University of Denmark, November 2023

Key assumptions
15,000 km driven per year per vehicle
EV mileage = 5 km per kWh
Denm. electricity consumption = 36 TWh
Denm. peak power consumption = 6 GW
Denm. current generation capacity = 18 GW

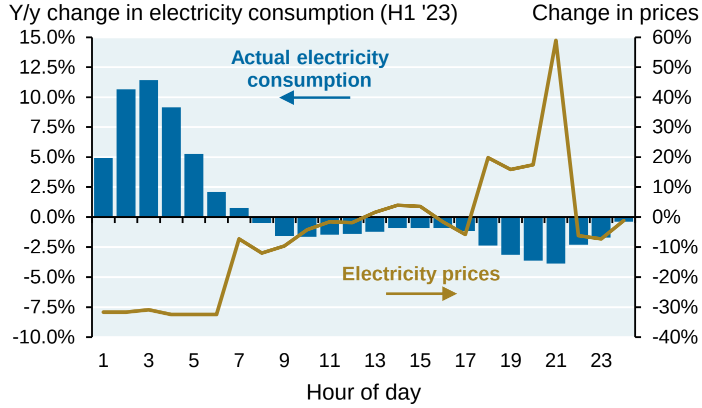
The reality lies in between, highlighting the need for pricing policies for EV charging that do not just reflect the availability of surplus renewable energy, but **also reflect the impact of EV charging on peak loads, capacity needs and transmission infrastructure**. This is precisely what Denmark now does; residential customers pay four separate components on their electricity bills: a spot price which depends on the day-ahead market; **a grid impact fee which depends on the month/hour of the day**; a fixed energy fee; and a VAT tax. The second component is the key one and contrasts with the US where the grid/infrastructure component of electricity bills is typically fixed irrespective of when electricity is consumed. On the right: note how electricity prices can spike substantially in Denmark based on the time of day, which ends up shifting consumption. Synergi, a Finnish electricity management company, reports similar results: EV owners using smart charging can reduce their annual energy bills by 70% as their charging is typically deferred to 11 pm – 3 am.

Denmark grid infrastructure fees are time-of-day dependent
Retail price, Danish Krone per kWh, October-to-March average day



Source: Marinelli (Technical University of Denmark), August 25, 2023

Danish customers respond to higher electricity prices
Y/y change in electricity consumption (H1 '23) Change in prices



Source: Marinelli (Technical University of Denmark), August 25, 2023

[29] Mattia Marinelli (Technical University of Denmark), DTU Wind and Energy Systems, November 2023

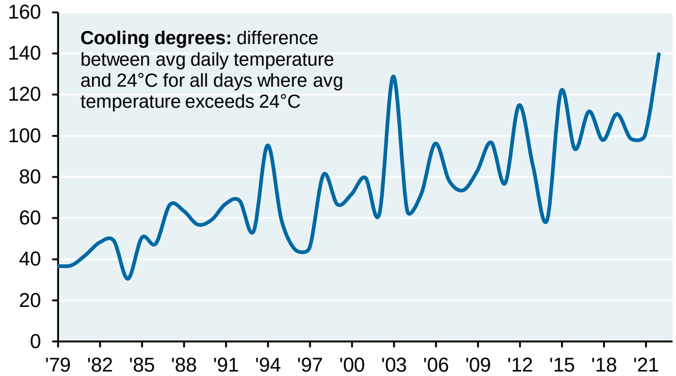
[30] As a reminder, watts = volts times amps. The 3.7 kW scenario is based on 230 volts (typical voltage in Europe) times 16 amps (typical max for domestic appliances) times 1 phase. The 11 kW scenario is based on 230 volts times 16 amps times 3 phases. Three-phase and single-phase power refer to different wiring configurations; in the US, single-phase is used in most residences while three-phase is normally reserved for commercial and industrial users with heavier loads. But in Europe, many Nordic and German residences use three-phase power as well for cooking and heating.

[c] European benefits from heat pump adoption might be partially reduced by increased air conditioning use

Europeans live in colder climates than the US. While only 8% of the US population lives above the 44th parallel, 82% of Europe's population lives above that level. That's one reason why air conditioning use in Europe has historically been so much lower than in the US. Only 1 in 10 households has air conditioning in Europe vs 90% in the US, and air conditioning represents only 1% of building energy use in Europe vs 16% in the US.

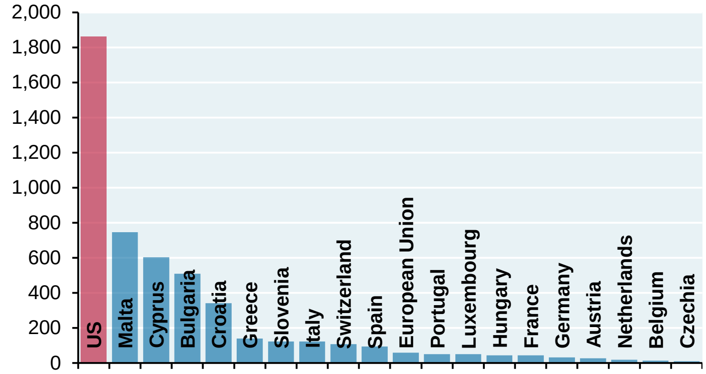
But: two things are changing. First, Europe is getting hotter, as shown in the first chart on rising cooling degree days. And second, Europe is installing more heat pumps for winter heating, most of which can be used for air conditioning as well. It will be important to monitor the degree to which increased air conditioning use offsets some of the benefits of more efficient, less emissions-intensive winter heating in Europe.

Increased need for cooling in the EU
Cumulative cooling degrees per year, Celsius



Source: Eurostat, JPMAM, 2022

Household electricity use for air conditioning
kWh per dwelling

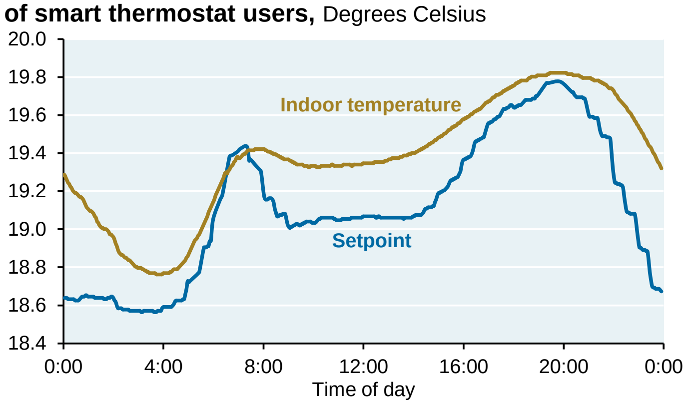


Source: EIA, OdysseMure, JPMAM, 2019

[d] Smart thermostats help conserve energy by encouraging people to use less heat and air conditioning when they're not home or asleep. But if too many smart thermostat setpoints coincide, there could be a concentrated burst of power demand that grids must be designed to accommodate[31]

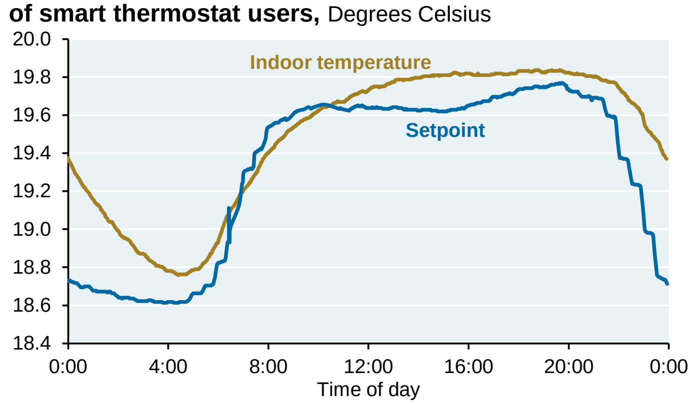
Researchers looked at time-of-day setpoints used by homeowners with smart thermostats. The charts show average winter setpoints and indoor temperatures. Setpoints to increase heat are concentrated around 7 am, which may reflect default settings rather than user choices. Setpoint timing is important from a load perspective **since more power is required to *increase* temperatures to a given level than to *sustain* them there**. And: peak smart thermostat demand tends to be concentrated around times of low renewable resource availability (7 am, 8 pm). Smart thermostats will need to be accompanied by policies that avoid time-of-day concentrations. Some real-world trials involving price signals have shown high responsiveness; but re-entry loads would have to be properly managed or else you end up with the same peaking problem pushed out to another time of day.

Winter weekday average setpoints and indoor temperature of smart thermostat users, Degrees Celsius



Source: Cornell University, Lee & Zhang, September 15, 2022

Winter weekend average setpoints and indoor temperature of smart thermostat users, Degrees Celsius



Source: Cornell University, Lee & Zhang, September 15, 2022

[31] *"Unintended consequences of smart thermostats in the transition to electrified heating"*, Cornell, Lee & Zhang, 2022

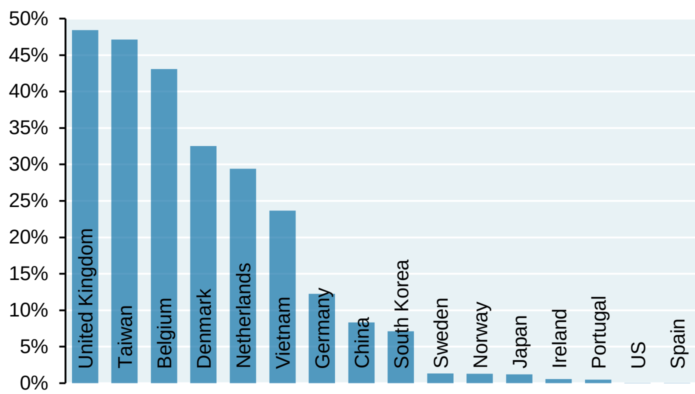
[e] Offshore wind turbulence in the US contrasts with greater capacity growth elsewhere

While the US has 146 GW of onshore wind, it has almost no offshore wind. Some Northeastern states aim to develop their own offshore wind given failure of projects to import Canadian hydropower. However, the last 12 months have seen US offshore wind developers walk away from 8.5 gigawatts of wind projects due to withdrawal of original bid submissions after as much as 50% inflation in component costs. These projects are likely to proceed, but it will take more time and higher power costs. The US is an underachiever on offshore wind compared to countries below. NREL highlights the supply chain buildout required to meet the Biden administration's 30 GW offshore wind target by 2030: a lot of new factories and ~$22 bn in capital investment[32].

The global wind turbine market is split into two groups: ~15 Chinese manufacturers which mostly supply its domestic market, and Western firms that supply everyone else (GE, Vestas, Nordex and Siemens Gamesa). As Western turbine makers experience cost and margin challenges, Chinese firms are increasingly competitive in Western markets. As shown below, S&P Global estimates that Chinese turbines are 70% cheaper.

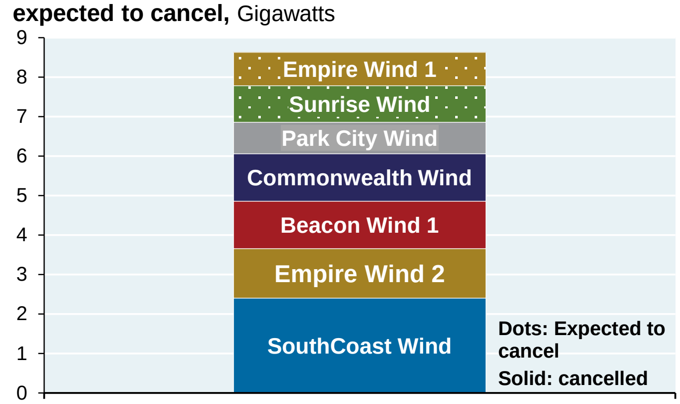
One more thing on offshore wind. Research from Europe shows that offshore wind farms can generate "**wakes**" which reduce wind speeds at adjacent wind farms, even as far away as 55 km. The decline in offshore wind capacity factors can be as much as 20%, resulting in production and revenue losses[33]. The study shows that most offshore wind farms in Northern Europe are less than 50 km away from the nearest wind farm.

