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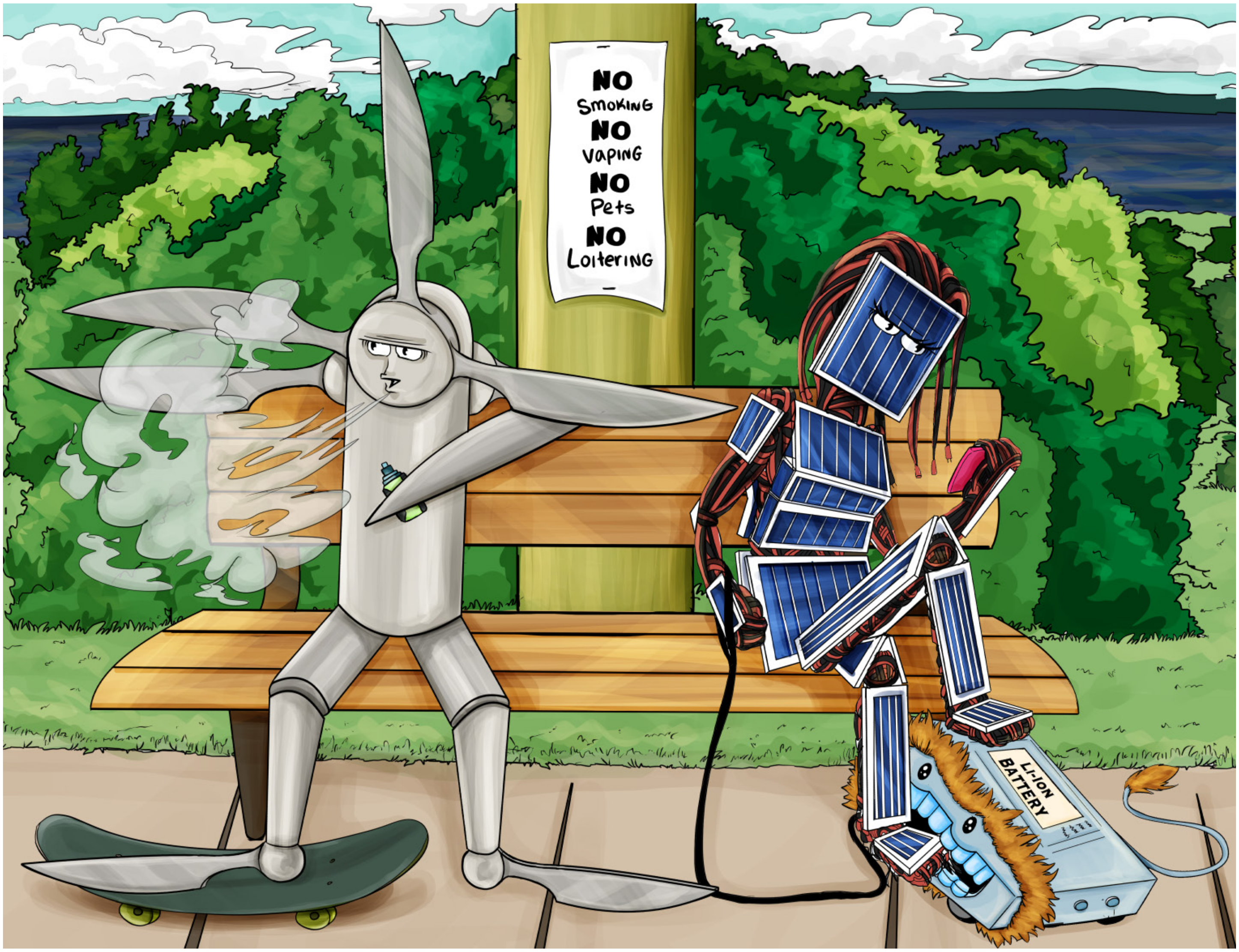
EYE ON THE MARKET ANNUAL ENERGY PAPER | 13TH EDITION



Growing Pains:
The Renewable Transition in Adolescence

Renewables are growing but don't always behave the way you want them to. This year's topics include the impact of rising clean energy investment and new energy bills, how grid decarbonization is outpacing electrification, the long-term oil demand outlook, the flawed concept of levelized cost when applied to wind and solar power, the scramble for critical minerals, the improving economics of energy storage and heat pumps, the transmission quagmire, energy from municipal waste, carbon sequestration, a whydrogen update, the Russia-China energy partnership, methane tracking and some futuristic energy ideas that you can just ignore, for now.

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

Growing Pains: The Renewable Transition in Adolescence

2023 Eye on the Market energy paper

As the renewable transition hits its teenage years, it's time to take stock of what has been accomplished so far:

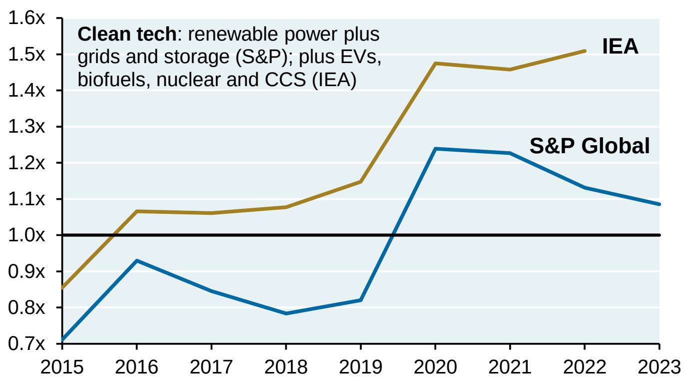
- "Clean tech" is outpacing fossil fuel investment even before new US/European energy bills
- Global wind+solar generation exceeded nuclear for the first time in 2021
- The IEA projects peak global fossil fuel demand this decade even under its slower transition case
- Projected renewable capacity additions of ~2,500 GW over the next five years would match the prior 20
- The pace of EV sales, residential heat pump adoption and US battery plant build-outs has increased
- Hybrid solar-storage projects are becoming more competitive with gas peaker plants
- China 2022 renewable capacity additions = US, Europe, India, Southeast Asia and Latin America combined
- Economies of scale: as illustrated below, the IEA has consistently underestimated solar capacity additions

Even so, decarbonization of energy use will be a gradual process. After $6.3 trillion spent on renewable energy and another $3.3 trillion spent on electricity networks since 2005, global energy use is still ~80% reliant on fossil fuels, from a low of 70% in Europe to 86% in EM ex-China. The global measure has declined by just 5% since 2005 due to challenges electrifying industrial, commercial, residential and transport energy. There's also too much focus on fossil fuel shares; what matters even more is the *amount* of fossil fuels used (chart, lower left).

For the most part, renewable energy displaces fossil fuels that power HVAC systems in homes and office buildings. Renewables also decarbonize 10%-15% of industrial energy use, and the stock of electric cars, vans, trucks, buses and bikes reduces global oil consumption by ~2 mm barrels a day, which is ~2% of oil use. But the pillars of modern society (steel, cement, ammonia, plastics) are still made primarily using fossil fuels, particularly in developing countries to whom the West has outsourced the most energy intensive kinds of manufacturing.

Clean tech spending outpacing fossil fuels

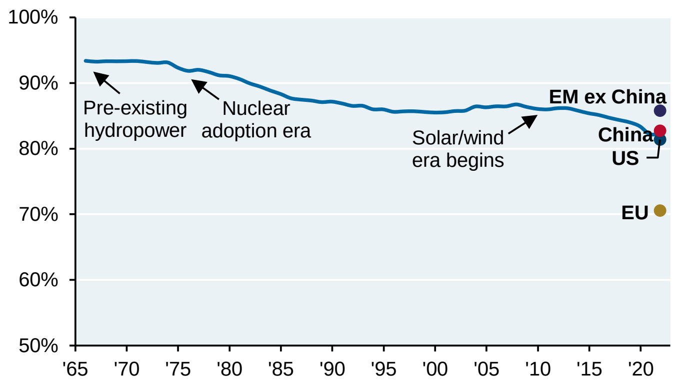
Ratio, clean tech / fossil fuel capital spending by year



Source: S&P Global, IEA, JPMAM. 2023.

Fossil fuel share of primary energy since 1965

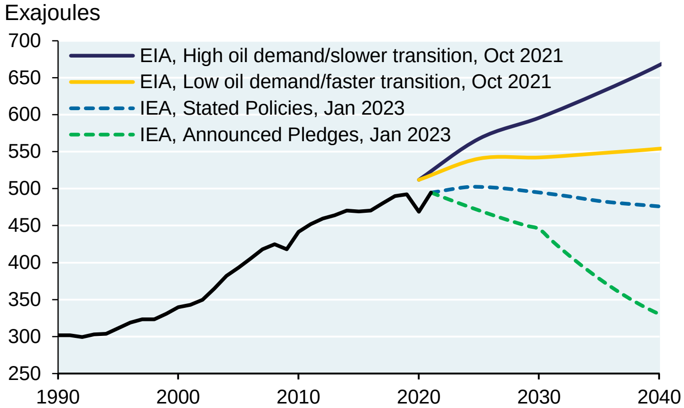
% of global primary energy consumption from coal, oil and nat gas



Source: BP Statistical Review of World Energy, JPMAM. 2022.

Future global fossil fuel demand: depends who you ask

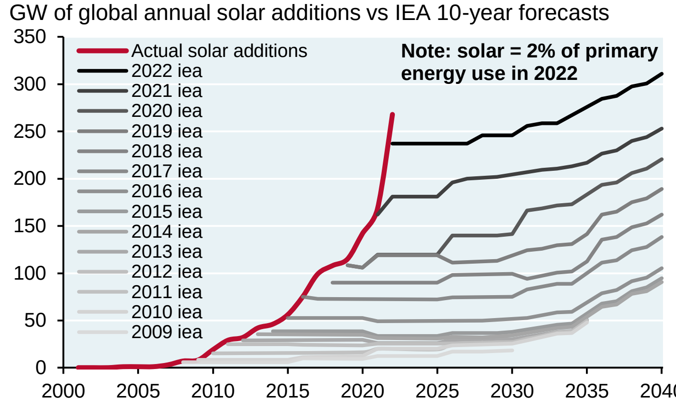
Exajoules



Source: Energy Information Admin., Int'l Energy Agency, JPMAM. 2022

IEA consistently underestimated solar capacity growth

GW of global annual solar additions vs IEA 10-year forecasts



Source: Carbon Brief, BNEF. 2022. IEA = International Energy Agency.

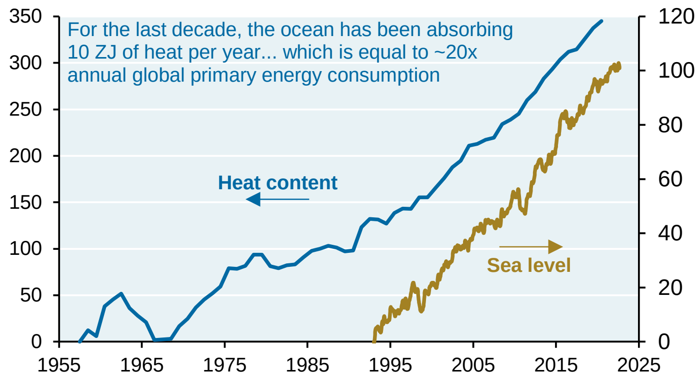
Evidence pointing to the need for a more rapid transition appears below: rising ocean temperatures and sea levels, falling ice sheet mass, rising greenhouse gas concentrations and rising emissions despite improving CO_2 intensity. **So let's look at the transition's primary obstacles**: permitting delays for generation and transmission, frequent lack of eminent domain in the West, availability of critical minerals and rising resource nationalism, high cost per unit of energy needed to decarbonize industrial heat, backup thermal power and storage costs required to accompany intermittent wind and solar power, challenges for grid managers integrating thousands of new wind and solar projects, the long useful lives of existing machines/vehicles/furnaces and the time it takes for societies to build new "prime movers" (engines and turbines) to utilize new forms of energy.

If that's what is constraining the pace of change, I remain totally unconvinced that starving the oil & gas industry of capital will make the transition go any faster, particularly since new pools of capital will step in[1] as long as demand for fossil fuels exists. Such an approach could also expose countries to energy shortages that renewables are currently unable to fill. While its energy prices have declined from peak levels, Europe is still paying a heavy price for mismanaging energy supplies while its transition is ongoing. Advice to a handful of countries with ample oil and gas reserves: the renewable transition is picking up speed, but "don't quit your day job". As shown on the prior page[2], **you will need those oil & gas reserves for many years to come unless the world delivers on a set of very ambitious pledges to decarbonize at a totally unprecedented pace**.

Michael Cembalest, JP Morgan Asset Management

Ocean heat content and sea level

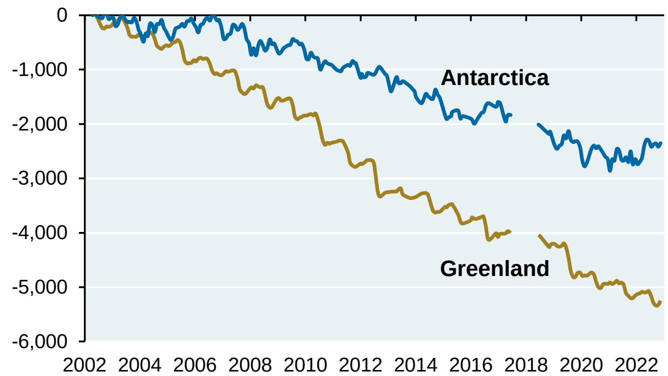
Zettajoules, vs 1957 baseline — Millimeters, vs 1993 baseline



Source: NASA/NOAA. 2022. 1 ZJ = 10^{21} joules.

Antarctica and Greenland ice sheet mass

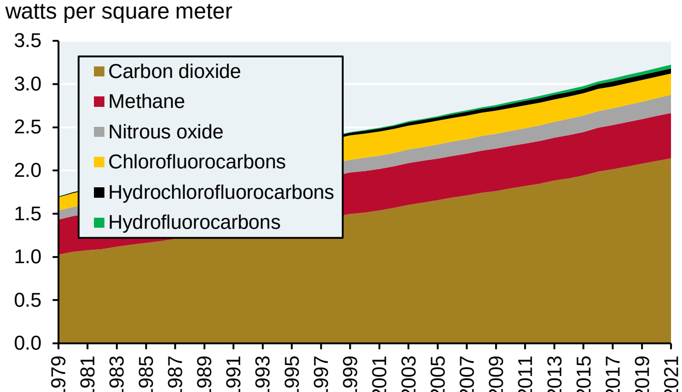
Mass variation, gigatonnes



Source: NASA. November 2022.