Offshore wind share of total wind capacity



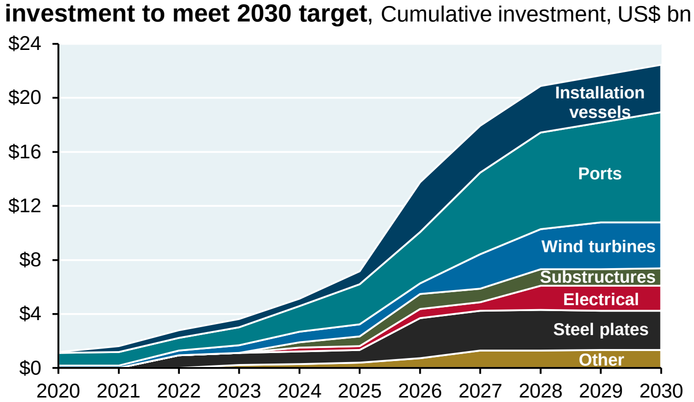
Source: IRENA Energy, JPMAM, 2022

8.6 GW of US offshore wind capacity: already cancelled or expected to cancel, Gigawatts



Source: Intelatus Global Partners, Individual project reports, JPMAM, 2024

US offshore wind supply chain requires at least $22bn in investment to meet 2030 target, Cumulative investment, US$ bn



Source: NREL, January 2023

Average selling price of onshore wind turbines
US$ per watt

Source: S&P Global, Q3 2023

[32] "*A Supply Chain Road Map for Offshore Wind Energy in the United States*", NREL, Shields et al, January 2023

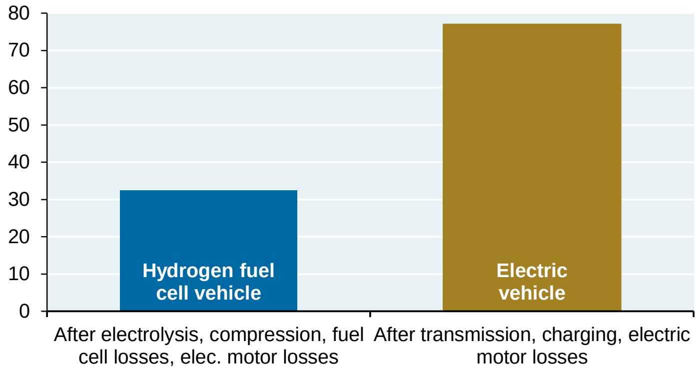
[33] "*Wind farm-induced wakes and regulatory gaps*", University of Bergen (Norway), Finseras et al, October 2023

Why-drogen Epilog: A tough year for the green hydrogen industry

In 2021 I wrote a skeptical long-form section entitled "Why-drogen" given all the unanswered questions on green hydrogen production, transmission and consumption. Since then, the hydrogen economy has seen some advances: Saudi Arabia's 2.2 GW NEOM ammonia/hydrogen project based on wind/solar and Shell's 200 MW Holland Hydrogen project based on offshore wind are now under construction. And in the US, there's 10 million tonnes per annum of *planned* green/blue hydrogen production, which would be enough to replace almost all US hydrogen consumption that is currently produced by natural gas and coal…if it gets built.

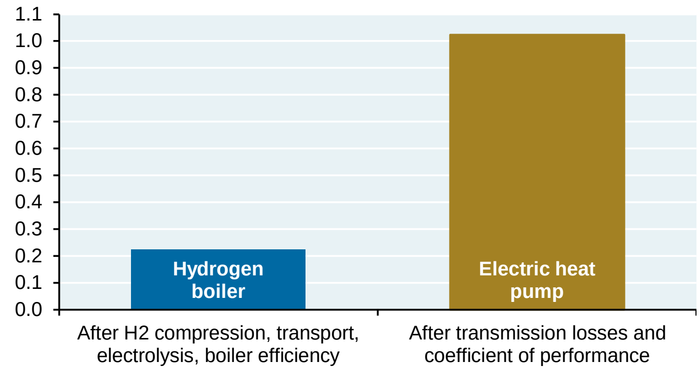
But there have also been a lot of cancelled projects due to the realization that **per unit of energy, hydrogen for road transport or winter heating is much less efficient than directly electrified alternatives**. While developers lined up at the public trough for $350 billion in global hydrogen subsidies in 2023[34] (tax credits, grants and R&D funding), the energy math usually argues against it other than for green hydrogen to replace fossil fuel-derived hydrogen currently used in ammonia/fertilizer, in oil refining and in direct reduction of iron ore to iron metal. This section walks through the latest developments, most of which imply that "No-drogen" is the common answer to "Why-drogen".

How much electricity is available to power an electric motor when starting with 100 kWh of wind power? kWh



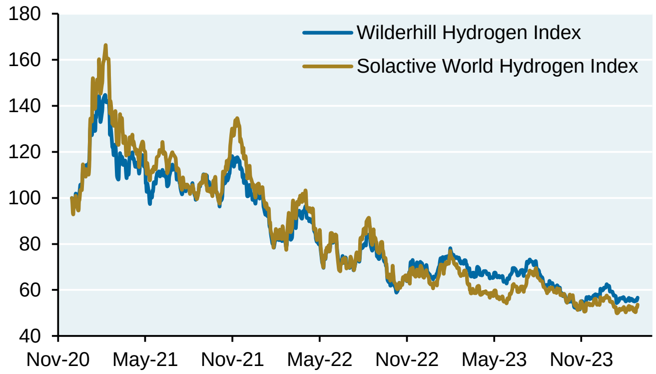
Source: EIA, DoE, DIW Berlin, JPMAM, 2023

How much heating value is available when starting with 100 kWh of wind power? Trillion BTU



Source: EIA, DoE, DIW Berlin, JPMAM, 2023

Hydrogen Index returns
Total return index, November 2020 = 100



Source: Bloomberg, JPMAM, March 1, 2024

[34] BNEF Hydrogen Subsidy Tracker, January 25, 2024

Low demand for electrolyzers and green hydrogen

- Some electrolyzer manufacturers are downgrading production capacity plans due to policy delays and insufficient green hydrogen demand[35]. Only 5% of green hydrogen projects have reached operation; and only 10% of announced green hydrogen capacity has confirmed buyers[36,37]. As a result, share prices of some electrolyzer manufacturers have fallen by 95% from 2021 levels (Plug Power, ITM Power, McPhy Energy)
- The EU established a 1.2% blending requirement for synthetic aviation fuel sourced from green hydrogen by 2030 and 35% (!!) by 2050. Synthetic fuel producers note that airlines are reluctant to pay a green premium, and are struggling to secure offtake agreements with airlines[38]

Rising electrolyzer costs and technological problems

- A March 2024 survey of alkaline and PEM electrolyzers found 46%-65% price increases since 2022, part of which is explained by slower-than expected market scaling[39]
- The world's largest green hydrogen project built in Xinjiang, China is operating at less than a third of installed capacity due to technical problems. In the second half of 2023, this 260 MW electrolyzer was expected to produce ~9,500 metric tons of green hydrogen; it produced only ~2,000 metric tons instead. In addition to these technical issues, the plant is missing some safety and flexibility features promised in the contract
- While Chinese electrolyzers are much cheaper than Western counterparts, savings to Western project developers are unlikely to offset concerns about quality, financing issues and policy risks

Rising costs of green hydrogen, matching requirements for tax credits and the need for subsidies

- BCG raised its expected minimum green hydrogen price target for 2030 from 3 euros/kg to 5 euros/kg[40]
- In 2020, ArcelorMittal announced new green steel plants with great fanfare; they would eventually use green hydrogen as a reducing agent for iron ore instead of carbon. Arcelor now concedes that green hydrogen is too costly to use and would render its steel uncompetitive, even after taking European subsidies into account. The company will either use fossil gas in a direct reduced iron (DRI) reactor or import green DRI from elsewhere, after which both approaches would rely on an electric arc furnace to produce steel
- The US Treasury ruled that hydrogen projects must adopt hourly matching of hydrogen production and green energy sourcing by 2028 to qualify for tax credits. This immediately set off complaints by the hydrogen industry which apparently wants tax credits for creating brown hydrogen while claiming that it's green
- BNEF estimates that for the Hydrogen Energy Ministerial's 2030 targets to be met, the hydrogen industry would need over $2 trillion in subsidies[41]

Overestimated GHG benefits

- The US Department of Energy concluded that the emissions footprint of most blue hydrogen projects (brown hydrogen + CCS) is too high to merit tax credits[42]
- A 30% green hydrogen blend in natural gas pipelines may only result in a 6% GHG decline due to increased need for compression stations and due to hydrogen leakage[43]

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[35] *"Green hydrogen electrolyzer makers putting brakes on capacity expansion",* Hydrogen Insight, Sept 2023
[36] *"Five Strategies for Optimizing Power-to-X Projects",* BCG and Oxford Global Projects, Sept 2023
[37] *"Hydrogen Demand: Tiny but Rising",* BNEF, Gao, November 2023
[38] "*Airlines are not willing to pay a premium for green hydrogen-based e-kerosene*", Hydrogen Insight, January 2024
[39] "*Electrolyzer price survey 2024: Rising Costs, Glitchy Tech*", BNEF, March 1, 2024
[40] *"Turning the European Green Hydrogen Dream into Reality: A Call to Action",* BCG, October 2023
[41] "*Clean Hydrogen's Missing Trillions*", Michael Liebrich, BNEF, December 2023
[42] *"Blue hydrogen unlikely to qualify for US tax credits due to high upstream emissions"*, Hydrogen Ins., Dec 2023
[43] *"Hydrogen blending in gas pipelines faces limits due to leakage: US DOE lab"*, S&P Global, October 27, 2023

For road transport, hydrogen is uncompetitive with directly electrified alternatives

- Maersk's APM Terminals division found that hydrogen costs for container handling equipment (tractors, carriers and stackers) are 25%-60% higher than battery powered equipment due to greater efficiency losses, higher fuel costs and greater equipment complexity; and concluded that these cost gaps will persist[44]
- Hydrogen truck makers Hyzon and Nikola both face delisting by Nasdaq for consistently trading below $1

Challenges for hydrogen shipping

- Green hydrogen's arguably best new use case, maritime shipping, faces huge obstacles. When compressed and chilled to 20°C above absolute zero (which would consume 33% of the energy in hydrogen), hydrogen's energy density by volume is still 4x less than maritime fuel; if converted into ammonia fuel, the energy conversions are expensive; there are safety concerns if used in confined ship engine rooms[45]; and any hydrogen leakage could have negative consequences for the ozone since global warming impacts of H_2 are 12x higher than CO_2[46]. The cost challenge for shipping: even after adjusting for hydrogen's higher energy density by mass compared to diesel, green hydrogen could still cost 5x-6x more than maritime fuel[47]

Cancelled and suspended hydrogen projects[48]

- **Electrolyzers**: ATCO (Canada), Schleswig-Holstein (Germany). Cited reasons: distance between hydrogen production facility and end use undermines commercial viability[49], high construction costs
- **Buses/trucks**: Liverpool (UK), Glasgow (UK), Montpellier (Fr). Cited reasons: unreliable green hydrogen supply, hydrogen vehicles as much as 6x more expensive than battery electric models
- **Trains**: Germany, Netherlands. Cited reasons: cheaper battery electric models, no bids by developers
- **Blue hydrogen/ammonia**: Nutrien (Louisiana), Shell-UK National Grid. Cited reasons: higher than expected capital costs, uncertain future demand for clean ammonia, no support for heating/blending
- **Residential heating**: UK. Cited reasons: insufficient green hydrogen supply
- **Green hydrogen-to-methanol**: Belgium. Cited reasons: escalating costs, no long-term buyers

Next year we will look at the question of naturally occurring "white" or "gold" hydrogen deposits. By then, the 50+ companies which have begun to look for them will have presumably either confirmed its abundance or not. The USGS believes that there might be some in the Atlantic coastal plain, the central US, parts of the Great Plains and the Upper Midwest. The USGS has committed to publishing its global resource potential models and a preliminary map of the areas that are most likely to contain geologic hydrogen resources later this year[50].

On shipping and fossil fuels. In 2021, 36% of all maritime shipping tonnage by weight was the movement of oil (15%), coal (11%), natural gas (5%) and refined petroleum products (5%). For this reason, some analysts note that if energy use for road transport, heating and industrial production were substantially decarbonized, energy use for shipping would simultaneously fall as well. True enough, but as shown in the introduction there are few signs that global consumption of fossil fuels is in decline. It could take decades for demand for maritime fuels to materially decline due to decarbonization.

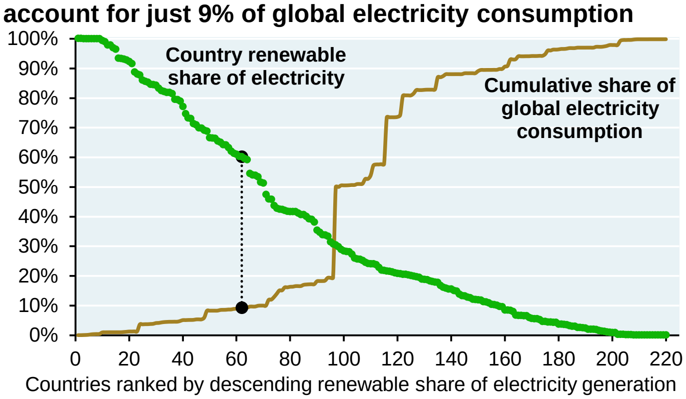
[44] *"Reaching a tipping point in Battery-Electric Container Handling Equipment"*, APM Terminals, October 2023
[45] "*Lies leaks and lethality: is ammonia a safe fuel for ships?*", The Lodestar, August 6, 2023
[46] "*New study estimates global warming potential of hydrogen*", CICERO, June 7, 2023
[47] "*Hydrogen Half Truths Keep Shipping Fuel Hopes Afloat*", Michael Barnard, Forbes, December 29, 2023
[48] Hydrogen Insight, Renew Economy, Glasgow Live, Recharge
[49] Since hydrogen is very difficult to transport, ~85% of hydrogen is consumed at the point of manufacture
[50] "*The potential for geologic hydrogen for next-generation energy*", US Geological Society, April 13, 2023

"Ignore the PUNIs": The distraction of small countries with unique natural energy resources

While China merits the attention it gets on its energy transition, some very small countries do not. One example: press articles on the high share of renewable power that some countries generate in one hour or one day of the year without mentioning how the rest of the year's energy needs are met. Or: articles highlighting renewable transitions in countries with unique natural resources without acknowledging that they're often irrelevant to the rest of the world. The acronym "PUNI" refers to Panama, Uganda, Norway and Iceland, prime examples of this phenomenon. Let's see why.

The first chart shows each country's renewable share of electricity generation in green alongside a cumulative tally of global electricity consumption. Key point from the chart: **there are 62 countries with renewable shares of electricity over 60%, but they only account for 9% of global electricity consumption** (Brazil and Canada account for around half of the electricity consumption in this cohort). Now let's see how this cohort is accomplishing such high levels of renewable electricity generation. Hint: it's not wind or solar.

62 countries with renewable electricity shares over 60% account for just 9% of global electricity consumption



Source: IEA, IRENA, World Bank, Harvard ECI, ESMAP, JPMAM, 2022

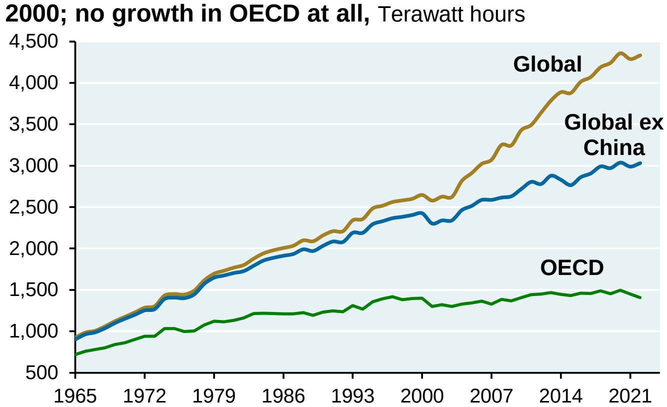
It's all about hydropower. The table shows how this 62-country cohort heavily relies on hydropower for its electricity generation; wind plus solar account for just 11%. Is there potential for even more hydropower? The International Hydropower Association estimates that global capacity could grow by 3x[51]. But as we reviewed in 2016, countries like the US have already exploited most of its readily available hydropower resources. Most hydropower potential studies are done at the topographical reconnaissance level and do not incorporate real-world constraints related to cost, local politics or environmental impact. That may explain why global hydropower generation is only growing at ~1% per year when excluding China, and why the OECD has seen no hydropower growth at all since the year 2000.

Electricity generation of aggregate cohort
Countries with > 60% of electricity from renewables

Source	TWh	Share of TWh
Hydropower	1,673,644	63%
Fossil fuels	363,855	14%
Wind	230,857	9%
Nuclear	198,100	7%
Biomass/biogas	126,528	5%
Solar	60,363	2%
Geothermal	9,691	0%

Source: IRENA, JPMAM, 2022

Ex-China, global hydropower growing at 1% per year since 2000; no growth in OECD at all, Terawatt hours



Source: EI Statistical Review of World Energy, JPMAM, 2023

51 "*Hydropower 2050: Identifying the next 850+ GW towards Net Zero*", International Hydropower Assoc., 2021

Are there countries with high renewable shares that do not just rely on hydropower, geothermal and biomass (HGB)? Just a few: Namibia, Uruguay, Denmark, Lithuania and Portugal where wind and solar provide at least 30% of electricity generation[52]. Note that they also benefit from substantial HGB contributions as well.

Renewable and wind/solar shares of electricity generation
Cohort: all countries with at least 60% of electricity generation from renewable energy

	Ren share	W/S share		Ren share	W/S share		Ren share	W/S share		Ren share	W/S share		Ren share	W/S share
1 Eswatini	100%	0%	13 Namibia	98%	35%	25 El Salva	86%	25%	37 Cameroon	80%	0%	50 Croatia	67%	18%
2 Lesotho	100%	0%	14 Greenlan	97%	0%	26 Kyrgyzst	86%	0%	38 Malawi	79%	0%	51 Fiji	67%	1%
3 Bhutan	100%	0%	15 Central	97%	0%	27 Luxembou	85%	43%	39 Austria	79%	16%	52 Burundi	66%	0%
4 Nepal	100%	0%	16 Belize	93%	2%	28 Mozambiq	85%	1%	40 Colombia	77%	1%	53 Lithuani	66%	45%
5 Iceland	100%	0%	17 Andorra	93%	1%	29 Uruguay	85%	34%	41 Sierra L	75%	2%	54 Pakistan	65%	9%
6 Paraguay	100%	0%	18 Zambia	93%	1%	30 Venezuel	84%	0%	42 Guatemal	73%	4%	55 Honduras	64%	16%
7 Ethiopia	100%	5%	19 Tajikist	93%	0%	31 Panama	83%	12%	43 Mali	73%	3%	56 Latvia	64%	3%
8 Albania	100%	1%	20 Ecuador	92%	0%	32 New Zeal	83%	7%	44 Zimbabwe	71%	1%	57 North Ko	63%	0%
9 Costa Ri	100%	13%	21 Tokelau	92%	92%	33 Denmark	82%	60%	45 Laos	71%	0%	58 Monteneg	62%	9%
10 Norway	99%	10%	22 Kenya	89%	5%	34 Angola	82%	0%	46 Nicaragu	70%	16%	59 Peru	61%	5%
11 Democrat	99%	0%	23 Guinea	88%	0%	35 Georgia	82%	1%	47 French G	70%	6%	60 Sudan	61%	0%
12 Uganda	98%	2%	24 Brazil	88%	17%	36 Afghanis	81%	3%	48 Sweden	69%	21%	61 Portugal	60%	37%
									49 Canada	69%	7%	62 Switzerl	60%	7%

Source: IRENA, JPMAM, 2022

Are these five countries relevant paradigms for the world's largest energy consumers? Not really. They're all tiny in terms of energy consumption and population. When compared to larger countries, Namibia has much higher solar irradiance; Denmark and Uruguay have much higher wind potential; Uruguay and Namibia have much lower population density as well as lower economic complexity. This latter figure measures each country's ability to produce complex products across industries, which in turn drives the need for more developed energy systems. Some also benefit from proximity to large countries for grid stabilization (Uruguay/Brazil, Denmark/Germany). If you're keeping score, that makes six separate factors which reduce **Uruguay's** relevance to larger countries. Portugal is the only one of the five without unique natural resource advantages.

PUNI countries deserve credit for developing wind, solar and HGB resources and reducing reliance on fossil fuels for electricity generation. But they're mostly inapt paradigms regarding the transition for larger developed and developing countries. **If you come across an article on any of the PUNIs, you can probably just skip it**.

Country	Wind share % of elec	Solar shale % of elec	HGB share % of elec	Prim Energy Consumption Petajoules	Popul Millions	Popul density Per sq mile	Econ complexity 0-100 scale	Solar irradiance Percentile	Wind potential kW / capita
Renewable share of electricity > 60% and wind/solar share of electricity > 30%									
Namibia	2%	34%	63%	80	3	8	29	100	285
Denmark	55%	5%	22%	678	6	352	83	3	56
Lithuania	39%	5%	21%	324	3	111	78	4	10
Portugal	30%	7%	23%	842	10	289	74	33	13
Uruguay	31%	3%	50%	234	3	50	62	40	80
Large primary energy consumers									
China	9%	5%	17%	157,034	1,412	385	87	24	2
US	10%	5%	7%	89,555	332	91	90	30	16
Germany	23%	11%	12%	12,055	83	605	98	6	2
France	8%	4%	12%	9,857	68	303	88	12	9
India	4%	5%	12%	39,529	1,408	1,109	69	50	0
Japan	1%	11%	12%	16,731	126	854	100	14	15
South Korea	1%	4%	3%	12,216	52	1,340	98	20	12
Indonesia	0%	0%	19%	9,858	274	371	52	36	1
Turkey	11%	5%	27%	6,675	84	280	70	35	1

Source: IEA, IRENA, World Bank, Harvard ECI, ESMAP, JPMAM, 2022

[52] We do not analyze Tokelau, a Pacific island dependency of New Zealand with a population of 1,500; or the Grand Duchy of Luxembourg (pop. 600k) where most stores close at 6 pm every day.

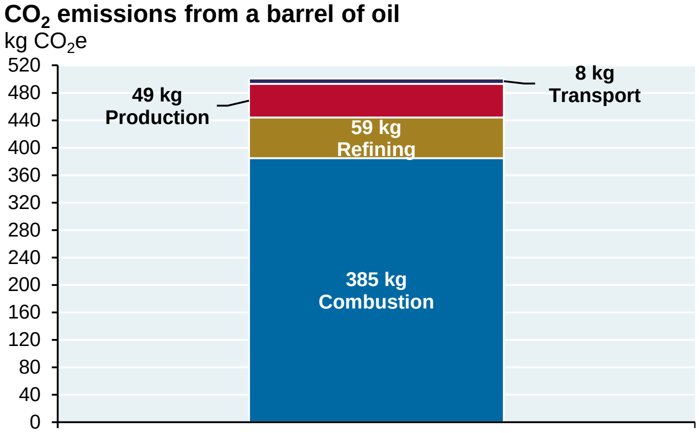
On "Net Zero" Oil: worth trying if it can be done close to very ambitious pro-forma projections

Net Zero Oil is based on the following concept: produce a barrel of oil, and simultaneously sequester enough CO_2 from the atmosphere to substantially offset the ~500 kg of CO_2 emissions from combusting the oil plus whatever additional emissions result from the sequestration approach chosen. Sounds simple; it's not.