Greenhouse effect: radiative forcing by GHG

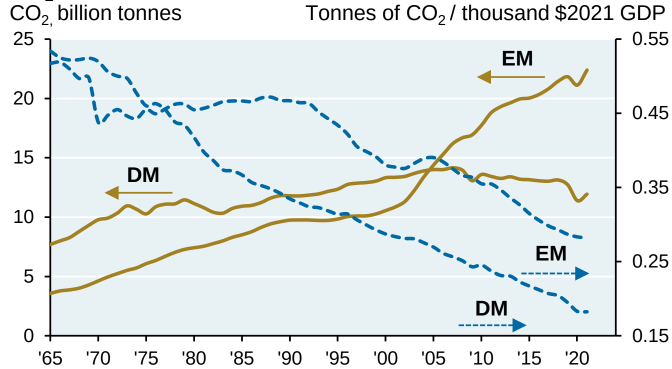
watts per square meter



Source: NOAA Global Monitoring Laboratory. 2022.

CO_2 emissions volumes vs intensity

CO_2, billion tonnes — Tonnes of CO_2 / thousand $2021 GDP



Source: BP, Conf. Board, JPMAM. 2022. Note: DM = Developed Markets; EM = Emerging Markets.

[1] **Warren Buffett** has a $60 bn stake in Chevron & Occidental, offered several billion to buy Dominion gas/ transmission assets until anti-trust concerns forced a withdrawal, and owns stakes in Kinder Morgan pipelines.

[2] EIA 2021 projections on the prior page precede Russia's invasion of Ukraine and European policy responses, as well as the US energy bill. I expect the next EIA release in Sep 2023 to show lower trajectories of fossil fuel use.

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Acronyms

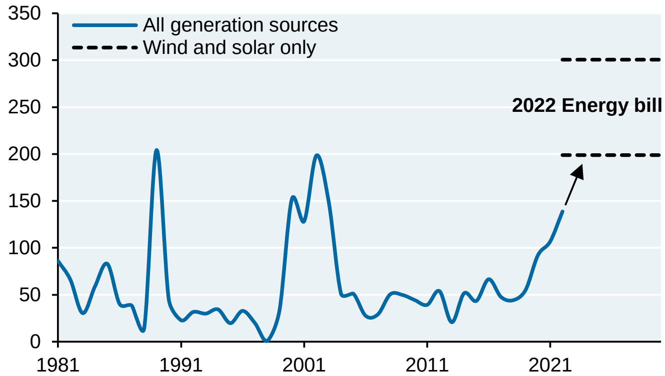
ANL: Argonne National Laboratory; **bcm**: billion cubic meters; **BP:** British Petroleum; **bpd:** barrels per day; **BTU:** British thermal unit; **CCS:** carbon capture and storage; **DACC:** direct air carbon capture; **E&P:** exploration and production; **EIA:** Energy Information Administration; **EPA:** Environmental Protection Agency; **EV:** electric vehicle; **FERC:** Federal Energy Regulatory Commission; **GJ:** gigajoule; **GW:** gigawatt; **HVAC:** heating, ventilation and air conditioning; **HVDC:** high-voltage direct current; **IEA:** International Energy Administration; **IRENA:** International Renewable Energy Agency; **ISO:** independent system operator; **ITC**: investment tax credit; **kbd:** thousand barrels per day; **kt:** kilotons; **LBNL:** Lawrence Berkeley National Laboratory; **LCOE:** levelized cost of energy; **LFP:** lithium iron phosphate; **LNG:** liquefied natural gas; **MJ:** megajoule; **MW:** megawatt; **NHTSA:** National Highway Traffic Safety Administration; **NIB:** neodymium, iron and boron; **NMC:** nickel, manganese and cobalt; **NREL:** National Renewable Energy Laboratory; **O&M:** operations & maintenance; **PPA:** Power Purchase Agreement; **PV:** photovoltaic; **REE:** rare earth elements; **TW:** terawatt; **TWh:** terawatt-hour; **USDA:** US Department of Agriculture; **USGS:** US Geological Survey

Executive Summary: a detailed look at the goals and realities of the energy transition

The West has set a high bar. In each chart, dotted lines represent annual wind and solar capacity additions needed to meet stated targets by 2030, while solid lines show historical capacity additions from *all* generation sources. In other words, **the US and Europe need to sustain new wind and solar additions at a pace equal to historical peak additions, or above them. The goals are particularly ambitious in Germany, whose transition is fraught with electricity price and reliability risk[3].** As we explain in the sections that follow, constraints related to critical minerals, project siting and grid connection may restrain capacity additions below these targets.

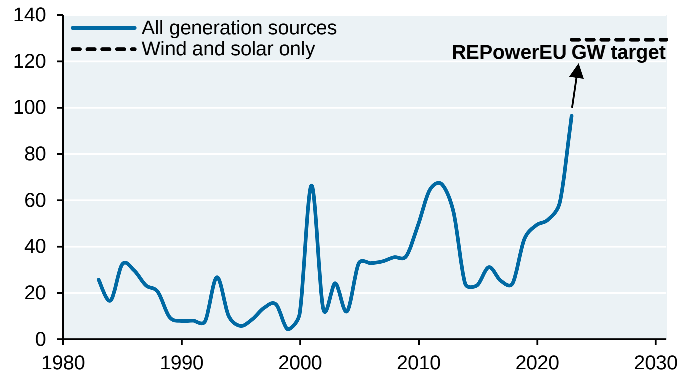
China's situation is different. Its stated wind and solar goals are within reach compared to the pace of recent capacity additions. But China needs more than just new wind and solar power, which is why it is building coal as well. In 2022, China approved 106 GW of new coal capacity, the highest figure in 7 years, and which is equal to the last 5 years of decommissioned coal capacity in the US and Europe combined.

US capacity additions and projections
Gross electricity capacity additions, watts per year per capita



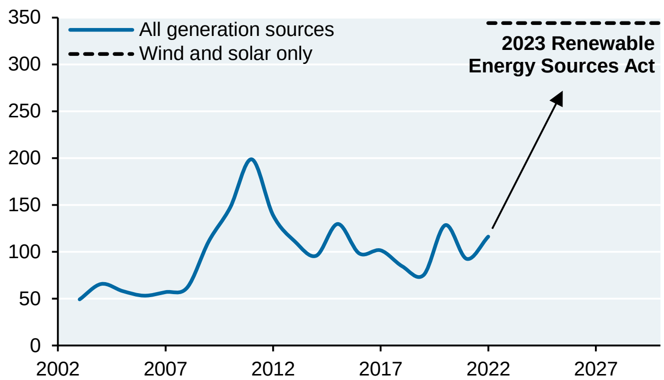
Source: EIA, Princeton (REPEAT), JPMAM. 2022.

European Union capacity additions and projections
Gross electricity capacity additions, watts per year per capita



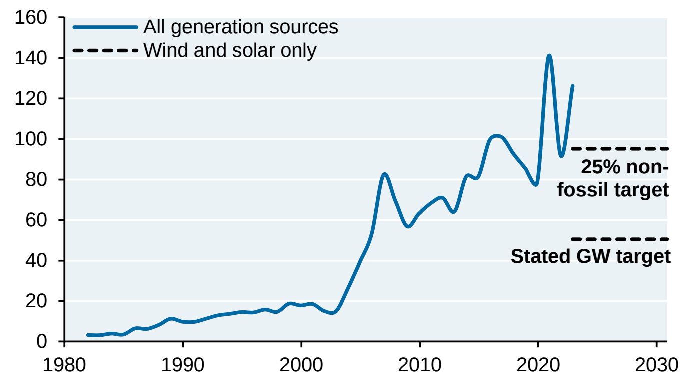
Source: European Commission, EIA, JPMAM. 2022.

Germany capacity additions and projections
Gross electricity capacity additions, watts per year per capita



Source: Fraunhofer ISE, JPMAM. 2022.

China capacity additions and projections
Gross electricity capacity additions, watts per year per capita



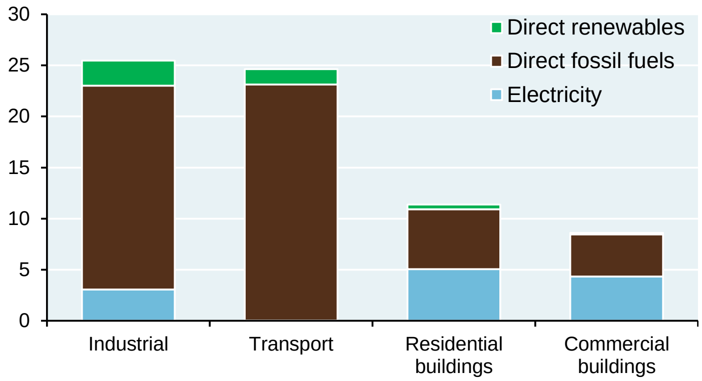
Source: SCMP, CREA, EIA, JPMAM. 2022.

[3] **Germany** plans to shutter its last three nuclear plants in April and accelerate its exit from coal to 2030, while adding wind, solar and natural gas plants that can eventually run on hydrogen. At the same time, electricity demand is projected to rise by 33% due to increased use of EVs, heat pumps and electrolyzers, requiring Germany's electricity grid to double in size. Germany is already the second-most expensive electricity market in Europe; earlier this year, Bloomberg NEF estimated the cost of Germany's plan at **$1 trillion** by 2030.

The evidence is stacked against this plan being achieved other than at a very high cost that could accelerate the exodus of German manufacturing. The head of German chemicals trade union *Verband der Chemischen Industrie* commented that Germany risks "turning from an industrial country into an industrial museum." In addition, McKinsey estimates that Germany's peak load *capacity* will fall to 90 GW by 2030 while its peak load *demand* will rise to 120 GW, creating a large potential 30 GW shortfall.

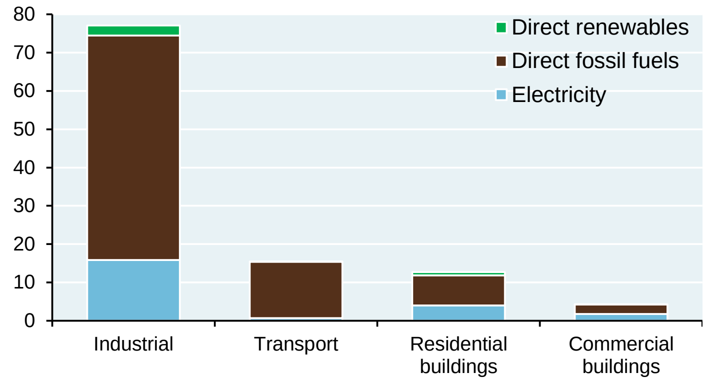
If these new capacity targets are met and the grid is further decarbonized, CO_2 emissions would fall but not achieve the holy grail of decarbonization. The reason: electricity is only 20%-30% of total energy consumption. The holy grail is (a) **electrification** of energy demand currently met via direct combustion of fossil fuels so it can then be decarbonized, and (b) **combustion of renewable or synthetic fuels** in place of fossil fuels. As shown below, direct fossil fuel use is substantial across all four end-use sectors whether we're talking about a developed country like the US or a highly industrialized, developing country like China.

US final energy consumption by sector and fuel
Quadrillion BTUs of final energy consumed by sector



Source: Energy Information Administration, JPMAM. 2021.

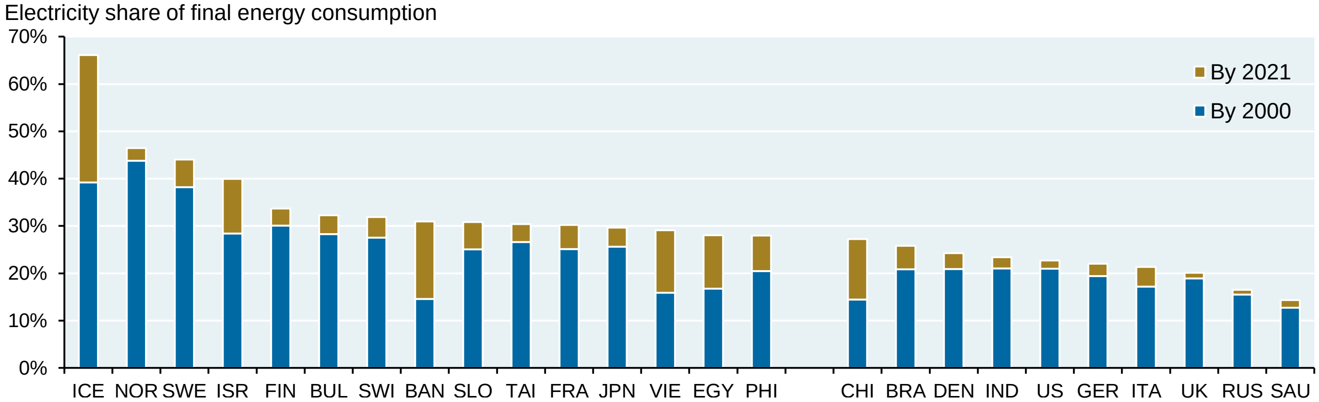
China final energy consumption by sector and fuel
Quadrillion BTUs of final energy consumed by sector



Source: Energy Information Administration, JPMAM. 2021.

Over the last 20 years, the pace of electrification has been slow. The next chart shows electricity as a share of energy consumption as of the year 2000, and as of 2021. A few countries rely on electricity for more than 30% but they're typically smaller with abundant hydro or geothermal power[4]. Most larger countries rely on electricity for less than 25% of energy consumption, with small gains of 3%-5% since the new millennium began.

The gradual advance of electrification, 2000 to 2021
Electricity share of final energy consumption

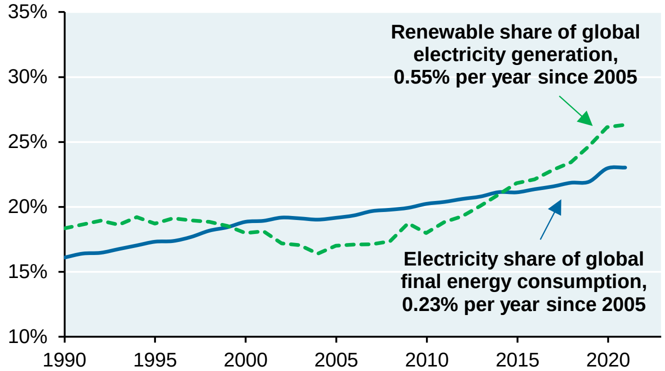


Source: BP Statistical Review of World Energy, JPMAM. 2022.