At JP Morgan's inaugural Sustainability Summit last May, one of the energy CEOs in attendance noted the lack of any discussion or support for their efforts to develop "Net Zero Oil". I was called out for being behind the curve since I did not mention anything about it in my presentation, and since I repeated my long-standing view that the highest ratio in the history of science is the number of scientific papers written on carbon sequestration divided by the actual amount of carbon sequestration. I was seen as a Net Zero Oil opponent even though I had never heard much about it, which was my fault.

After the Summit, I agreed to spend time with the company's engineers and write a briefing memo on Net Zero Oil for our CEO Jamie Dimon and other members of the JP Morgan Operating Committee. The next three pages are the verbatim contents of that memo. Bottom line: there are a lot of technical hurdles to overcome and the cost of decarbonized oil might be extremely high; but I will keep an open mind regarding the potential for direct air carbon capture and other related costs to come down over time for hard to abate sectors.

CO_2 emissions from a barrel of oil



Source: IHS Markit, 2019

Energy brief: on Net Zero Oil and Direct Air Carbon Capture

Net Zero Oil is a concept that entails capture and geologic sequestration of CO_2 for enhanced oil recovery, with sufficient sequestration to offset the lifecycle emissions of the oil produced in the process and emissions resulting from sequestration. One example relies on Direct Air Carbon Capture (DACC) as a source for the CO_2, using zero emission energy to power the DACC process. This brief discusses the carbon math involved.

The Occidental approach: enhanced oil recovery using mostly zero emission sources of energy for DACC

Oxy is building its first DACC plant so projections and estimates should be judged accordingly[53]. Oxy intends to use mostly zero carbon sources of energy for DACC, sourced from a combination of (a) dedicated solar power, (b) zero carbon power from the grid via derivative contracts and (c) power/heat from natural gas whose emissions are captured/sequestered. An example of the latter is projected to be sourced from NET Power (NPWR) which aims to combust natural gas with pure oxygen to generate power and captured CO_2 at a lower cost than traditional gas plants with co-located carbon capture. NET Power is also a new venture, aiming to deliver its first commercialized plants in 2026-2027. As a result, our energy math estimates are pro-forma and subject to proof of concept/cost discovery as Oxy DACC and NET Power plants are constructed.

The carbon math of net zero oil/DACC using grid electricity

Most CO_2-EOR projects in the US currently rely on naturally occurring underground deposits of CO_2 and some point source capture from anthropogenic sources. As a result, clearly assigning a GHG reduction benefit to oil produced in these CO_2-EOR systems is a complex exercise that involves assuming counterfactual GHG emissions baselines and conventional oil production displacement rates. However, if exclusively atmospheric CO_2 were utilized via DACC for CO_2-EOR, ascribing the GHG emissions benefits to the oil produced becomes more straightforward. The emissions impact per barrel of CO_2-EOR oil using atmospheric CO_2 requires estimates of:

Assumption	Value	Assumption type	Source
CO_2 injected to produce a barrel of oil	0.46 metric tons	Limited observation set	Azzolina[54]
Lifetime CO_2 emissions from a barrel of oil	0.5 metric tons of CO_2	Robust observation set	Multiple sources[55]
Energy intensity of DACC, including compression	366 kWh of electricity and 5.25 GJ of heat per metric ton of CO_2	Theoretical; first plants being built	Keith[56]
Carbon intensity of natural gas-powered electricity	0.44 metric tons of CO_2 per MWh	Robust observation set	EIA[57]
Carbon intensity of natural gas combustion	50.3 kg of CO_2 per GJ	Robust observation set	EIA[58]
Split of zero emissions power and natural gas	zero carbon sources are 40% in the median US state	Robust observation set	EIA[59]
Upstream methane emissions from natural gas production and distribution	13 g of CO_2 per MJ of natural gas	Robust observation set	Littlefield[60]

[53] According to conversations with Oxy engineers in 2023, its DACC materials inputs are typically cheaper and less volatile (calcium carbonate, caustic potash and PVC) when compared to greater reliance on steel, concrete and other materials by facilities deploying solid sorbent DACC technology

[54] *"CO_2 storage associated with CO_2 enhanced oil recovery",* Azzolina et al, Int'l Journal of GHG Control, June 2015

[55] Carnegie Endowment, Energy Futures Initiative and Clean Air Task Force

[56] *"A Process for Capturing CO_2 from the Atmosphere",* David Keith (Harvard) et al., Joule, June 2018

[57] *"U.S. electricity net generation and resulting CO_2 emissions by fuel in 2021",* EIA

[58] *"Natural gas and the environment",* EIA

[59] *"Net generation by state and source"*, EIA

[60] *"Life Cycle GHG Perspective on US Natural Gas Delivery Pathways"*, Env. Science & Technology, Littlefield et al, Nov 2022

Using the assumptions above, we estimate that **Oxy's net CO_2 emissions per DACC-EOR barrel would be 0.22 metric tons**. Compared to lifecycle emissions of crude oil of 0.5 metric tons, this represents "**55% decarbonization**". As part of this calculation, only 79% of each metric ton of CO_2 captured counts towards emissions reductions since some CO_2 must be captured to offset upstream and thermal grid emissions. The assumptions in the table are for the Nth plant and not the first one, so this is aspirational at this point.

How might DACC-EOR oil achieve higher rates of decarbonization than the 55% baseline case?

1. Using only zero carbon power would increase EOR oil decarbonization to 67%. The impact is not large since electricity only accounts for 20% of the energy in the typical DACC process (the rest is gas combustion)
2. If remote sensors reduced upstream methane emissions by half, EOR oil decarbonization would rise to 70%
3. If 20% more CO_2 were injected per barrel of oil, EOR oil decarbonization would rise to 84%
4. Finally, if the energy load of DACC fell by 1/3 (possibly resulting from the use of industrial heat pumps for thermal heat), EOR oil decarbonization would rise to 92%. In other words, "92% decarbonized oil".

DACC-EOR oil decarbonization scenarios

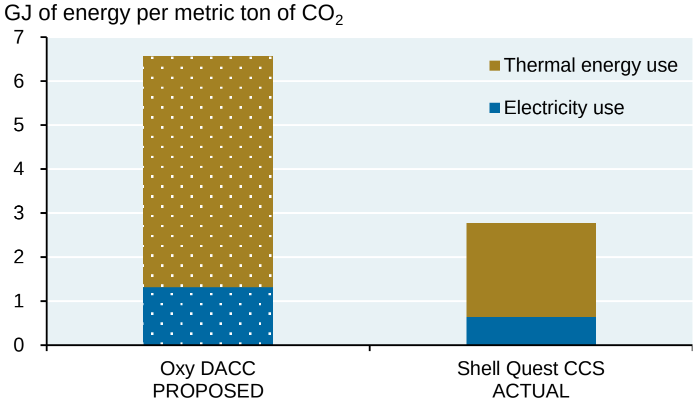
Scenario	Net emissions, metric tons of CO_2 per barrel	EOR oil decarbonization %
Traditional oil production, refining and combustion	0.50	NA
Oxy process with grid power	0.22	55%
Oxy process using 100% zero-carbon power	0.17	67%
Oxy process, 100% zero-carbon power, 50% reduction in upstream methane emissions	0.15	70%
Oxy process, 100% zero carbon power, 50% reduction in upstream methane emissions, 20% more CO_2 injected per barrel	0.08	84%
Oxy process, 100% zero carbon power, 50% reduction in upstream methane emissions, 20% more CO_2 injected per barrel, 1/3 decline in energy intensity per ton of CO_2 for DACC	0.04	92%

Source: EIA, Harvard Univ., Carnegie Endowment, Energy Futures Initiative, U. North Dakota, USGS, Occidental, JPMAM, June 2023

Challenges. The thermodynamics of DACC are very challenging, particularly when compared to point source CCS. As a reminder, CO_2 is only 0.04% of the atmosphere compared to 10%-15% concentrations in power plant flue gas and 80%+ in some industrial flue gases. The DACC energy assumptions used in the analysis above are based on an academic paper from 2018; Oxy is now trying to substantiate or improve upon those estimates.

If we take Oxy assumptions at face value, DACC would use 2.4x more energy than CCS. But is this realistic? A Shell Quest steam methane reformation project with CCS in Edmonton captures and buries ~1 mm metric tons of CO_2 per year. The source of CO_2: concentrated syngas from hydrogen production under 10,000x more partial pressure than atmospheric CO_2; ~78% of the syngas CO_2 is captured[61]. According to Shell[62], its CCS project requires 2.8 GJ of energy per ton of CO_2, including energy for compression. **Could Oxy's DACC process really be accomplished at only a 2.4x energy premium to Shell Quest? That needs to be proven given thermodynamic challenges involved.**

Energy required for DACC vs CCS
GJ of energy per metric ton of CO_2



Source: Quest CCS Project, Keith (Harvard) et al., 2022.

[61] To be clear, Shell Quest is only capturing CO_2 from syngas and not from the smokestack. After taking energy demands of CCS into account, Shell Quest is only capturing 35% of total project CO_2 emissions

[62] Quest GHG and Energy Report, 2021

One last geologic issue: CO_2 resurfacing. Any CO_2 that unexpectedly resurfaces would need to be recaptured, recompressed and reinjected, all of which requires additional energy; or it would need to be deducted from the net carbon benefits of DACC-EOR oil. Large scale sequestration projects are typically tracked regarding actual geologic CO_2 retention rates, particularly when the project qualifies for 45Q tax credits.

Implications for DACC as an emissions mitigation approach for hard-to-abate sectors

Learning curves have been steep across a wide range of energy technologies, generating lower unit costs and increased efficiency. Wind, solar, EV battery and utility scale storage costs are notable examples. Other examples include improved efficiency of natural gas combined cycle plants, residential and industrial heat pumps and internal combustion engines; and the increase in wind capacity factors as a function of turbine/rotor dimensions and offshore locations. But other improvements have been harder to come by, such as the low round trip efficiency of electrolysis/hydrogen fuel cells used in transport (still just ~26%[63]) and the negligible improvement in crystalline silicon PV cell efficiency (from 24% in the year 2000 to 26% in 2023).

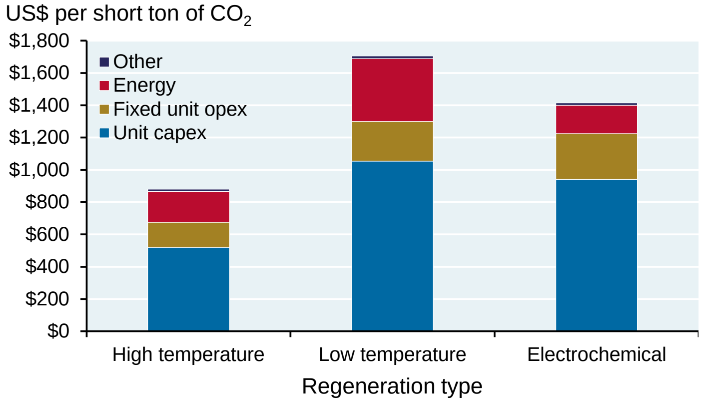
Will there be a steep DACC learning curve[64]? If there were, DACC could be used to offset emissions from hard-to-abate sectors such as aviation, primary steel production, cement, chemicals and agriculture. **But if there isn't, it will be a very expensive form of abatement.** As shown below, the latest estimates for first-of-a-kind DACC plants are over $800 per ton of CO_2. Even if these costs fell by two thirds, they would probably be the most expensive solution you would ever see on a carbon abatement cost curve.