[4] **Smaller countries with high electrification shares of primary energy, or high renewable shares of electricity, are rarely roadmaps for larger ones**. Countries like Uruguay, Iceland, Norway, Costa Rica, New Zealand, Sweden and Denmark tend to have lower population density, lower transmission needs and most importantly **lower economic complexity**. The latter is estimated by Harvard in its Atlas of Economic Complexity, and also by MIT's Observatory of Economic Complexity. These measures assess each country's ability to produce a wide range of complex products across industries, which in turn drives the need for more developed energy systems. Also: these countries often benefit from unique and abundant hydro, geothermal or sugarcane biomass resources, and some benefit from proximity to larger countries for grid stabilization (Uruguay/Brazil, Denmark/Germany).

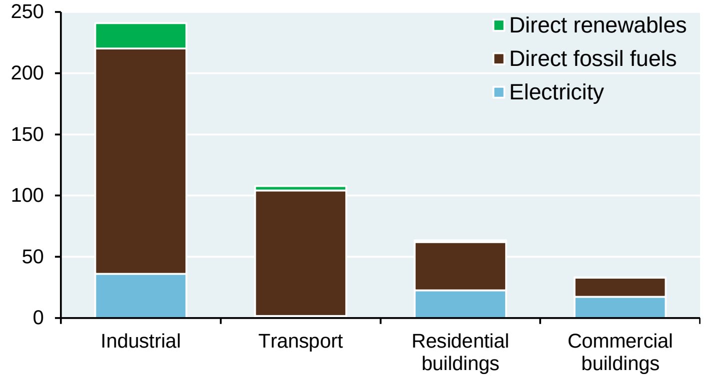
The two energy transitions. As shown on the left, there are actually two energy transitions taking place: the decarbonization of electricity generation via the addition of renewable power (green dotted line), and the electrification of energy use so that it can then be decarbonized (blue line). The latter is harder to do than the former. Let's discuss decarbonization potential in the order of each sector's direct fossil fuel use: first the industrial sector, then transport and then residential and commercial buildings.

Grid decarbonization outpaces electrification of energy use
Percent



Source: BP Statistical Review of World Energy, JPMAM. 2022.

Global final energy consumption by sector and fuel
Quadrillion BTUs of final energy consumed by sector

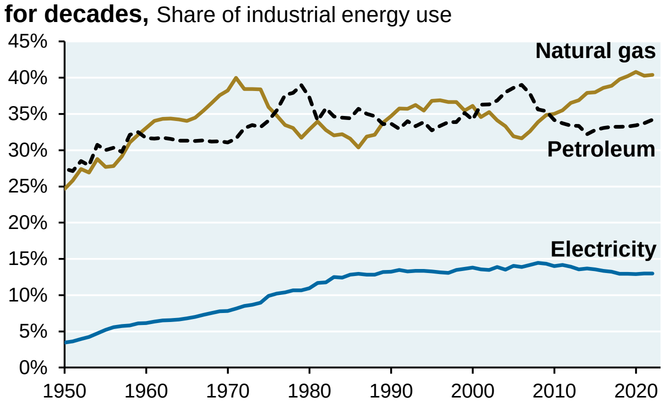


Source: Energy Information Administration, JPMAM. 2021.

***Industrial energy use*[5].** Plastics, cement, steel, ammonia/fertilizer and other industrial materials form the building blocks of the modern world. Pathways for decarbonizing them include increased electrification of industrial heat, substitution of fossil fuels used for process heat and increased renewable electricity on the grid. We've written before on the physical/chemical constraints and costs of electrifying industrial production (see link on page 10). The short answer: direct electrification often results in the loss of waste heat used in many industrial chemical reactions, many non-metallic products are harder to electrify, and electricity currently costs a lot more than natural gas per unit of delivered energy when used for industrial heat.

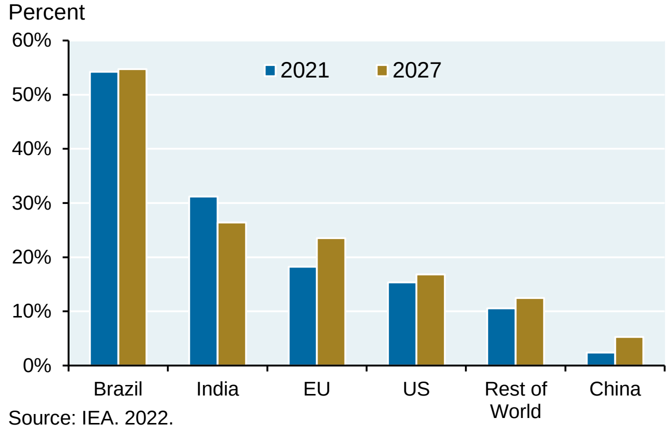
As confirmation of this point, note how the electricity share of US industrial energy use has been **unchanged for decades**. Electricity shares of industrial energy use are low everywhere: Africa 10%, US 12%, Japan 13%, India 15%, Europe 17% and China 21%. Where are the electrification opportunities? One quarter of industrial energy uses require temperatures less than 100ºC, which are presumably easier to electrify; and highly efficient industrial heat pumps can be used for drying, pressing, sterilizing, staining and steaming. Within the related category of industrial heat, projected gains in renewable shares over the next few years are generally small.

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



Source: EIA, JPMAM. January 2023.

Renewable share of industrial heat consumption
Percent

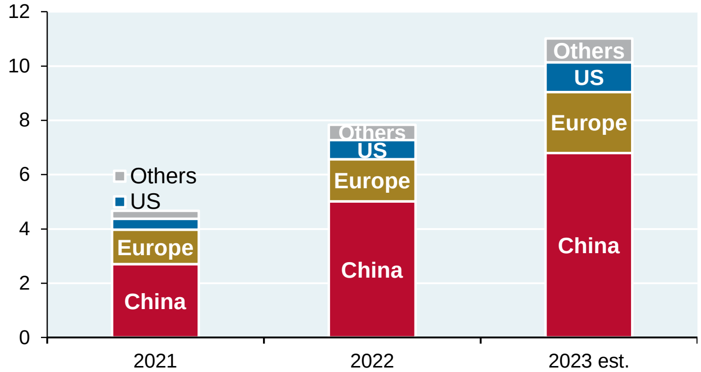


Source: IEA. 2022.

[5] In the US, **industrial energy consumption** is 80% manufacturing, 9% mining with the rest split between construction and agriculture. Within manufacturing, the major subsectors are chemicals 37%, petroleum and coal products 22%, paper 11%, primary metals 8%, food 6% and non-metallic minerals 4%.

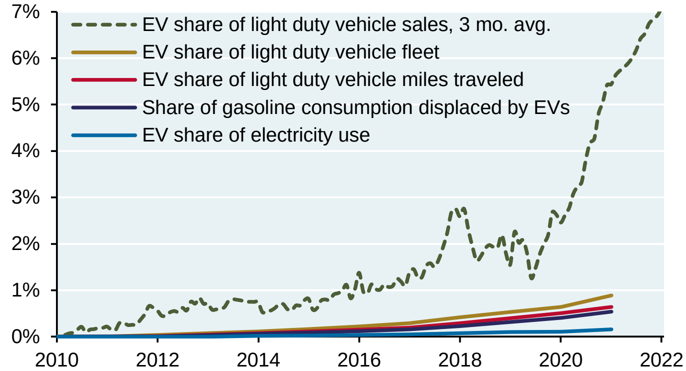
Transportation/oil demand. EV sales were 10% of global passenger car sales last year, rising 68% in 2022 with another 40% gain projected for 2023; and that's just battery electric vehicles without including plug-in hybrids. The top 4 global spots were held by Tesla, BYD (whose order book is now 3x Tesla's), SAIC and VW Group. EV performance metrics are also improving: Argonne National Lab cites longer average EV range (300 miles), faster 0-60 acceleration (5 seconds), more power (250 kW) and better fuel efficiency (29 kWh per 100 miles) for EVs sold in the US. As shown on the right however, it takes many years of high EV *sales* to electrify large portions of the *fleet* given the 12-13 year average life of modern combustion engine vehicles, using the US as an example.

Global sales of battery electric vehicles
Number of vehicles, millions



Source: WSJ, LMC Auto, EV Volumes. January 16, 2023.

It takes time for EV sales to impact entire fleet
Percent

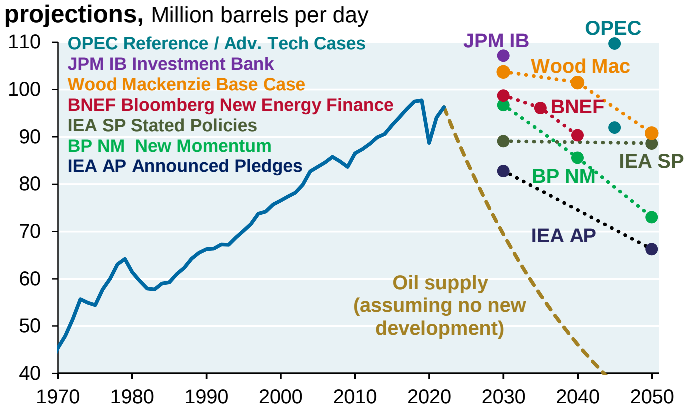


Source: ANL, JPMAM. 2023.

Rather than getting caught up in competing projections of EV penetration, let's get to the bottom line: **what might global oil demand look like in 10-15 years?** Such projections are complex: they require estimates of EV demand, population, mileage traveled, vehicle replacement, incentives and home-sourcing rules[6], ICE mileage and projections of demand from **non-transport sectors** which account for almost half of global oil consumption; although to be clear, refining and part of the "Other" category are linked to passenger cars/EVs as well.

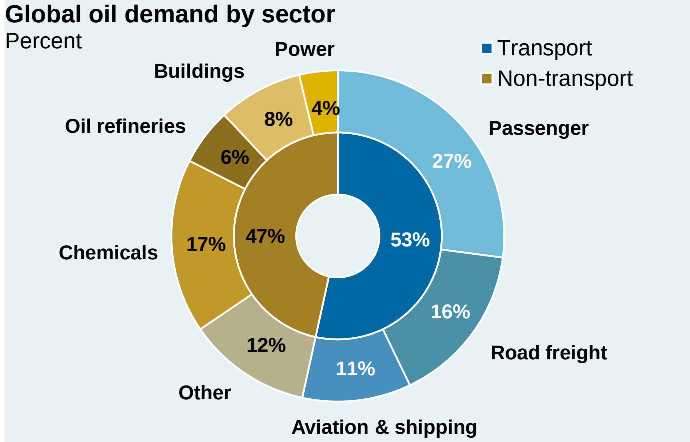
Some widely cited estimates appear below. If they're right, **oil demand will finally stop rising inexorably into the future, but it could take 20 years for global oil demand to meaningfully decline.** Some BP and IEA scenarios project larger demand declines, but they're backloaded after 2030.

Oil demand, supply from existing fields and demand projections, Million barrels per day



Source: BP, EIA, IEA, OPEC, Wood Mac, BNEF, JP Morgan IB, JPMAM. 2023.

Global oil demand by sector
Percent



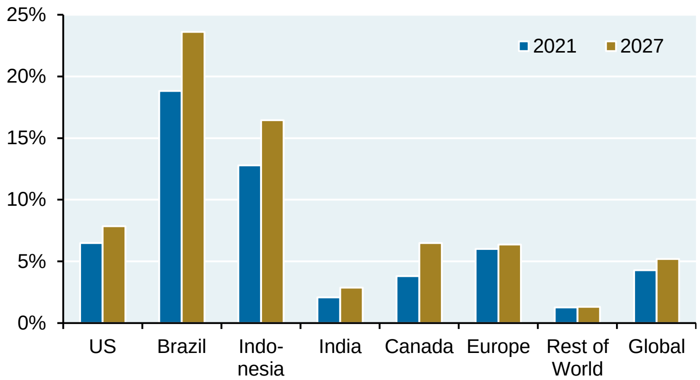
Source: IEA, JPMAM. 2022.

[6] On March 31st, Treasury released final guidance on EV subsidies which will be effective April 18. It's a long story, but the bottom line is that Sen. Manchin's objectives partially survived: EV subsidies will be confined to vehicles whose battery assembly and critical minerals are predominantly sourced from the US or its allies, with clauses disallowing subsidies when battery components or critical minerals are sourced from "foreign entities of concern", with further guidance forthcoming. These tests get stricter over time; and they are applied separately, with battery assembly and critical minerals each accounting for 50% of the $7,500 subsidy.

There's a lot written about biofuels but apart from Brazil and Indonesia, biofuel contributions to fuel supplies are small. The US now supports biofuels with $10 billion in tax credits for new production and infrastructure, but the boost to biofuels as a share of transport fuel use may be just 2%-3% on top of existing ethanol consumption[7]. Similarly, renewable aviation fuels (RAF) may represent just 1% of global jet fuel consumption 5 years from now, with the US possibly reaching 2% with a $1.75 per gallon Sustainable Aviation Fuel Credit in the energy bill[8]. RAF pathways need more compelling proof statements than anything we've seen so far. As shown in the 2nd chart, estimated costs for renewable aviation fuels are 2x-8x higher than jet fuel prices[9].

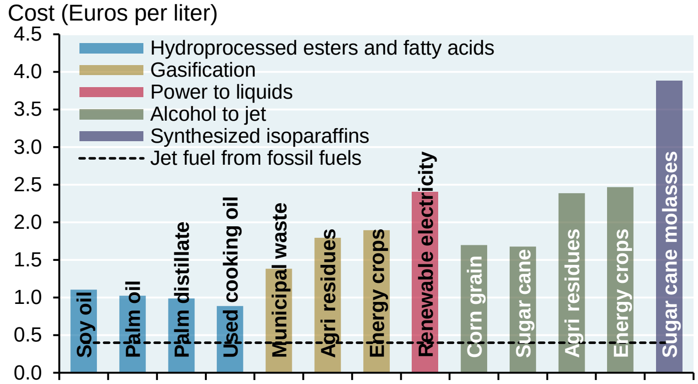
Something to watch: the risk of biofuel feedstock supply constraints regarding animal fats, waste oils and other residue oils (3rd chart). In the box: the never-ending food fight over **corn ethanol's carbon footprint** as bushels of US corn grown for ethanol are now roughly the same as those grown for human and livestock consumption.