DACC-EOR conclusions:

- Even if DACC and Net Power plants are completed as planned, "Net Zero Oil" would probably refer to oil that is significantly but not entirely decarbonized
- Net Zero Oil is projected to only be 100% decarbonized if CO_2 injection rates increase, DACC costs decline sharply, 100% zero carbon energy is used and upstream methane emissions fall
- DACC is currently very energy intensive; if/when 5-8 DACC plants are built, we will have a better sense for the learning curve decline in capital costs and in energy consumption per ton of CO_2

DACC first of a kind plant cost estimates

US$ per short ton of CO_2



Source: BCG, World Economic Forum, June 2023

[63] Center for Sustainable Road Freight (UK); this figure includes AC/DC conversion, electrolysis, compression, transfer and fuel cell losses

[64] The Oxy/Carbon Engineering DACC assumption of ~1,800 kWh per tonne of CO_2 (including process heat) is lower than other estimates we have seen from the IEA, the World Resources Institute and Climeworks. An even greater reduction in energy intensity of ~1/3 from Oxy levels was estimated by Feron in a 2022 paper presented at the International Conference on Greenhouse Gas Technologies. The approach involves the use of amino acids, cooling towers and industrial heat pumps, and has no direct thermal energy requirement.

A proper burial: can sequestration of bio-oil gain more traction than CCS?

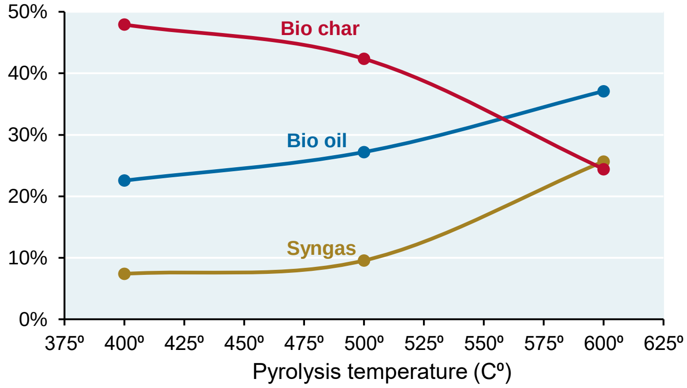
In 2023, JP Morgan announced a $200 mm carbon removal plan designed to offset its Scope 1 emissions which are expected to be ~800,000 metric tons over the next decade. Most of JP Morgan's carbon removal plan relies on existing point source CCS technology, but there's another sequestration approach the firm is using as well.

JP Morgan entered into a carbon removal contract with **Charm Industrial,** a company which converts corn stover (stalks, leaves and cobs) and wastewood from wildfire prevention treatments into something called "bio-oil". Bio-oil is produced via pyrolysis, which refers to the decomposition of biomass into solid char, liquid bio-oil and gaseous syngas. The process occurs at very high temperatures in the absence of any oxygen in order to avoid combustion. The carbon-rich liquid bio-oil is then sequestered underground, counting as carbon removal since the source of the carbon is "biogenic"; in other words, it was recently in the atmosphere before it was absorbed as CO_2 via photosynthesis by corn plants. Burying bio-oil appears to be the best option since its energy density is too low for use as a transportation or heating fuel.

As shown below using common switchgrass as an example, product yields from pyrolysis vary with the temperature at which it occurs. According to Charm Industrial, its pyrolysis process yields roughly 50% bio-oil and 25% each in bio-char and syngas.

Pyrolysis yields from switchgrass

Product yield



Source: Journal of Analytical and Applied Pyrolysis, 2011

Charm Industrial process

Bio-oil: sequestered and buried. For every cubic meter of bio-oil produced, the associated mitigation is roughly 1.8 tonnes of CO_2. Emissions associated with transport, pyrolysis and injection reduce that figure by ~20%

Syngas: used to generate energy for pyrolysis process

Bio-char: buried with bio-oil or applied to soil to improve nutrient retention, enhance soil structure

As a devout skeptic of point source CCS and direct air carbon capture, could bio-oil be any different?

- There's no need for bio-oil pipelines since it is transported by truck and contains 2.3x more carbon per unit of volume than compressed CO_2[65]
- Bio-oil can be buried in common wells that had previously been used for industrial waste or for oil extraction, or old salt caverns left behind by oil and gas exploration. In other words, bio-oil does not require more specialized geological formations typically required by CCS/DACC

That said, pyrolysis, pumping, blending and trucking all have carbon footprints and require proper accounting. In a recent batch of bio-oil produced and sequestered for JP Morgan, Charm cited a net carbon removal rate of ~80%[66]. In addition, the cost of sequestration via bio-oil is also extremely high now, at $500-$600 per tonne of CO_2. And as of December 2023, Charm owned just three pyrolyzers with plans to build more in 2024. Last point: there are also risks that after coming into contact with hot porous rocks, bio-oil becomes more viscous and polymerizes, constraining the ability of a cavern to absorb more injected fluids.

[65] Assuming bio-oil density of 1.2 grams per mL and 42% carbon share of bio-oil by weight; density of compressed CO_2 = 0.8 metric tons per cubic meter; and carbon's weight of 27% in CO_2

[66] This net carbon removal rate was inspected and confirmed by Isometric, which has launched a bio-oil sequestration protocol for measurement, reporting and verification

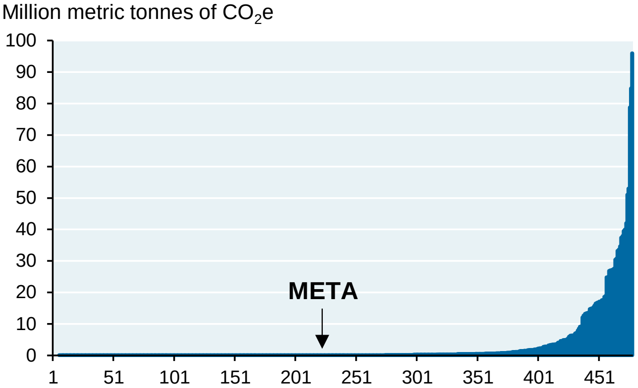
The biggest issue of course is scale. Charm has reportedly sequestered 7,000 tonnes of CO_2 to date and aims to get to ~20,000 tonnes per year in the next few years. For context: one of Charm's clients is Meta, a relatively carbon-light company with a footprint of just 66,000 tonnes of scope 1 CO_2 emissions in 2021. Within the Communication Services and Information Technology sectors, Meta is well below the cluster of higher emissions companies. Note how around half of this cohort have practically no scope 1 emissions at all. Some tech companies pay very high prices to mitigate their scope 1 footprints, which is easy to do when emissions are low. Robert Hoglund at Carbon Gap has done some interesting research showing that GHG emissions are almost perfectly inversely correlated with profits per tonne of GHG. In other words, the big emitters are probably way less price inelastic regarding prices paid per ton of mitigation than most tech companies.

Meta's scope 1 emissions only include fuel consumption in its buildings, planes and vehicles[67]. Its *total* carbon footprint is 8.5 *million* tonnes of CO_2, and Meta is a drop in the bucket compared to emissions of the S&P 500 and the entire US economy. We will keep watching this space, but I am not sure how bio-oil is any more scalable than CCS, and it might even be less scalable. Charm's business model may be profitable for its backers; but that is a separate issue from whether bio-oil can meaningfully contribute to big picture decarbonization efforts.

	Metric tonnes of CO_2e	Multiple of current Charm Industrial sequestration
Charm sequestration to date	7,083	
Charm scale up target (annual)	18,667	3x
Meta scope 1 emissions	66,934	9x
Meta scope 1, 2, and 3 emissions	8,533,471	1,205x
Scope 1 emissions of S&P 500	1,476,977,428	208,524x
US CO_2 emissions from energy	5,586,000,000	788,649x

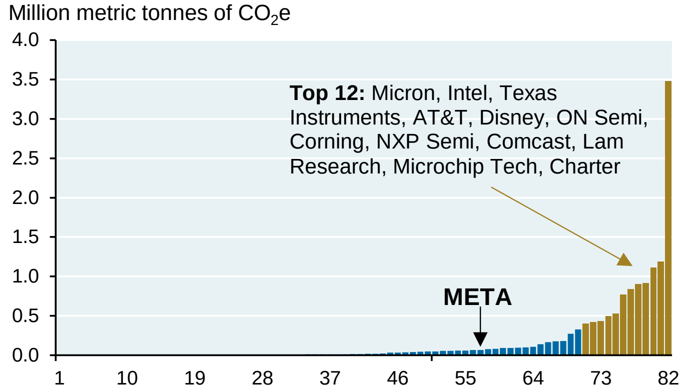
Source: Bloomberg, EPA, individual company filings, JPMAM, 2023

Scope 1 Emissions of S&P 500 companies
Million metric tonnes of CO_2e



Source: Bloomberg, JPMAM, January 3, 2024

Scope 1 Emissions of S&P 500 Info Tech & Comm Services
Million metric tonnes of CO_2e



Source: Bloomberg, JPMAM, January 3, 2024

[67] **Scope 1** emissions occur from sources controlled or owned by an organization, such as emissions associated with fuel combustion in their boilers, furnaces and vehicles

Scope 2 emissions mostly refer to electricity consumption for HVAC and data centers and reflect the CO_2 intensity of grids that electricity is sourced from. JP Morgan uses direct renewable power and renewable energy credits to offset part of its Scope 2 emissions

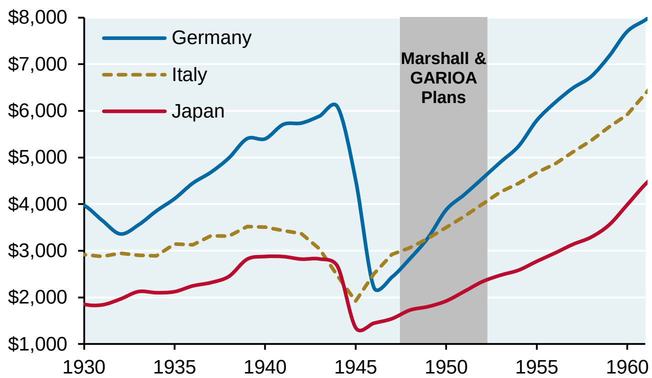
Scope 3 emissions refer to activities such as employee travel/commuting. JP Morgan uses "nature-based" credits to offset part of its Scope 3 emissions. Most nature-based credits are derived from forestation, grassland and afforestation projects. The latter refers to efforts to develop forests where none have existed in recent times; this can be challenging since if a given biome were conducive to forest growth, it would typically already exist there. Leakage, compliance and verification issues have been challenges for users of nature-based credits

What if? A thought experiment on the reconstruction of Gaza and the role of distributed solar power

During WWII, Germany drained conquered European territories of resources and labor to feed its war machine, with industry and agriculture forcibly reoriented at the expense of native populations. The tide turned with the Battle of Stalingrad in February 1943 in which one million Russian troops died. By the end of the war, Germany was in shambles: 40% of its dwelling units were destroyed or damaged, food production and caloric intake fell in half, industrial production fell by 30% and one third of all males born from 1916-1924 died during the war[68]. In Italy: bridges, industrial enterprises and hundreds of thousands of homes were destroyed first by Allied bombers and then by the retreating Germany Army. In Japan: 2.5 million people died during the war, major parts of Tokyo and other cities were in ashes and one third of the nation's wealth was destroyed.