Biofuel share of transport demand
Share of transport demand



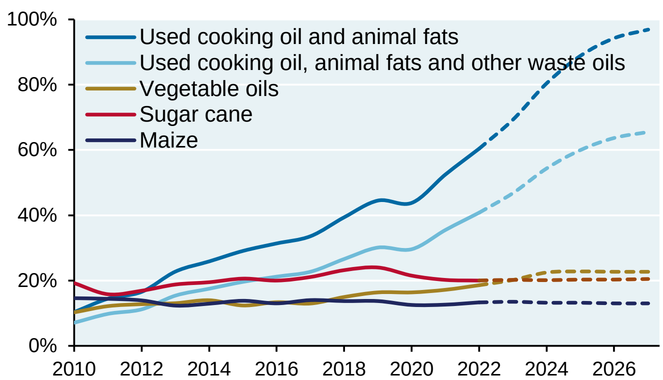
Source: IEA. 2022.

Renewable jet fuel cost estimates
Cost (Euros per liter)



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

Biofuel demand share of global production / supply
Percent



Source: IEA, JPMAM. 2023.

Food Fight: competing studies on corn ethanol

A 2022 study published in the Proceeding of the National Academy of Sciences (from researchers at the University of Wisconsin-Madison) concluded that ethanol is worse for the environment than gasoline, contradicting a prior study commissioned by the USDA. The new study estimates that ethanol's carbon intensity is **24% higher** than gasoline, while the 2019 USDA study found that ethanol's carbon intensity is **39% lower.**

The new study accounts for emissions resulting from land use changes (i.e., tilling of cropland that would have been retired or enrolled in conservation programs).

Unsurprisingly, the CEO of the Renewable Fuels Association described the new study as "fictional and erroneous" and filled with worst-case assumptions.

[7] In the US, our commodities analysts expect 300 kbd of biodiesel by 2024 (~8% of US diesel production)

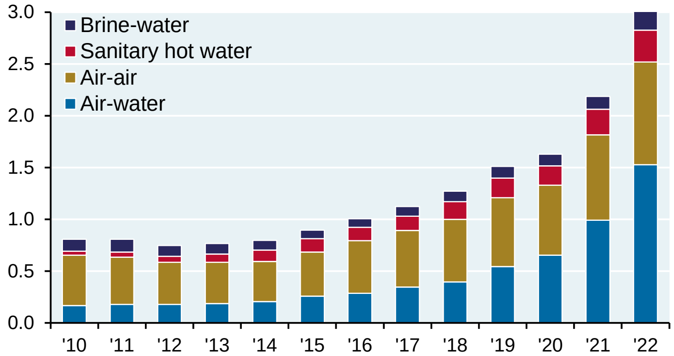
[8] **I refer to the "energy bill" rather than the "Inflation Reduction Act"**, since a large part of the projected IRA deficit reduction comes from revenues raised by the Internal Revenue Service after a $45 bn infusion for new enforcement agents. As explained in the September 2022 Eye on the Market, GAO data on revenues raised per IRS audit are lower than the implied CBO estimates used to score the IRA.

[9] "*Net zero aviation fuels: resource requirements and environmental impacts*", Royal Society, February 2023

Commercial and residential building heat. Decarbonization of building heat takes several forms: increased use of renewables on the grid, increased electrification of heat via heat pumps (discussed last year, see link on p.10), renewable district heat (mostly used in Scandinavia) and direct use of geothermal and solar thermal energy.

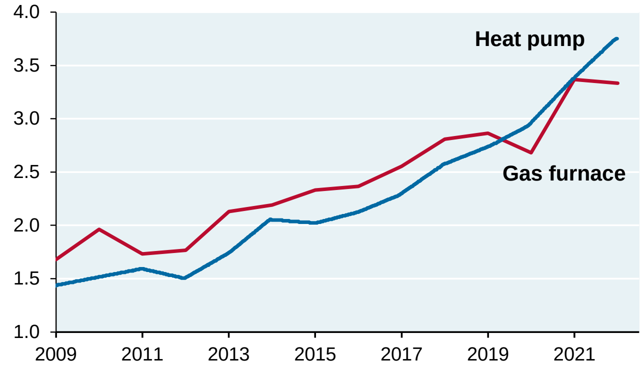
Renewable gains for building heat may be faster than in the industrial sector. European heat pump adoption is rising as boiler sales decline, and in the US, propane and heating oil customers are probably the primary drivers of heat pumps overtaking gas furnace sales. Significant improvements in heat pump technology have taken place over the last decade: as per the fourth chart, CO_2 emissions from an air-to-air heat pump are now lower than the most efficient gas boiler, despite higher thermal losses from grid electricity vs onsite gas combustion. **An offset in Europe**: homes adding heat pumps are adding air conditioning too, and many for the first time; declines in winter energy use could be partially offset by rising summer energy use (see second box).

European heat pump sales reach 3 million units
Annual sales, millions



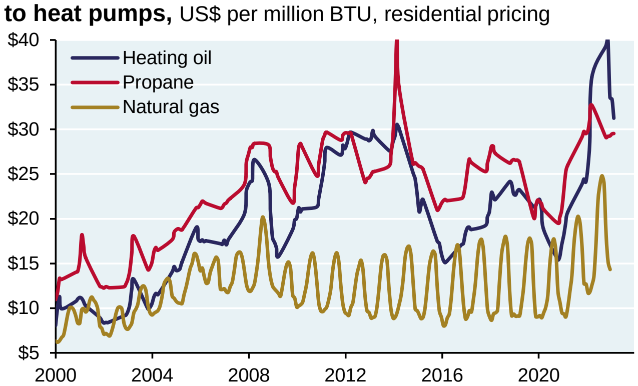
Source: European Heat Pump Association. February 2023.

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



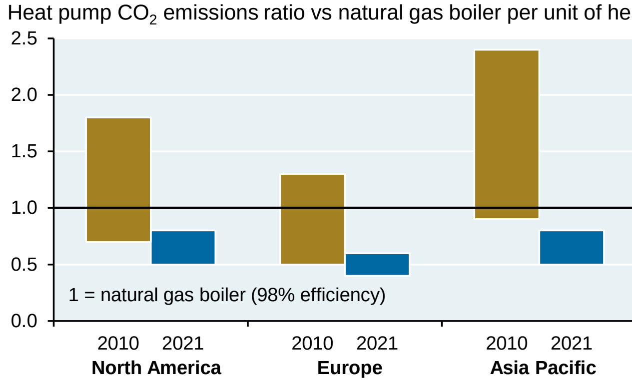
Source: Air Conditioning, Heating and Refrigeration Institute. 2023.

Heating oil and propane users; greater incentive to switch to heat pumps, US$ per million BTU, residential pricing



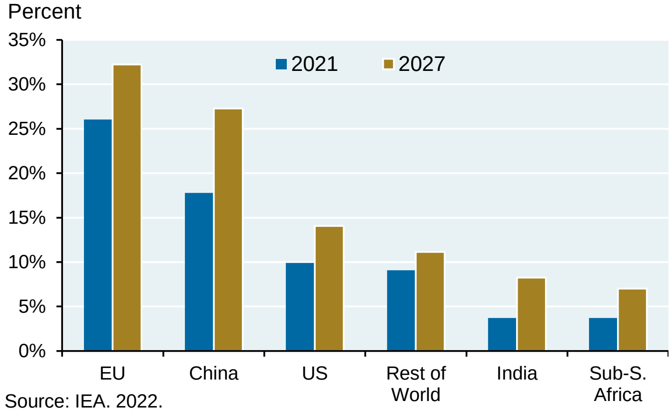
Source: EIA, JPMAM. February 2023.

Large efficiency gains in heat pump technology since 2010
Heat pump CO_2 emissions ratio vs natural gas boiler per unit of heat



Source: IEA, JPMAM. 2022.

Renewable share of building heat consumption
Percent



Source: IEA. 2022.

IEA projections of renewable heat shares are rising. These increases reflect two primary factors: falling building heat consumption since heat pumps require less energy per unit of heat than on-site fuel combustion; and the by-product of more renewables on the grid that generate the electricity which is used by the heat pumps themselves.

US vs European air conditioning trends
US homeowners use ~1,800 kWh per dwelling each year for air conditioning. In most countries in Europe, this figure is less than 100 kWh. Heat pumps are also air conditioners….so the energy/CO_2 benefits of heat pumps in Europe will likely be offset by summer use.

Concluding remarks for this year's Executive Summary

I see quite a few energy papers whose authors project seismic changes in the energy landscape out to 2050, with some component transitions projected to occur in 2035, 2040 or even later. I have no idea how they claim to have visibility that far out; just think about what happened in the world over the last 3 years. Decarbonization of electricity, passenger cars and winter heating in homes and buildings is advancing in many parts of the world; that part is clear and fossil fuel use will almost certainly start to plateau in the developed world, but the process will take years/decades. On industrial energy use, the future is less clear given obstacles discussed above, particularly in the developing world. That's about as far as I can see.

One think tank that modeled the US energy bill on behalf of the US Senate projected massive solar and wind expansion and GHG declines out to 2035. Its report was also accompanied by the following caveat, if you were able to spot it:

> "*Several constraints that are difficult to model may limit these growth rates in practice, including the ability to site and permit projects at requisite pace and scale; to expand electricity transmission, CO_2 transport and storage to accommodate new generating capacity; and to hire and train the expanded energy workforce to build these projects*."

So, as long as the realities of the world in which we live don't get in the way, the goals are all achievable. That's how I recommend that you interpret long-dated energy projections from Wall Street firms, energy think tanks and governments: they typically assume that investors and lenders take advantage of subsidies in an optimized world in which economic incentives are the sole drivers of change.

The ultimate path of fossil fuel demand depicted on page 1 will be determined by technology, policy, trade, chemistry, physics, geopolitics, trade, cost and nationalism, all of which we discuss in these papers each year. My view: fossil fuel use will evolve closer to the slower of the two IEA scenarios. **If that's the case, it would be premature to rely on renewable energy for more than it is organically capable of providing**, **and countries that constrain access to fossil fuels[10] alongside renewables may regret it.**

In this year's topic sections we start with "levelized cost", a flawed concept which does not incorporate the reality of energy systems with a lot of intermittent renewable power, and which inspired this year's cover art. Other topics include transmission, the availability and cost of transition minerals, the dispute over small modular reactor nuclear waste, peaking US gasoline demand, the infrastructure and energy challenges required for meaningful carbon sequestration, making energy from garbage, improving energy storage economics, methane tracking, the Russia-China energy axis and the distraction of "futurist" ideas that are unlikely to make a large contribution to decarbonization anytime soon (electric planes, fusion, DACC, space solar, etc).

Michael Cembalest
JP Morgan Asset Management

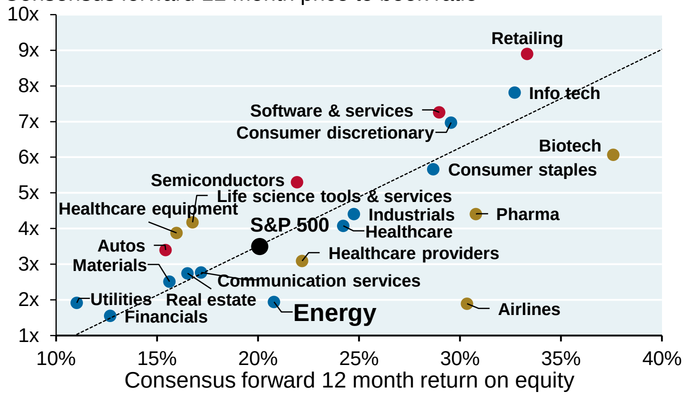
Before getting into this year's topics, here's a link to what we wrote on three issues discussed last year: hydrogen (or "**whydrogen**", as we refer to it), **electrification of industrial energy use** and the technology and grid demands of **residential heat pumps**. Their fundamentals haven't changed much so rather than include them again, we created a web page for clients to access them: Eye on the Market Energy Archives.

[10] Some energy projections refer to the end of the age of US oil & gas resource expansion. **Perhaps, but it wouldn't be for a lack of available supply**. According to EIA/USGS data, unproven reserves of US oil & natural gas are 6.9x and 5.3x higher than US proven reserves.

Energy investment update

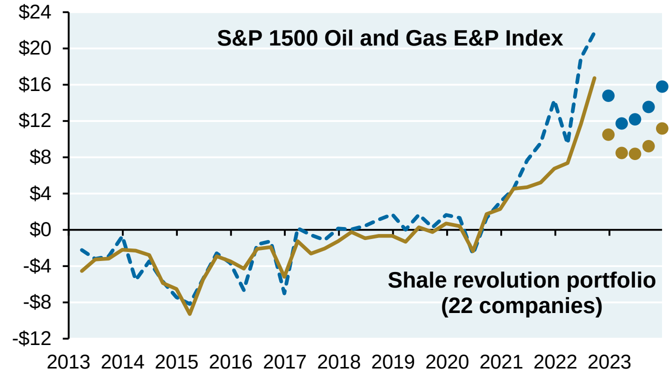
While the energy discount to the market has recovered from its 90-year low in 2020, the sector still trades at a discount to the market on a P/E basis and when looking at ROE vs price to book value. The performance gap between renewables and traditional energy continues to narrow from 2021 levels. Energy companies are profitable again after a decade of negative net cash flow, and US shale sector reinvestment rates have fallen to the lowest levels in a decade.

S&P 500 valuations vs return on equity
Consensus forward 12 month price to book ratio



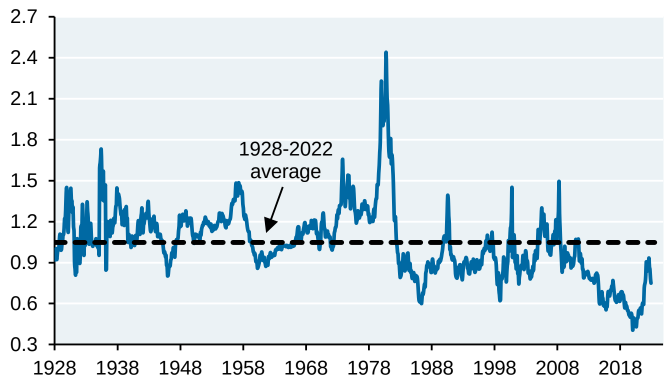
Source: Factset, JPMAM. March 25, 2023.

Oil and gas industry finally turns a profit
Free cash flow, $ billions



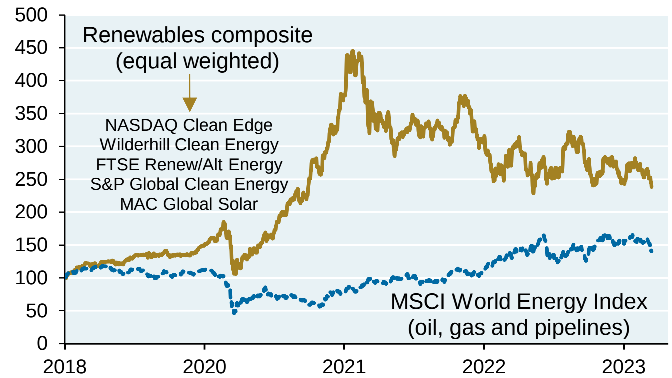
Source: Bloomberg. Q4 2022.

Energy sector valuations have risen from all-time lows vs market, Energy stocks price to book divided by market price to book



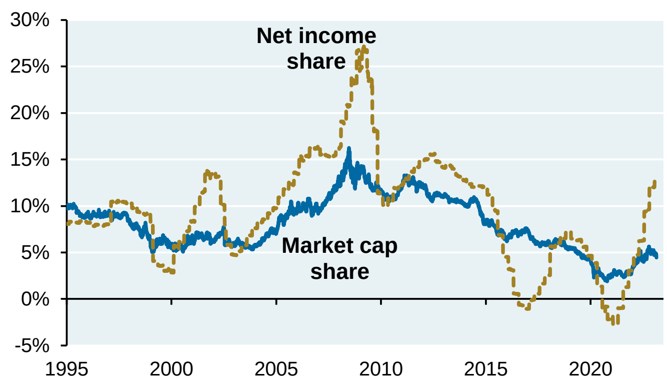
Source: Empirical Research. February 2023. Equal weighted portfolio.

"Reports of my death were greatly exaggerated"
Index (100 = Dec 2018)



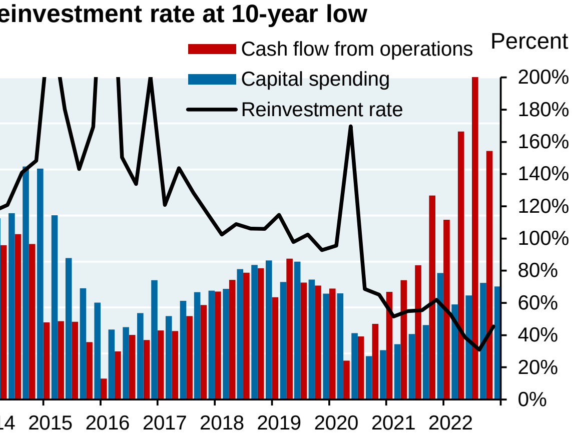
Source: Bloomberg, JPMAM. March 17, 2023.

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



Source: Factset, JPMAM. March 17, 2023.

US shale reinvestment rate at 10-year low
US$, billions



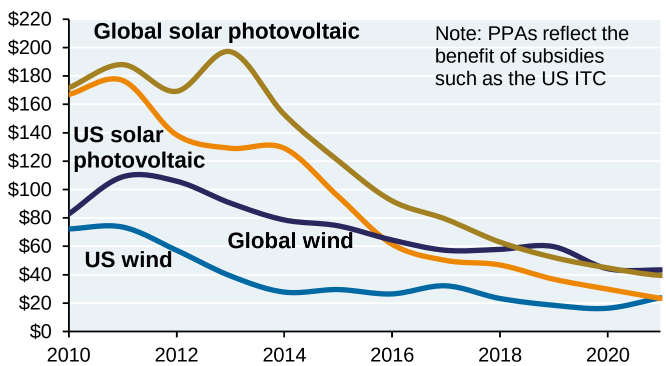
Source: Bloomberg, JPMAM. Q4 2022.

Essential energy charts

We update many essential charts each year to track the energy transition. Here are some that do not appear elsewhere in the Executive Summary or in the individual sections.

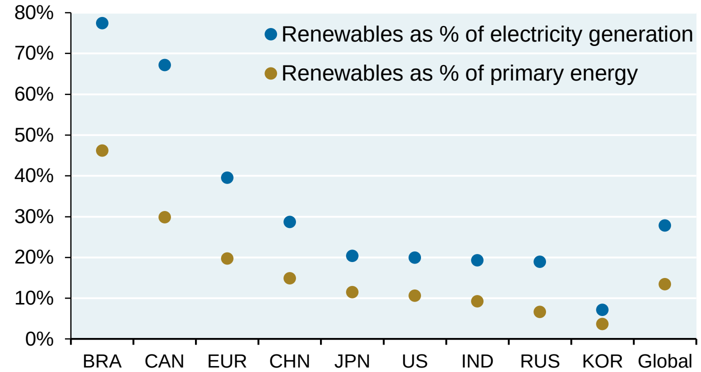
On this page: the decline in wind and solar power purchase agreement prices; renewable shares of primary energy and electricity by region; global wind and solar generation overtakes nuclear power; how electrification is mostly used by homes and buildings for space cooling and other HVAC in the US; coal reliance by country; and how Chinese coal additions offset decommissioning in the rest of the world.

Average power purchase agreement by year of operation
Real 2020 $ per megawatt hour



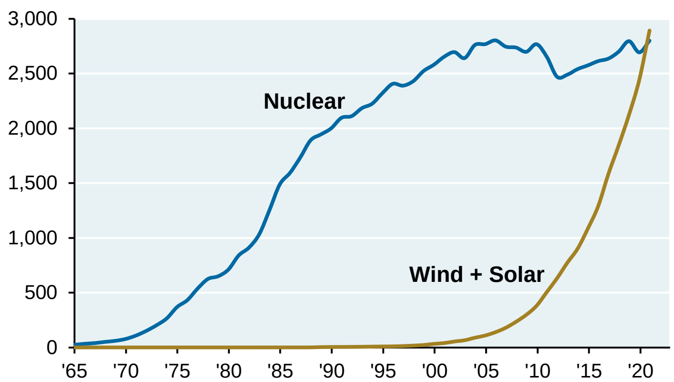
Source: Lawrence Berkeley National Laboratory, IRENA. 2021.

Renewable share of primary energy and electricity
Percent, including hydropower



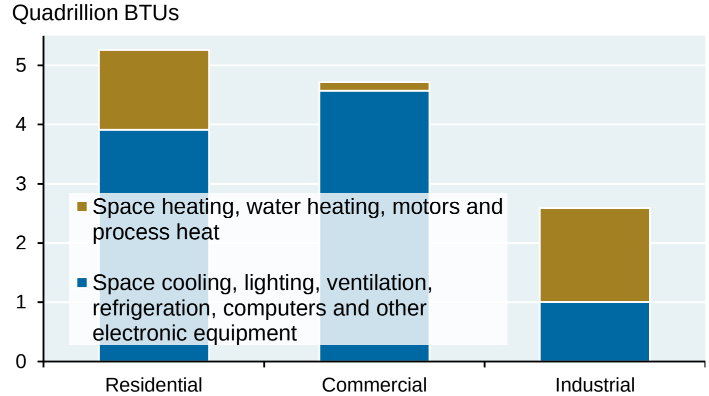
Source: BP, JPMAM. 2022. Note: largest 9 countries by primary energy use.

Global nuclear vs solar+wind electricity generation
Terawatt-hours



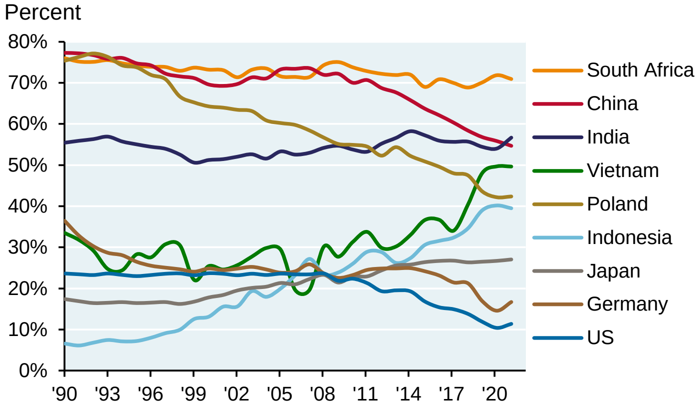
Source: BP Statistical Review of World Energy, JPMAM. 2022.

US electricity uses: primarily HVAC
Quadrillion BTUs



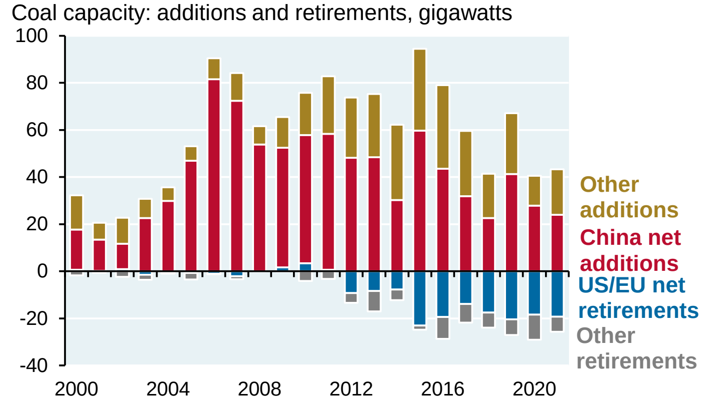
Source: EIA, JPMAM. 2022. Transport too small to plot at 0.06 quads.

Coal share of primary energy consumption
Percent



Source: BP Statistical Review of World Energy, JPMAM. 2022.

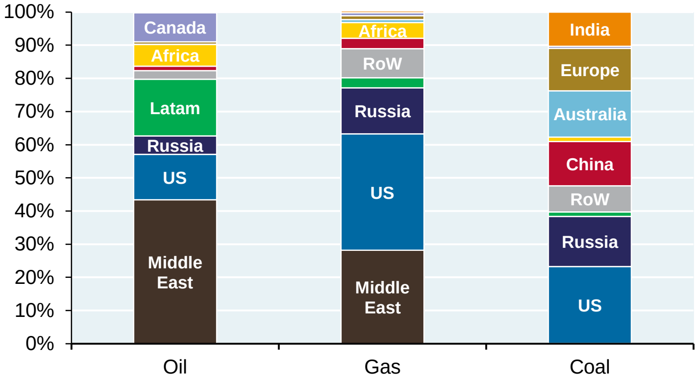
The impact of China on global coal capacity
Coal capacity: additions and retirements, gigawatts



Source: Centre for Research on Energy and Clean Air. 2021.

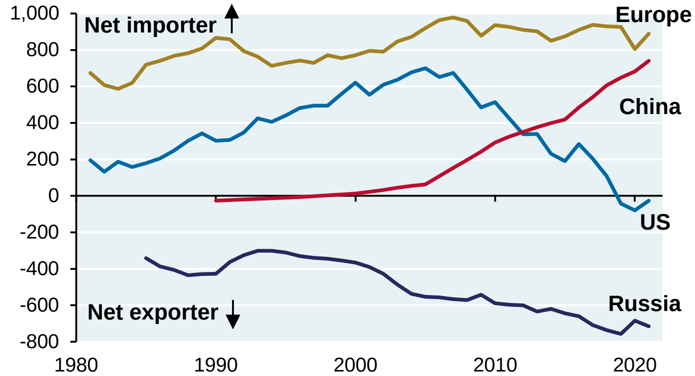
On this page: share of global oil, gas & coal reserves by country; changes in regional energy independence since 1980; EV metals costs per battery type; shares of energy intensive manufacturing in developed and developing countries; a related chart showing the projected decline in primary energy consumption in the developing world, offset by rising energy consumption growth in the developing world (but not China); and the cost of electricity vs natural gas per unit of energy when used for industrial heat.

Share of global fossil fuel reserves, 2020
Percent, including unproven but recoverable reserves for the US



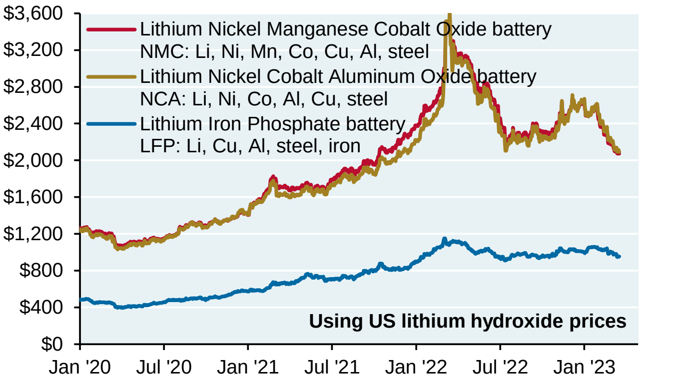
Source: BP Statistical Review of World Energy, EIA, JPMAM. 2022.

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



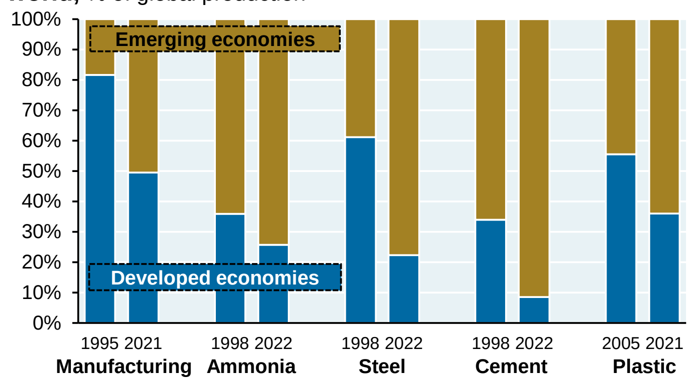
Source: BP Statistical Review, NBS China, JPMAM. 2022.