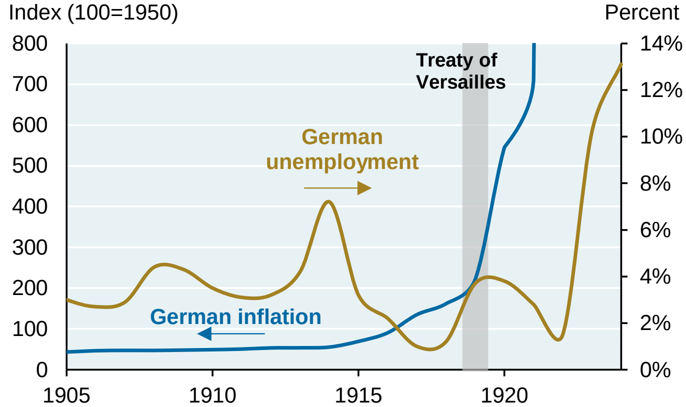
When the US State Department designed the Marshall Plan to revive Germany and the rest of Europe, it was highly unpopular with more than 50% of Americans opposing it. Eventually the Plan passed and boosted Europe's recovery. It is generally regarded as a 20th century policy success: when the war ended, policymakers focused on what would come next and tried to influence the course of future events. This was in stark contrast to the aftershocks in Germany following the reparations required by the Treaty of Versailles after WWI.

Post WWII Axis power recoveries
GDP per capita, 1990 US$



Source: Angus Maddison, World Economy Historical Statistics, 2024

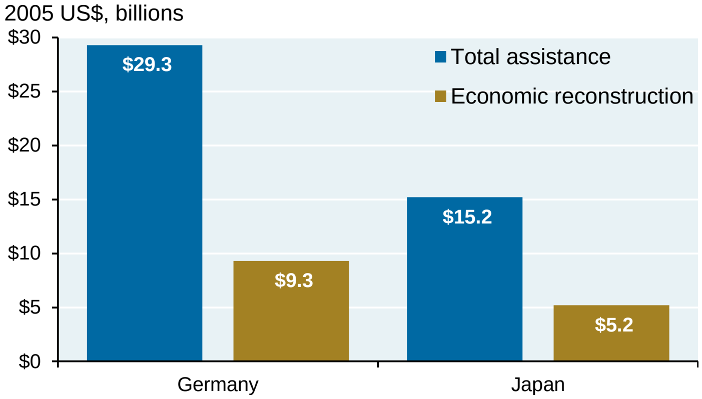
Post WWI Treaty of Versailles and its aftermath in Germany
Index (100=1950) Percent



Source: Angus Maddison, World Economy Historical Statistics, 2024

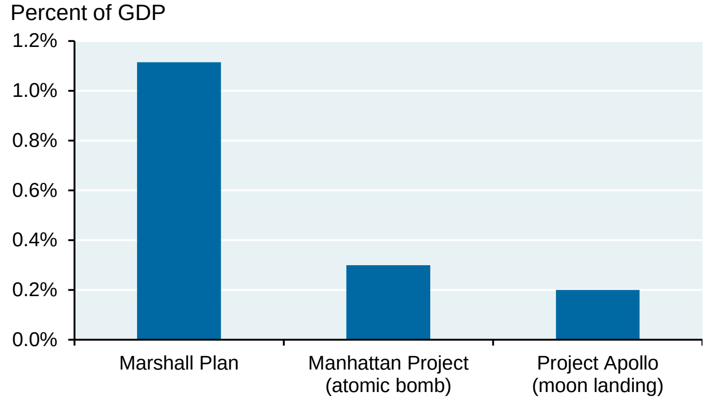
If Americans were ambivalent about helping Germany after the war, you can imagine how they felt about Japan given its attack on US soil in December 1941. Even so, while there was no explicit Marshall Plan for Japan, the US still provided Japan roughly half the economic aid that it had provided to Germany. The US also helped engineer Japan's recovery via an advantageous exchange rate set at 360 Yen/$. With the benefit of a cheap exchange rate, the era of Japanese trade surpluses began and lasted well into the 21st century.

US assistance to Germany and Japan, 1945-1952
2005 US$, billions



Source: Congressional Research Service, March 2006

The cost of select government programs
Percent of GDP

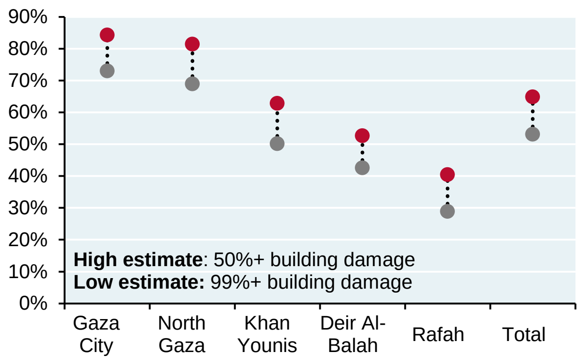


Source: Vaclav Smil (U Manitoba), Eichengreen (Berkeley), JPMAM, 2024

[68] "*Unbalanced sex ratios in Germany caused by World War II and their effect on fertility*", European Economic Review, Kesternich et al, September 2020

I am reminded about this history given the situation in Gaza. According to satellite analysis, 55%-65% of all buildings in Gaza had likely been damaged or destroyed by February 2, 2024 by Israel in response to the October 7 attacks and hostage-taking by Hamas. The accompanying map illustrates spatial findings from researchers Jamon Van Den Hoek and Corey Scher with white boxes indicating damaged and destroyed areas. Separately, the Hebrew University of Jerusalem found that Israel has destroyed 40% of buildings within the one-kilometer buffer zone it plans to maintain along the Israel-Gaza border[69].

Building damage in Gaza
Percent of buildings likely damaged or destroyed



Source: Damage analysis of Sentinel-1 satellite data, Van Den Hoek (Oregon State) and Scher (CUNY), February 2, 2024

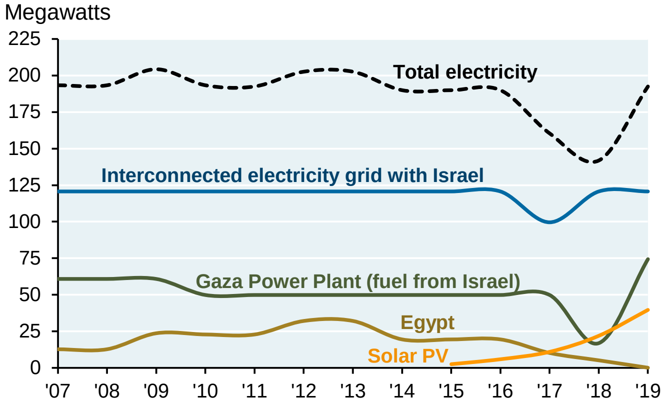
Other damage assessments
- 90% of schools
- All 7 universities
- 2/3 of hospitals
- 22% of agricultural land, including greenhouses and olive groves
- More than half of all bakeries
- Half of all water/sanitation facilities
- Remaining wastewater treatment plants and sewage pumping stations are non-operational due to lack of electricity

BBC, Foreign Policy, CSIS, France24, UNOCHA

What if the West financed reconstruction of the electricity grid in the Gaza strip once buildings are rebuilt? And what if this effort were centered around rooftop solar to increase Gaza's energy independence? This is not a futuristic idea: in 2022 China added 61 GW of distributed solar capacity, even more than the 45 GW of utility-scale solar it added[70]. There are a million caveats involved with this scenario but before you get too caught up in them, remember what Germany, Italy and Japan looked like in 1946. The lesson from the prior page: coordinated international investment can go a long way after wartime destruction.

Furthermore, Gaza had been successful in adding over 8,000 rooftop solar sites to its electricity mix by the end of the prior decade. Of the solar PV shown below, over 90% was rooftop solar while the remainder was ground-based. This rooftop solar growth took place despite unfavorable financing conditions, ongoing conflict with Israel, intraparty conflicts within Gaza, Israeli maritime blockades of Gaza, sub 1% growth rates, 45% unemployment and Israeli-imposed restrictions on agriculture and industry. Before going further I will point out that the source for this information is a paper from three professors at the Hebrew University of Jerusalem[71].

Gaza average daily electricity mix, 2007-2019
Megawatts



Source: "*Light at the End of the Panel*", New Political Economy, 2022

As of 2021, the Gaza Strip depended primarily on Israel for energy. Israel supplied almost 100% of the fossil fuels powering Gaza's sole electricity power plant, which provided between 60 and 80 MW of electricity. Israel also supplied 120 MW via its interconnected electricity grid. Since Gaza energy demand is estimated at 450 MW, it suffered from a shortage of 250–270 MW. This energy shortage severely impacted essential services (health, water, sanitation) in Gaza and undermined its economy, mainly manufacturing and agriculture (Fischhendler et al, Hebrew University of Jerusalem, 2022)

69 France24 (February 2, 2024) citing Adi Ben Nun of the Hebrew University of Jerusalem

70 "*China takes its climate fight to the rooftops*", Bloomberg News, March 23, 2023

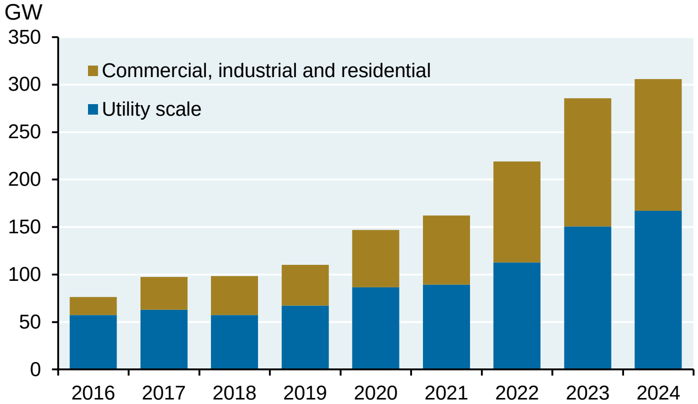
71 "*Light at the End of the Panel: The Gaza Strip and the Interplay Between Geopolitical Conflict and Renewable Energy*", New Political Economy, 2022, Fischhendler, Herman & David, Hebrew University of Jerusalem

While Gaza's rooftop solar began in refugee camps and dense urban areas, eventually more efficient larger sites were developed. Support for solar development in Gaza came from the World Bank, UNDP, OPEC and the EU. CSIS estimates that Gaza had developed the densest rooftop solar system in the world[72]; at least a third of Gaza's population and more than 50% of its businesses used solar panels in March 2023. Gaza's success in building rooftop solar was part of what is a global trend: for the last several years, global rooftop solar PV additions have roughly matched new utility-scale solar installations.

The potential for rooftop solar in a rebuilt Gaza

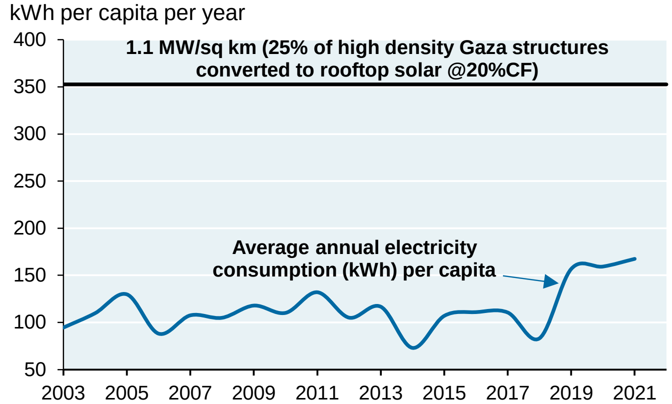
The chart below (right) shows electricity consumption in Gaza alongside an estimate of what a reconstructed grid could look like. Before the war, 18 of Gaza's 365 sq km was made up of high-density structures[73]. After a lengthy period of reconstruction[74], if we assume that 25% of the associated roofspace is converted to rooftop solar at ~90 watts per square meter[75] with a capacity factor of 20%[76] at a cost of $1 per watt, solar power could provide ~350 kWh per capita per year at an upfront capital cost of ~$500 million. In other words, a modest amount of international aid in a rebuilt Gaza could substantially improve energy supplies and energy security.