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



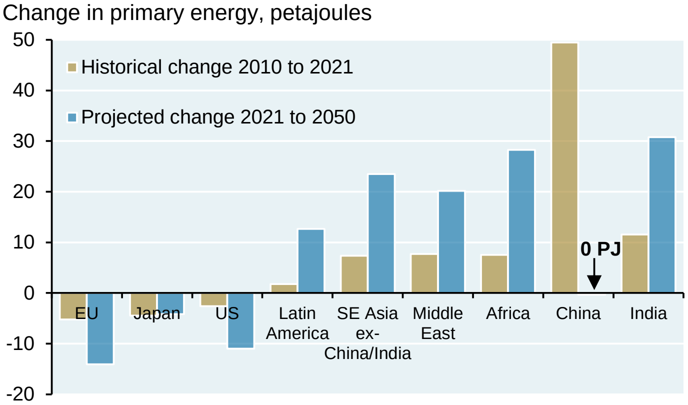
Source: Univ. of Birmingham (UK), ANL, Bloomberg, JPMAM. March 20, 2023.

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



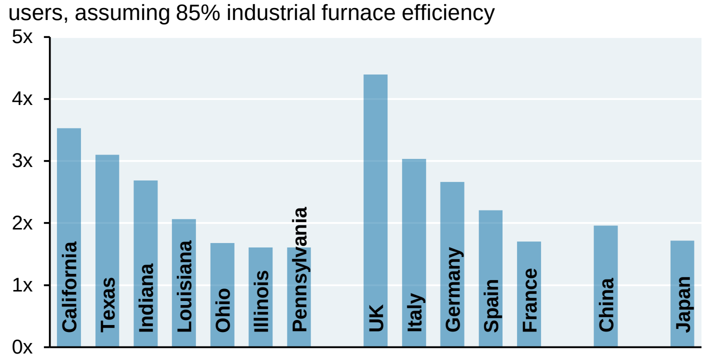
Source: UN DESA, Worldsteel, Plastics*Europe,* USGS, JPMAM. 2022.

Projected EM energy use offsets DM declines
Change in primary energy, petajoules



Source: IEA Stated Policies Scenario. 2022.

Electricity: 1.5x-4.5x more costly than gas for indus. heat
Electricity cost per MJ divided by natural gas cost per MJ, industrial users, assuming 85% industrial furnace efficiency



Source: EIA, Eurostat, CEIC, JPMAM. October 2022. States shown are largest industrial users of US primary energy.

[1] Numbers in, Garbage out: the practical irrelevance of "levelized cost of energy" for wind and solar power

"Levelized cost of energy" is a distraction if you're trying to understand total system costs of electricity. Why? When computed for individual generation or storage technologies, LCOE does not properly take account of:

(a) the need for backup power, storage and reserve margins to maintain system reliability

(b) the value of electricity supplied at different times of the day or year

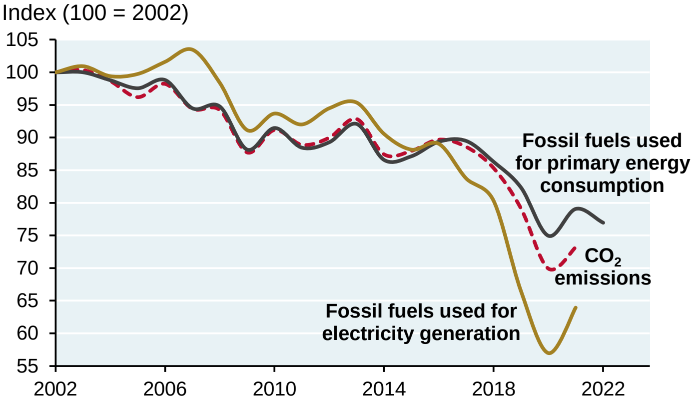
(c) the need to overbuild wind and solar capacity to meet demand in deeply decarbonized systems

In other words, LCOE only measures the cost of a marginal MWh of wind or solar power and typically does not include any of these other capital or operating costs. That's why I generally ignore it, and I'm amazed at how many people still don't realize that **LCOE is a misleading basis for estimating total system costs to governments, electricity consumers and taxpayers.**

I spoke about this recently with Paul Joskow[11] at MIT. Paul reminded me that LCOE was originally developed to compare costs of dispatchable baseload nuclear and coal plants with the same capacity factors (similar generation attributes), and reminded me of something he wrote back in 2011: 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".[12] Paul continues to believe that "LCOE comparisons of baseload and intermittent, non-dispatchable generation make little sense, and that what's needed instead is a system-wide model rather than simplistic LCOE calculations".

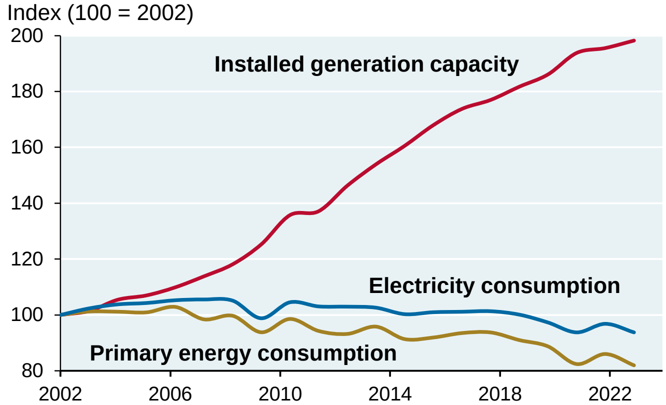
Consider **Germany**, whose ambitious Energiewende transition is one of the world's most advanced efforts at decarbonization. As Germany's renewable energy use rose to 17% of its primary energy consumption and 45% of its electricity consumption, its CO_2 emissions and fossil fuel consumption declined. So far so good, but how much did it all cost? Even though overall German energy and electricity consumption fell, **installed electricity generation capacity doubled**. What in the Hölle is going on here, and how could marginal LCOE for wind/solar be of any use understanding total costs if this is what high renewable systems require? Let's take a closer look.

Germany CO_2 emissions and fossil fuel use
Index (100 = 2002)



Source: AG Energiebilanzen, BP, JPMAM. 2023.

Germany generation capacity and energy use
Index (100 = 2002)



Source: Bundesverband BDEW, Fraunhofer Institute, JPMAM. 2023.

[11] Paul L. Joskow is the Elizabeth and James Killian Professor of Economics Emeritus at MIT. He was the President of the Alfred P. Sloan Foundation from 2008 through 2017 and returned to MIT in 2018. He was the Director of the MIT Center for Energy and Environmental Policy Research from 1999 through 2007. He is a Research Associate at the National Bureau of Economic Research and a member of the Council on Foreign Relations.

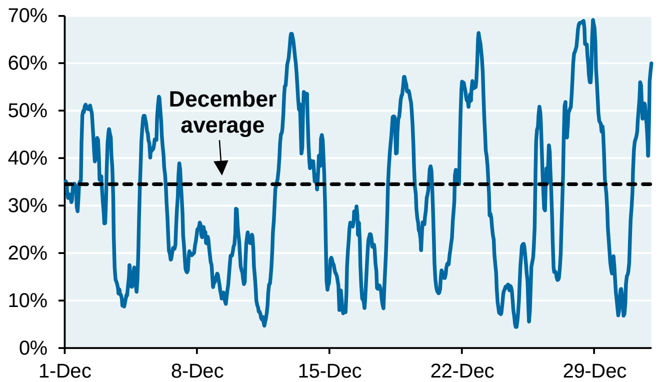
[12] "*Comparing Costs of Intermittent and Dispatchable Electricity Generating Technologies*", Paul Joskow, American Economic Review, 2011

"Intermittency gone wild": what's wrong with LCOE, using real-life examples

Texas wind capacity factors averaged 32% in December 2022. But that doesn't mean that wind provided steady power at 32% of installed capacity; as shown on the left, Texas wind generation varied from a low of 5% of capacity to a peak of 70% during the month. Why this matters: **LCOE is so blissfully unaware of reality that it is calculated the exact same way whether Texas wind capacity factors are 32% for every hour of December, or if they average 32% but vary from 5%-70%. This is preposterous since in the latter scenario, backup thermal power/storage needs are much higher than in the former**. **LCOE is the cocktail napkin of energy math.**

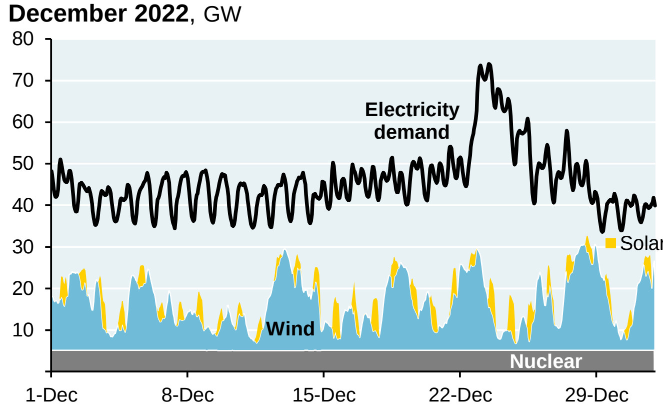
What actually happened? On Dec 23, temperatures dropped to 13°-28°F vs average levels of 45°F, causing electricity demand to spike to its highest level ever while renewable output collapsed. Rising electricity demand was met by natural gas output doubling. Even if Texas wind and solar capacity were 5x (!!) larger, the need for gas fired power that day would only have been 20% lower. In other words, a massive gap that only backup power could fill, none of which is accounted for in LCOE. What about energy storage? Low wind conditions lasted for 3 days, in which case many billions of dollars of 4-6 hour storage would have been needed instead.

ERCOT wind capacity factors by hour, December 2022
Percent



Source: EIA, JPMAM. December 2022.

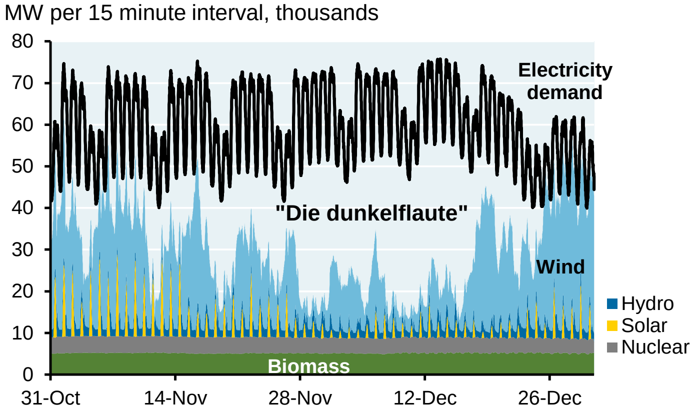
ERCOT baseload and renewable generation vs demand, December 2022, GW



Source: EIA, JPMAM. December 2022.

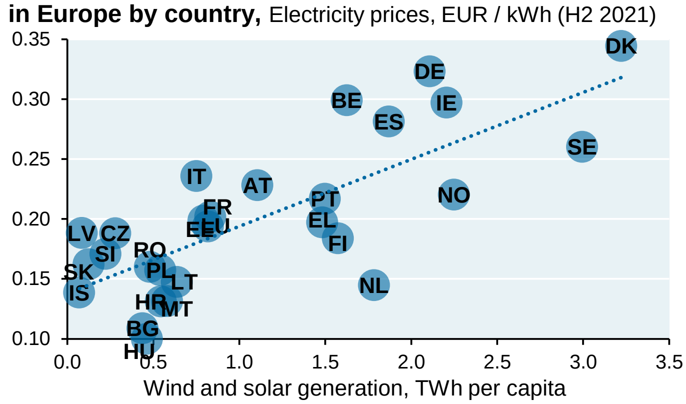
In Germany, low wind conditions can last for weeks[13], persisting for such a long time that they have their own word: a "**dunkelflaute**". During last December's dunkelflaute, the electricity demand gap was met by more generation from coal and imported LNG. The situation may be more challenging next winter when the last of Germany's nuclear plants may have been decommissioned. LCOE is of little use in Germany for the same reasons as in Texas: it completely ignores backup power needs. It's no coincidence that electricity costs in Europe tend to rise with renewable penetration; that's another sign that LCOE is missing the bigger picture.

Germany generation by source, Nov - Dec 2022
MW per 15 minute interval, thousands



Source: Fraunhofer ISE, JPMAM. 2022.

Household electricity prices vs wind and solar penetration in Europe by country, Electricity prices, EUR / kWh (H2 2021)



Source: Eurostat, JPMAM. 2022.

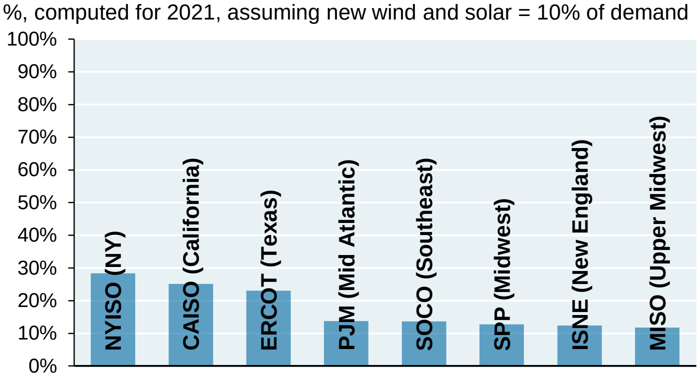
[13] **Offshore wind** can disappear too: for a week in March 2022, UK offshore wind capacity factors averaged just 12%. Also: contiguous regions share common wind patterns. In adjacent ERCOT, SPP, MISO and PJM regions in the US, pairwise correlations of wind generation by hour ranged from 0.58 to 0.68 in 2021.

Alternative assessments of high renewable systems: capacity credits and load carrying capacity

Grid managers have developed their own language to analyze stability, adequacy and cost for systems with high renewable penetration. I will briefly discuss two of them: capacity credits and effective load carrying capacity.

Capacity credits refer to the amount of thermal capacity that can be disconnected when adding more wind and solar power to a given grid. Using data from US ISOs, we computed the amount of natural gas that can be disconnected when adding solar and wind to meet another 10% of demand. **The result: due to wind and solar intermittency and the need to meet demand and maintain system reliability, only 10-30 MW of natural gas could be disconnected for every 100 MW of new wind and solar capacity**. These capacity credits decline as more wind and solar are added to the system, which the IEA acknowledges as well: "the system value of variable renewables such as wind and solar decreases as their share in the power supply increases". **Bottom line**: capacity credits are another way of illustrating that LCOE ignores systemwide capacity requirements.