Global solar PV capacity additions



Source: IEA, 2023

Electricity consumption per capita in Gaza



Source: CSIS, Environment America, JTC, Our World in Data, JPMAM, 2023

Any efforts to galvanize international aid for Gaza might be made more difficult by the history of Hamas diverting international aid[77], and its founding charter. Since 2007 when Hamas took power in the Gaza strip, it has financed its activities via levies/taxes on trade with Egypt, new import taxes, business taxes and taxes on income earned by Palestinians working in Israel. While aid from Qatar resulted in reconstruction of homes and infrastructure, black markets for construction materials also ended up reportedly being used by Hamas for military purposes. From 1994 to 2020, Europe and the US accounted for 75% of the $40 billion in international aid provided to Gaza and the West Bank[78], but this figure doesn't include Iran. US Congressional estimates of Iranian financial support for Hamas range from $100 mm to $350 mm per year. As for the Hamas founding charter and its core principles, you can read about it here and judge for yourself[79].

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[72] "*Gaza's solar power in wartime*", CSIS, Will Todman et al, November 21, 2023

[73] "*Land/cover use in Gaza in 2023*", Dr. He Yin, Kent State University Department of Geography

[74] UNCTAD projects that it could take many decades for Gaza's economy to recover to prewar levels

[75] "*Buildings & Parking Lots: Ready for a Recharge*", Morgan Stanley Research, May 6, 2022

[76] "*National Survey Report of Photovoltaic Applications in Israel*", International Energy Agency, 2017

[77] "*How the West Inadvertently Funded Hamas*", Wall Street Journal, October 19, 2023

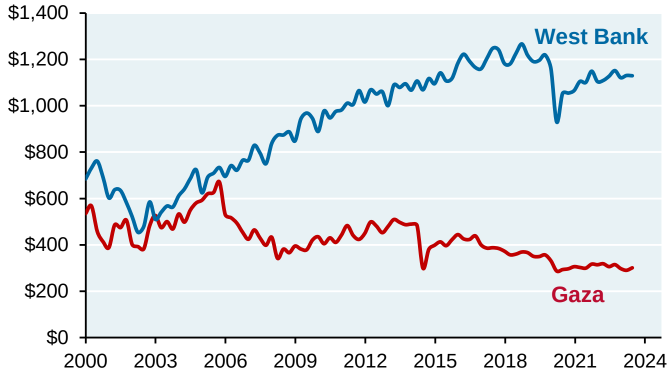
[78] "*International Aid to the Palestinians*", August 4, 2022, Omar Shaban, Arab Center DC

[79] "*Understanding Hamas's Genocidal Ideology: A close read of Hamas's founding documents clearly shows its intentions*", Bruce Hoffman (Georgetown, Council on Foreign Relations), The Atlantic, October 2023. **Quick summary:** destruction of Israel, creation of an Islamic State based on Sharia Law and rejection of all political settlements and negotiations

Whatever international aid levels were, they did little to prevent the crippling economic situation in Gaza that existed before the latest war and which is illustrated below. Note how the income gap between Israel and Gaza is the third largest in the world of all contiguous countries, behind only Yemen/Saudi Arabia and North/South Korea. The myriad reasons for this are well beyond the scope of this analysis.

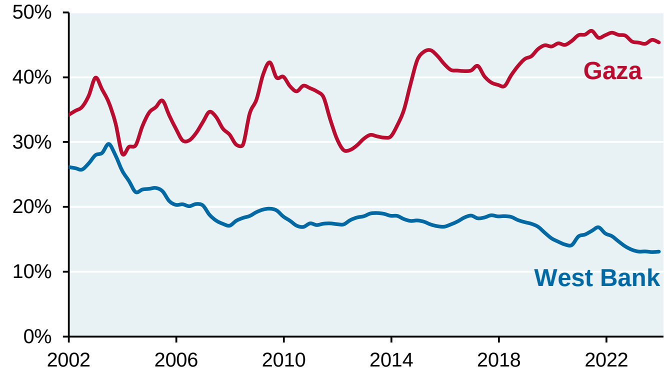
At the end of last year's paper, I wrote about the impossible odds facing nuclear fusion, space-based solar power and electric planes. The odds of a Western-funded Gaza solar rebuild also seem impossible right now. One thing's for sure: like post-WWI Germany in 1919, the story is almost certainly not going to end where things stand now. It could either get much better, or much worse.

GDP per capita
2015 US$



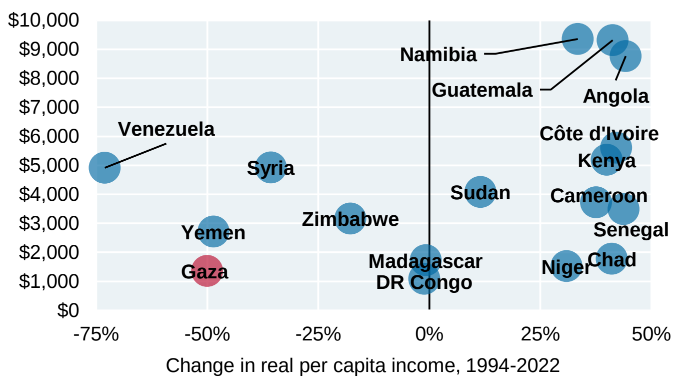
Source: Palestinian Central Bureau of Statistics, JPMAM, Q3 2023

Unemployment rate
Percent, smoothed 4 quarters



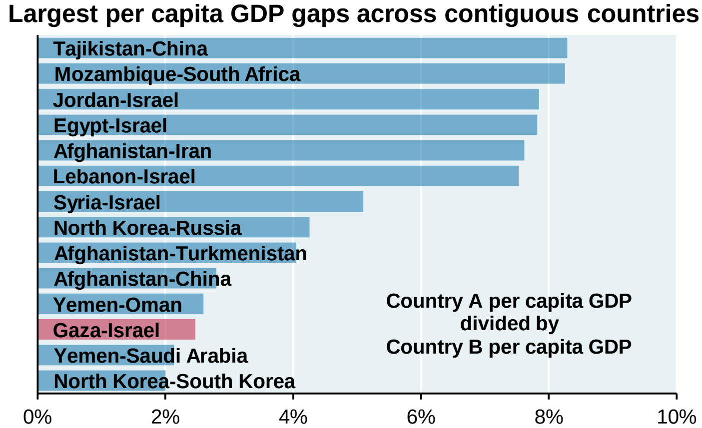
Source: Palestinian Central Bureau of Statistics, JPMAM, Q3 2023

Lowest per capita income and income growth, 1994-2022
2022 per capita income, PPP US$



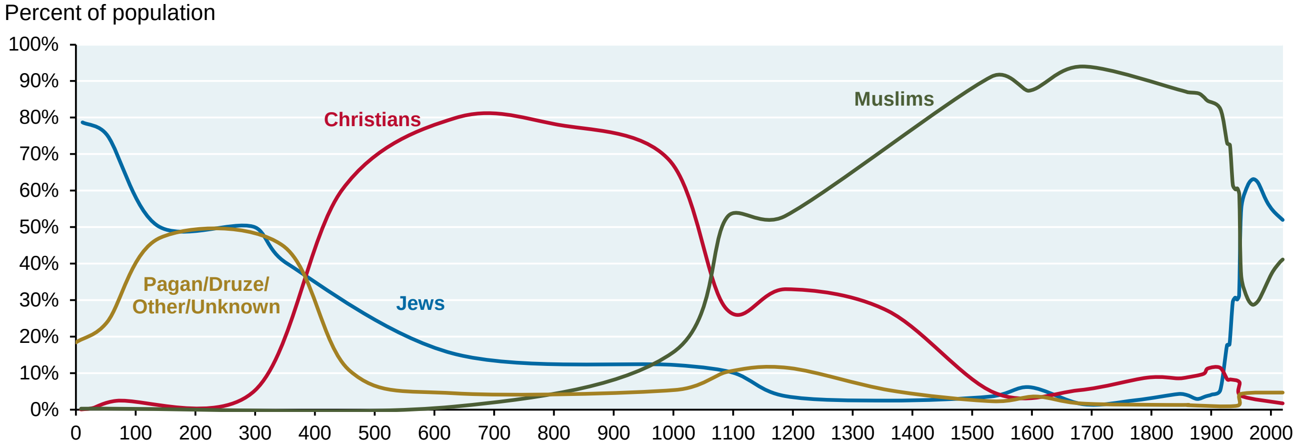
Source: Conference Board, IMF, JPMAM, 2024

Largest per capita GDP gaps across contiguous countries



Source: IMF, World Bank, JPMAM, 2023

Religious demography of Israel-Palestine region since the Year 1 AD
Percent of population



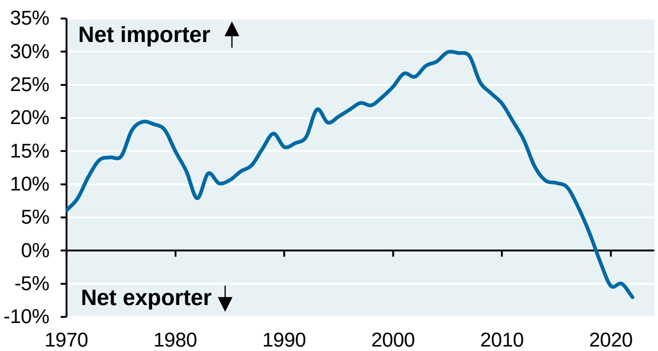
Source: Lyman Stone, Demographic Intelligence/McGill University, 2023

Appendix I: on US and European energy supply/demand and global LNG markets

Despite an almost total decline in Suez Canal containership crossings, WTI oil prices in February 2024 were actually *below* where they were when the Israel-Hamas conflict began. The US is less exposed than it was in the 1970's to changing oil prices. This can partially be explained by the following:

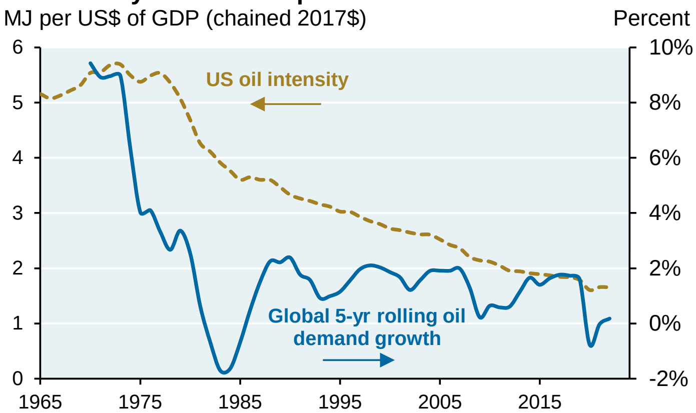
- The US is a net energy exporter vs its net import position in the 1970's. US net crude imports are down 75% from the 2005 peak, and net refined product *imports* of 4 mm bpd in 2005 flipped to net *exports* of 4 mm bpd of refined products by 2019. As shown on page 21, this is mostly a by-product of the shale revolution
- The oil intensity of US GDP growth is 65% lower than it was in the 1970's
- Annual global oil consumption growth has declined from 8%-10% in the early 1970's to 0%-2% today (although as you can see in the 4th chart, there's no peak in oil consumption yet)
- Geopolitical benefits to OPEC of an oil embargo would be less clear now: 75% of Saudi oil exports go to Asia, China gets half its oil from the Middle East and the US gets most of its imported oil from Canada, Mexico and other non-OPEC sources
- Saudi Arabia also has spare capacity to bring online if needed. Spare capacity is measured in different ways; as shown below it is at a high level for a non-recessionary period

US energy dependence and independence
Net imports of oil, natural gas and coal as a share of total primary energy consumption