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



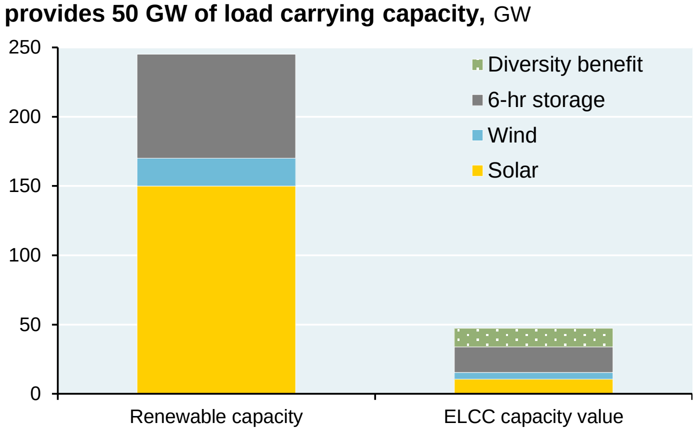
Source: EIA data, JPMAM computations. 2022.

Effective load carrying capacity (ELCC)

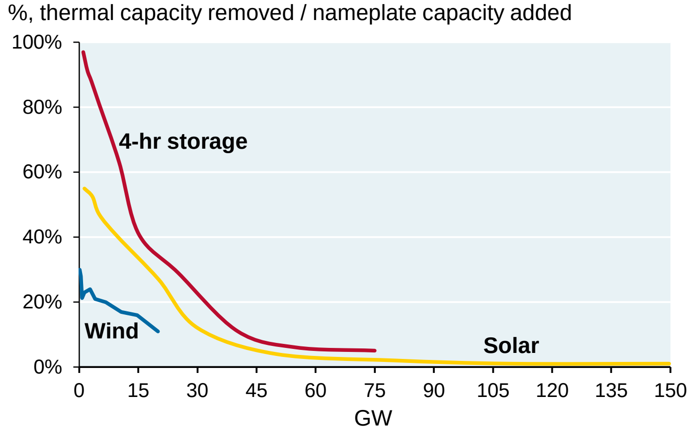
- Used by CAISO, PJM, NYISO and MISO in Resource Adequacy Planning presentations; and by utilities such as Duke, El Paso Electric, Nova Scotia Power and entities in Colorado, Portland and New Mexico
- Incorporates reserve margin requirement
- Probabilistic scenario analysis by hour, week and month of all the factors affecting the grid: wind and solar generation, other generation sources already on the grid, load demand, possible generator outage rates due to weather conditions, etc
- Incorporates the diversity benefit from adding wind, solar and storage at the same time

A more robust approach. Some grid managers use **effective load carrying capacity** (ELCC) to assess the impact on system reliability from adding renewables; see box for a description of how it works and who uses it. One example: assume that California builds a deeply decarbonized system with 20 GW of wind, 150 GW of solar and 75 GW of storage. As per the chart on the left from E3 Energy and Environmental Economics, this system would only have 50 GW of reliable load with which to meet demand (ELCC=50 GW). Alternatively stated: if this system needed 50 GW of reliable power and was designed with renewables only, it would need 245 GW of wind, solar and storage to make it work. The marginal ELCC of wind, solar and storage are at their highest when renewables are first added to the system; their contribution to system reliability falls rapidly after that. **LCOE reflects none of these realities, which is why the ISOs and utilities shown in the text box look at ELCC instead**.

California's ELCC: 245 GW of wind/solar/storage only provides 50 GW of load carrying capacity, GW



The marginal ELCC of California's solar, wind and storage
%, thermal capacity removed / nameplate capacity added

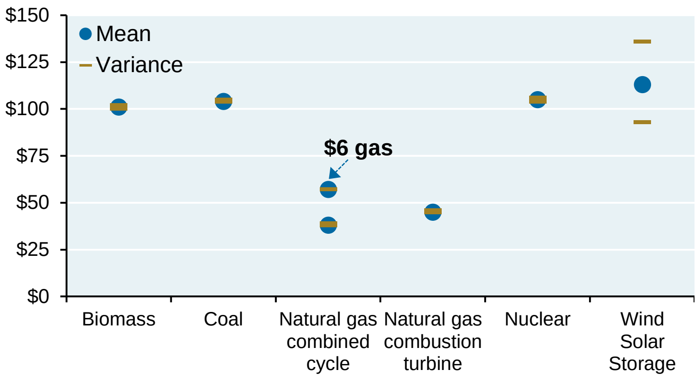


Source: "*Long-Run Resource Adequacy under Deep Decarbonization Pathways for California*", E3, June 2019.

One final way to illustrate the big picture: "levelized full system costs of electricity". An analysis from Rice University used ERCOT in Texas to analyze total system cost. The approach assumes that 95% of system load must be met from one of the following: biomass, coal, natural gas combined cycle plants, natural gas combustion turbines, or wind+solar+storage (allowing for a small amount of dispatchable thermal power). Once adequate capacity to meet demand is determined, the all-in cost of that capacity is computed. Using this approach, wind+solar+storage systems are ~2x more expensive than natural gas. While this approach has its limitations, it's a **better estimate of the true cost of wind, solar and storage than LCOE**. The same approach applied to Germany yields even higher full system costs for wind+solar+storage[14].

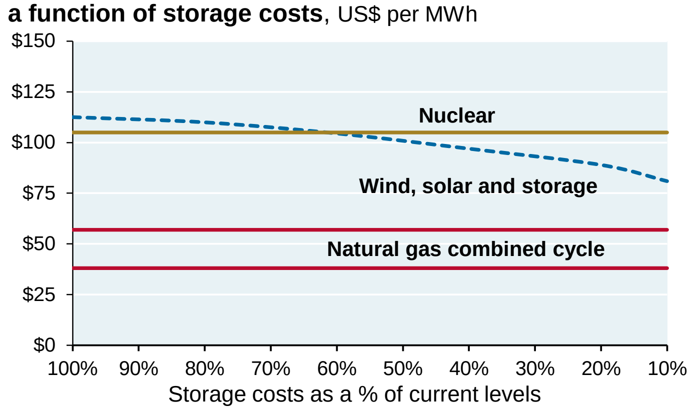
Would lower-cost energy storage help? The analysis also assessed whether falling storage costs could reduce the full system costs of deeply decarbonized systems. The answer: not by very much, even when storage costs fall by 50% or more from today's levels.

ERCOT: levelized full system cost of electricity
US$ per MWh



Source: *"Levelized Full System Costs of Electricity - 2023 Updates"*, Idel. 2023.

ERCOT: levelized full system cost by electricity source as a function of storage costs, US$ per MWh



Source: "*Levelized full system costs of electricity - 2023 Updates*", Idel. 2023.

To conclude, a **stark warning from PJM**[15], the Independent System Operator running the Mid-Atlantic region and the largest ISO in the US:

- The growth rate of electricity demand is likely to continue to increase at ~1.5% per year from electrification coupled with the proliferation of high-demand data centers
- Coal and gas generators are being retired at a rapid pace due to government and private sector policies as well as economics (retirements by 2030 = 21% of installed capacity)
- Retirements are at risk of outpacing new resources, due to a combination of industry forces including siting and supply chain issues; 95% of the PJM generation queue is renewables with completion rates of just 5%(!)
- PJM's interconnection queue is composed primarily of intermittent and limited-duration resources. Given their operating characteristics, PJM states that it "**needs multiple megawatts of these resources to replace 1 MW of thermal generation"**
- The current path could erode PJM's reserve margin from 23% in 2023 to just 5% by 2030

On the issue of so-called "levelized costs of energy", my work here is done.

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[14] **Texas vs Germany**. Seasonal electricity demand variation is much higher in Texas due to higher summertime air conditioning use. Texas benefits from higher capacity factors than Germany for wind (35% vs 20%) and solar (23% vs 11%); and benefits from peak solar capacity factors coinciding with periods of higher demand.

On wind capacity factors, some researchers believe that rising Arctic temperatures reduce the temperature gap vs the equator, and **thereby weaken the jet stream** ("*Global stilling: is climate change slowing down the wind*", Yale School of the Environment, Jim Robbins, Sep 2022). If so, wind capacity factors might undershoot targets, and instances of wind "dunkelflautes" might increase (global stillness).

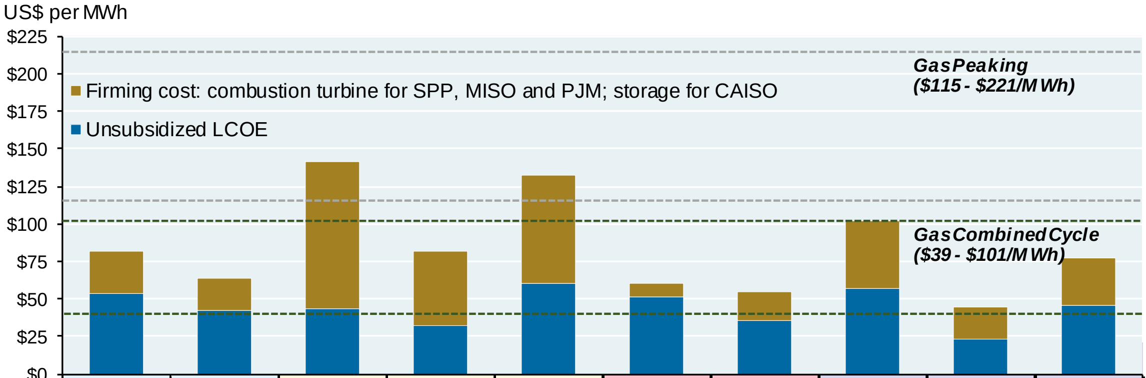
[15] "*Energy transition in PJM: Resource Retirements, Replacements and Risk*", PJM, February 24, 2023

April 2023 update: revised LCOE from Lazard finally incorporates backup power and storage costs

After 16 years of LCOE reports, Lazard finally recognized/conceded the inherent flaws of LCOE this year. While it's not incorporated in their core LCOE figures (which are still of little practical use), Lazard now includes an extra supplemental exhibit on the cost of "firming the intermittency" of wind and solar power. For MISO, SPP and PJM regions, Lazard now incorporates the cost of a backup combustion turbine into wind/solar costs; and for the CAISO region, the cost of utility scale energy storage.

Lazard's revised unsubsidized LCOE figures for wind and solar shown below are generally above median costs for combined cycle natural gas plants. Lazard continues to use questionable assumptions such as an operating life of only 20 years for a new natural gas peaker plant or combined cycle plant when 30 years would make more sense[16], and I haven't dug into the rest of their assumptions yet. But at least Lazard finally recognizes that their widely cited LCOE estimates are completely missing the big picture.

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



	MISO	MISO	CAISO	CAISO	CAISO	SPP	SPP	PJM	PJM	PJM
	Solar	Wind	Solar	PV + Storage	Wind	Solar	Wind	Solar	PV + Storage	Wind
ELCC	50%	16%	7%	51%	15%	85%	17%	38%	70%	15%
Capacity Factor	20%	43%	25%	51%	30%	21%	50%	19%	70%	39%
Resource Penetration	3%	25%	32%	32%	19%	1%	56%	5%	5%	7%

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

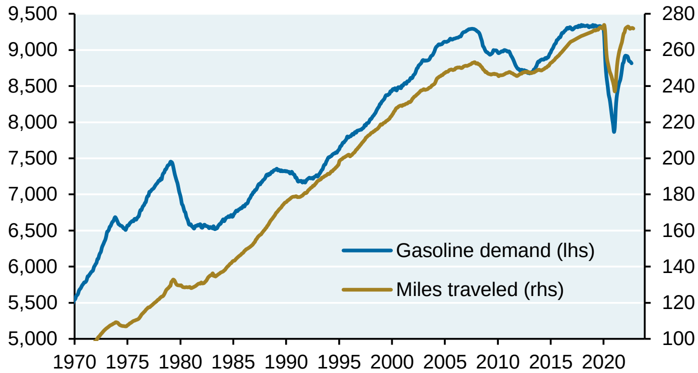
[16] The average life of existing natural gas combined cycle plants is already 22 years (EIA), and new gas facilities in Alabama, Florida, Minnesota, Utah and Wisconsin have projected operating lives of 30-40 years

[2] Crude oil in, refined products out: declining US gasoline demand, rising demand for other oil products

My colleagues at JP Morgan's Commodities Research group published an interesting analysis on oil refining[17]. In 2022, despite a rebound in vehicle miles traveled to 2019 levels, US motorists consumed 6% less gasoline than in 2019. Part of the explanation: an increase in vehicle fuel economy (perhaps a reaction to high gasoline prices) and also a small increase in electrification. Where this gets interesting…let's take this to the extreme: **what if US gasoline demand already peaked and is in permanent decline (which is what the authors believe), while at the same time, demand for refined products such as jet fuel and distillates (heating oil, petrochemical feedstocks, diesel, waxes, lubricating oils) remains the same or keeps growing?** This would be a big deal for US refiners since gasoline accounts for 44% of US refined products demand, higher than in other countries. In other words, falling gasoline demand could put downward pressure on US refining margins.

US gasoline consumption vs vehicles miles traveled

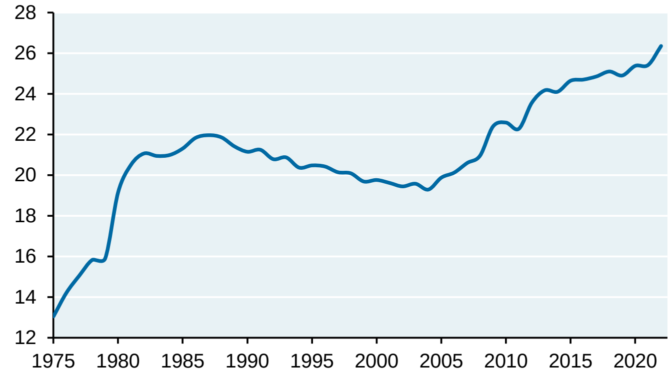
Million barrels per day — Billion miles traveled



Source: EIA, JPMAM. 2022.