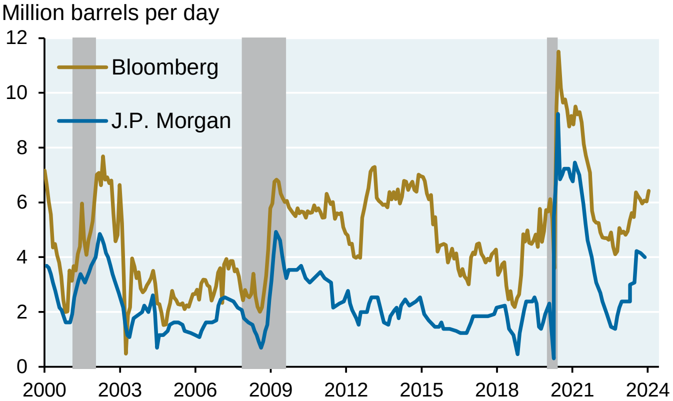
Source: EI Statistical Review of World Energy, JPMAM, 2023

Oil intensity and consumption
MJ per US$ of GDP (chained 2017$)



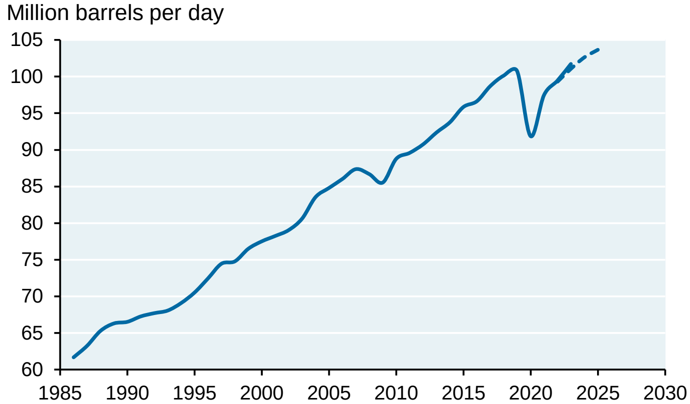
Source: Bloomberg, Energy Institute, JPMAM, 2023

Estimated OPEC spare capacity
Million barrels per day



Source: Bloomberg, J.P. Morgan, January 2024

Global oil demand
Million barrels per day



Source: IEA, JP Morgan Global Commodities Research, January 2024

As for Europe, the region has survived based on a combination of fortuitously warm winter weather, greater energy efficiencies, reduced energy consumption and increasing amounts of imported LNG:

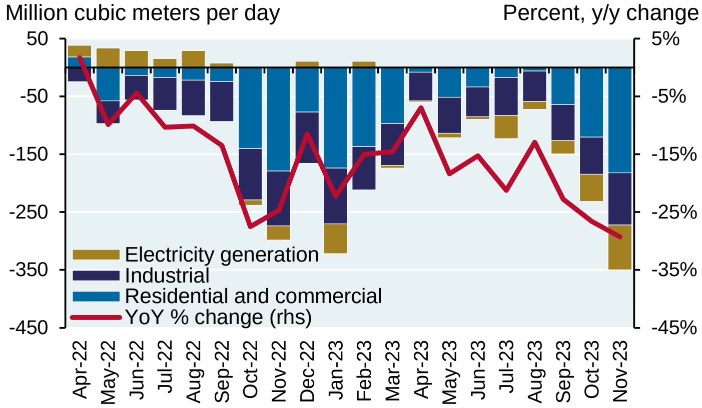
- 15% decline in gas consumption in 2023 vs 2022
- By December 2023, imported LNG volumes tripled vs January 2021
- 46 mtpa of LNG regasification capacity added in 2023, a 25% increase vs January 2022 levels

The global LNG market may remain tight until a large increase in supply in 2025, depending in part on the outcome of recently announced restrictions in the US on the export of LNG.

Update: in January 2024, the Biden administration froze approval for new liquefaction plants exporting US LNG to countries without a free trade agreement with the US (note that there is no such agreement between the US and EU). To be clear, **current LNG exports and projects under construction will not be affected**, and there is an exemption for US allies in case of emergency. In other words, no impact over the short or medium term on US LNG exports to Europe or Asia. The ban seems mostly political in nature in an election year given minimal climate or national security implications. There are only four projects in the DoE approval queue that would be affected (Sempra, Commonwealth LNG and Energy Transfer). A Venture Global project in Louisiana could also be impacted; its FERC approval is pending and is required before consideration by the DoE.

European natural gas demand

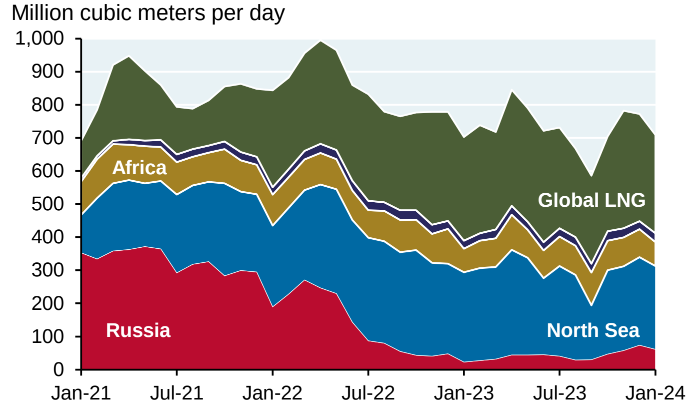
Million cubic meters per day | Percent, y/y change



Source: Mitsubishi UFJ Financial Group, December 2023

European imports of natural gas and LNG

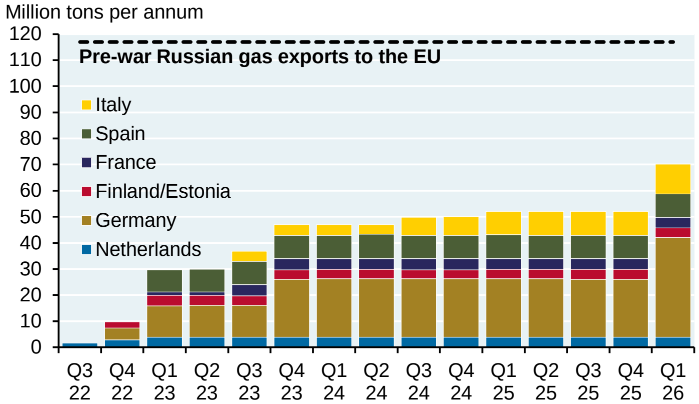
Million cubic meters per day



Source: J.P. Morgan Commodities Research, January 2024

Projected new European LNG regasification capacity

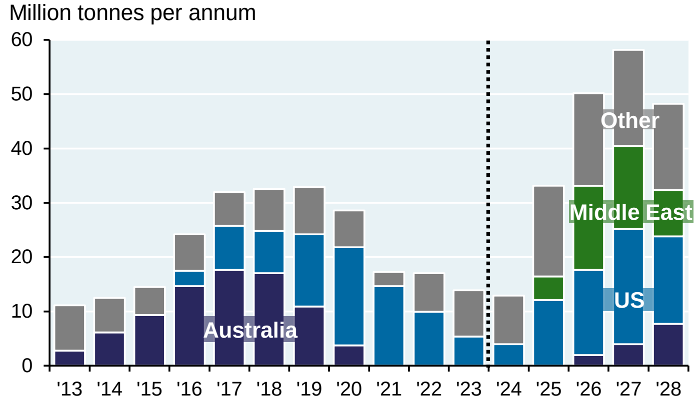
Million tons per annum



Source: Mitsubishi UFJ Financial Group, December 2023

Global LNG supply

Million tonnes per annum



Source: Mitsubishi UFJ Financial Group, December 2023

Appendix II: EV misadventures with Electrify America, Waymo and Jeep

Electrify America: yes, but only part of the time

MotorTrend published a travelogue by a new owner of a Ford F-150 Lightning EV. Called away on an emergency trip, the family piled into their F-150 on a full charge and headed north, following the vehicle's recommended route along Interstate 5. The route was selected due to its Electrify America charging network.

- Unfortunately, 4 of the 6 Electrify America towers at the designated stop were offline with a large wait for the two working towers
- Electrify America was unable to remotely fix the broken towers and Ford's software is apparently unable to adjust trips accordingly. As a result, the family went to another local charging station despite its lower charge rate, but that charger wasn't working either
- The family returned to the original Electrify America station and waited two hours to plug in their F-150, charging at 33 kW which was 10% of the tower's advertised capacity. After one hour on the charger, the battery was 64% full so they scheduled another stop 100 miles north only to find another subpar tower which only charged at 40 kW. After 25 minutes they gave up, booked a hotel and charged overnight

"*Our last Ford F-150 Lightning EV pickup road trip was a nightmare*", MotorTrend, Christian Seabaugh, December 22, 2023. This travelogue is consistent with data from UC Berkeley and JD Power: almost 30% of chargers are not working in the SF Bay Area, and 20% of visits to charging stations nationwide end up with drivers not charging[80]. Best in class: Tesla, with a 99%+ global charging station reliability rate.

Waymo: electric vehicles can gaslight as well

In Phoenix last December, two Waymo self-driving vehicles crashed into the same pickup truck being towed by a tow truck. According to Waymo, this was due to an "exceptionally rare" combination of events: the tow truck was pulling the pickup truck in a backwards position and partially occupying another lane. These conditions were apparently too complex and unusual for Waymo vehicles to decipher. A Waymo EV approached from behind and crashed into the pickup truck. The tow truck kept on driving and several minutes later, a second Waymo EV crashed into the same pickup truck, also after approaching from behind. The director of the Robotics and Autonomy Center at George Mason University took exception to Waymo's characterization of these events as being that unusual, and is now "exhausted by the company's gaslighting"[81]. NHTSA Recall: #24E-013

Jeep: internal (spontaneous) combustion engine

My affinity for Jeep Wranglers was sorely tested after two recalls of my 2021 Jeep Wrangler plug-in hybrid 4xe. The first recall was for "loss of motor power", while the second was for "thermostat gasket failure leading to coolant leakage". In addition, the heater for the electric battery failed and was on back-order for several weeks.

Now, another recall. According to the December 2023 recall notice, "The high voltage battery on your vehicle may fail internally. The defect has not been identified and the root cause is still being investigated. An internally failed battery could lead to a vehicle fire with the ignition on or off". The recall continues: "Customers are advised to refrain from recharging these vehicles, and not to park inside buildings or structures or near other vehicles until the vehicle has the final repair completed." And the kicker: "The remedy for this condition is not yet available". Jeep recall notice B9A/NHTSA 237-787

[80] *"Reliability of Open Public Electric Vehicle Direct Current Fast Chargers"*, UC Berkeley, Rempel et al, April 2022, and "*JD Power 2023 U.S. Electric Vehicle Experience (EVX) Public Charging Study*", JD Power, August 2023

[81] Professor M. Cummings on LinkedIn, George Mason University, February 20, 2024. Gaslighting: manipulating someone into questioning their own perception of reality, from the 1944 film *Gaslight*

IMPORTANT INFORMATION

Investment strategies are selected from both J.P. Morgan and third-party asset managers and are subject to a review process by our manager research teams. From this pool of strategies, our portfolio construction teams select those strategies we believe fit our asset allocation goals and forward-looking views in order to meet the portfolio's investment objective.
As a general matter, we prefer J.P. Morgan managed strategies. We expect the proportion of J.P. Morgan managed strategies will be high (in fact, up to 100 percent) in strategies such as, for example, cash and high-quality fixed income, subject to applicable law and any account-specific considerations.

While our internally managed strategies generally align well with our forward-looking views, and we are familiar with the investment processes as well as the risk and compliance philosophy of the firm, it is important to note that J.P. Morgan receives more overall fees when internally managed strategies are included. We offer the option of choosing to exclude J.P. Morgan managed strategies (other than cash and liquidity products) in certain portfolios.

The Six Circles Funds are U.S.-registered mutual funds managed by J.P. Morgan and sub-advised by third parties. Although considered internally managed strategies, JPMC does not retain a fee for fund management or other fund services.

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