US real-world average fuel economy by model year

Miles per gallon

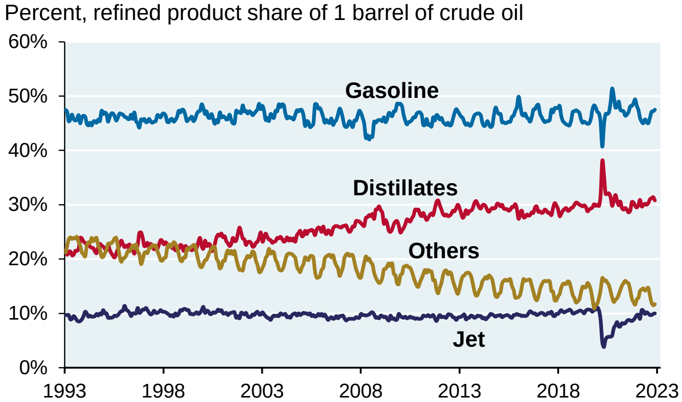


Source: J.P. Morgan Global Commodities Research. 2022.

What would refiners do if this were to happen? US refiners currently have limited ability to change the composition of refined products from each barrel of crude (the gasoline component of US crude oil refining has been unchanged for 30 years; only distillates rose a few percent vs other products). As a result, refiners might have to shrink capacity to make up for falling refining margins; in which case prices for distillates might rise due to declining supply. In addition, US refiners might have to spend capital to shift their refining output away from gasoline and towards other products (which is expensive); and/or switch to natural gas liquids as feedstock for chemicals. All of these outcomes could lead to higher refined product prices. Maybe a decline in work-from-home trends will boost gasoline demand and vehicle miles by commuters in the years ahead; but if it doesn't, there could be major changes in store for US refiners and non-US refiners serving the US market.

US refinery yields by product

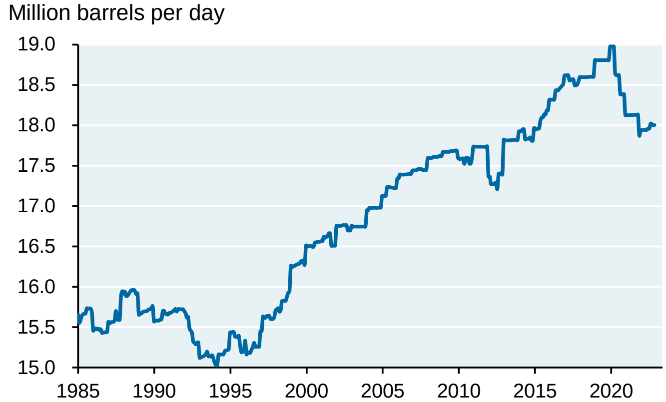
Percent, refined product share of 1 barrel of crude oil



Source: EIA, J.P. Morgan Commodities Research. December 2022.

US refinery crude oil distillation capacity

Million barrels per day



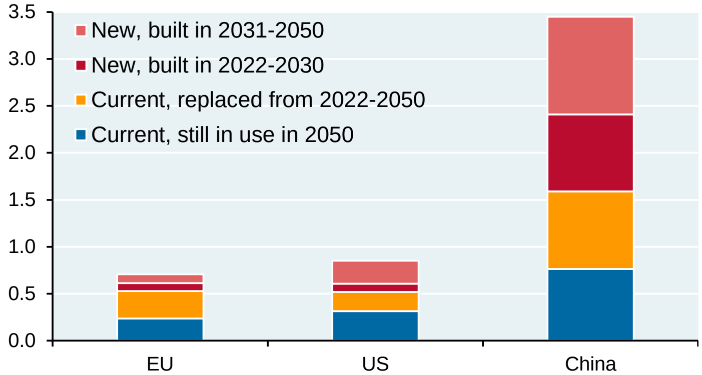
Source: EIA. December 2022.

[17] "*Cyclical and structural changes in US gasoline demand: driving more on less*", Natasha Kaneva and Prateek Kedia, JP Morgan Global Commodities Research, February 2, 2023

[3] Into the queue, but not out: the slow pace of grid expansion and renewable interconnection

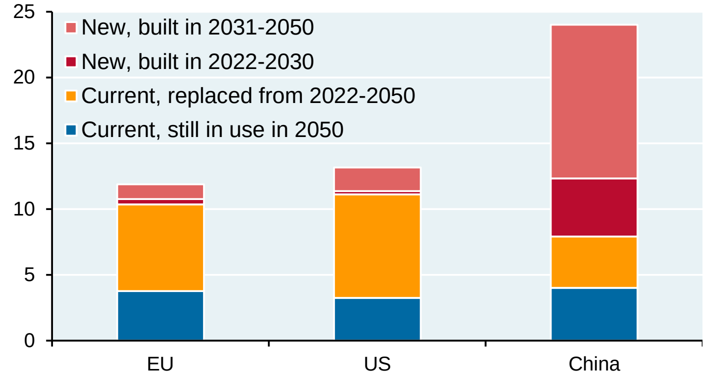
If the holy grail of decarbonization is electrification, the world will have to get better at moving electrons around. That's certainly what deep decarbonization plans expect: as per the IEA, existing grid infrastructure in the US, Europe and China will need to be substantially replaced or expanded by 2030 and 2050.

Transmission grid development
Kilometers, millions



Source: IEA, JPMAM. 2022.

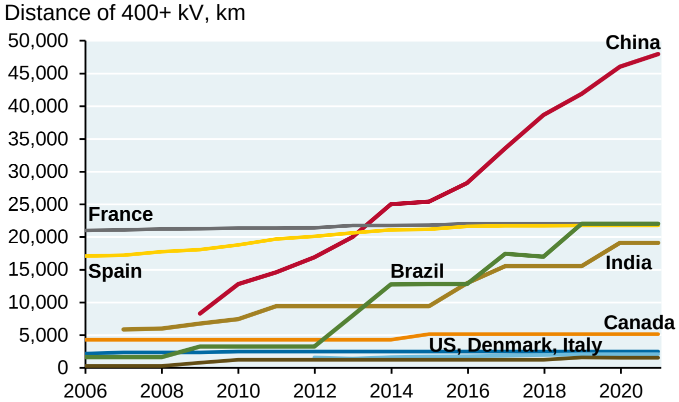
Distribution grid development
Kilometers, millions



Source: IEA, JPMAM. 2022.

Unfortunately, grid transformations look almost nothing like that in the US or Europe. The next chart shows growth in high voltage direct current lines (HVDC, > 400 kV) that optimize the transmission of renewable energy from remote locations. China, Brazil and India have been active over the last decade, while the US and Europe have not. The US has the around the same amount of HVDC as Denmark, and also the lowest projected HVDC intensity (kilometers of transmission per GW of generation capacity) in the entire table. According to LBNL, the opportunity loss from US underinvestment in regional grid linkages in 2022 was at its highest level in a decade, using regional electricity price differences as proxy[18].

High voltage direct current lines by country
Distance of 400+ kV, km



Source: Global Transmission Report, JPMAM. 2022.

High voltage direct current line outlook

Country	Current Length (km)	Current Intensity (km/GW)	Projected Length (km)	Projected Intensity (km/GW)	Projection year
China	47,990	22	65,988	30	2025
France	22,031	160	22,522	111	2031
Brazil	22,020	117	24,940	109	2031
Spain	21,766	194	22,209	138	2029
India	19,087	47	165,635	197	2026
Canada	5,117	34	5,117	34	N/A
US	2,462	2	2,462	2	2026
Denmark	2,083	150	2,847	84	2029
Italy	1,552	13	3,239	19	2029
UK	307	4	5,045	65	2030
Germany	223	1	5,562	24	2031
Mexico	0	0	2,242	20	2027

Source: GTR, JPMAM. 2022. Note: Intensity refers to kilometers of transmission per gigawatt of electricity generation capacity. HVDC lines defined as DC lines with voltage > 400 kV.

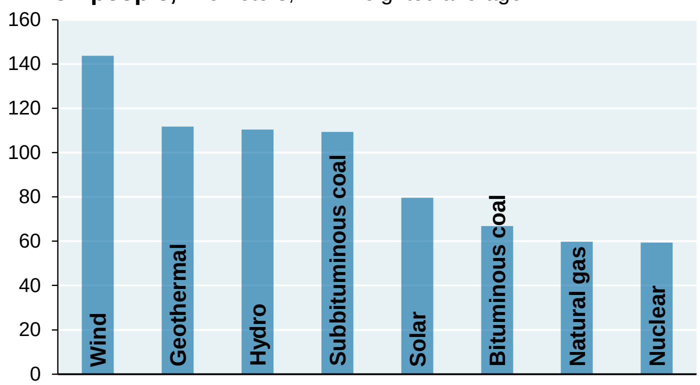
[18] *Berkeley Lab Electricity Markets Transmission Value Fact Sheet*, LBNL, February 2023; see Figure 1

In prior energy papers, I reviewed the state of affairs in US transmission: lack of eminent domain, failed efforts to create accelerated transmission corridors, the laundry list of cancelled transmission projects and a review of Northern Pass, an HVDC line that was supposed to bring hydropower from Quebec to Massachusetts at 5 cents per kWh until New Hampshire and Maine killed it (despite commitments from developers to bury most of it underground). I also discussed challenges for grid managers in integrating thousands of small wind, solar and storage projects compared to past integrations of coal, gas and nuclear.

This year, some new and updated charts on the US:

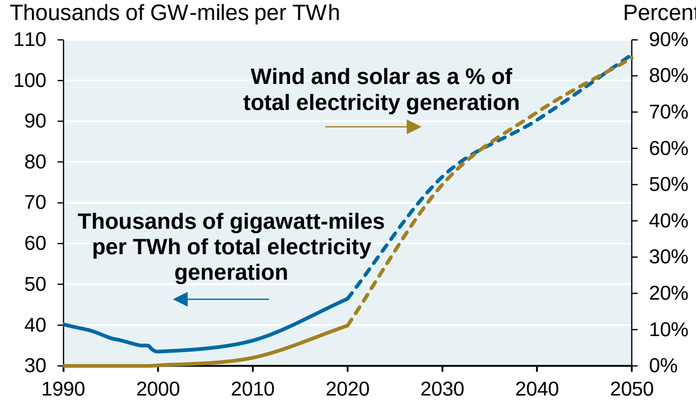
- The first chart shows how wind and hydropower are generally located further from population centers than natural gas and nuclear power. Using EIA data, we computed the MW-weighted average distance of all generation plants from population clusters of at least 2 million people. More distance = more transmission
- The second chart is Vaclav's preferred approach. For the last thirty years, the US grid operated with 35-45 miles of transmission per TWh of electricity generation. Using a typical deep decarbonization plan and its associated transmission requirements, we estimate that the "transmission intensity" of high renewable systems would be at least double the current level. **That's a lot of new transmission**
- But as we have explained, **grid expansion is way below a deep decarbonization trajectory**. The last two charts show history of the US grid and how the pace of expansion slowed from 1.5% to 1.0% in the last 5 years, including rebuilds and upgrades. Only ~300 miles of higher voltage transmission were brought online in the US in 2021, with half coming from the Western Spirit Transmission line to transmit New Mexico wind

Distance required for power generation facilities to reach 2 million people, Kilometers, MW-weighted average



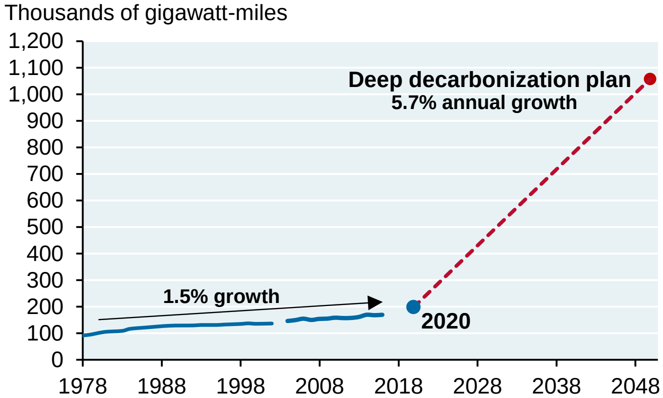
Source: EIA, Census Bureau, JPMAM computations. 2022.

Transmission intensity of a decarbonized grid
Thousands of GW-miles per TWh



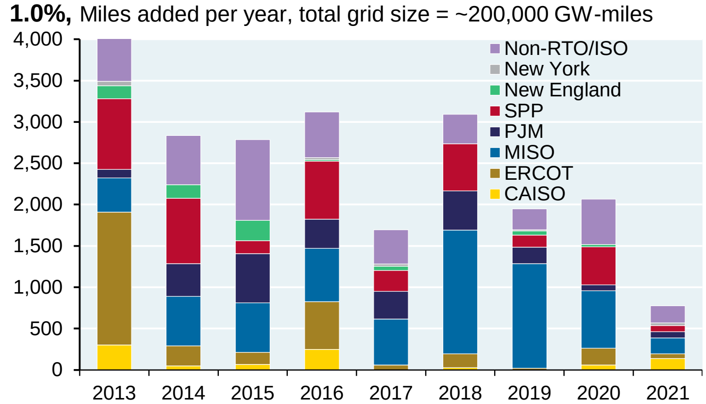
Source: DOE, UT Austin, Princeton Net Zero, JPMAM. 2022.

US transmission growth, history vs targets
Thousands of gigawatt-miles



Source: DOE, UT Austin, Larson et al (Princeton), JPMAM. 2022.

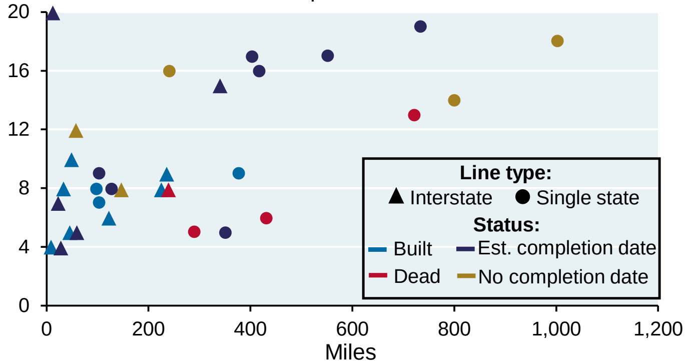
Recent transmission line growth has declined from 1.5% to 1.0%, Miles added per year, total grid size = ~200,000 GW-miles



Source: S&P Global, JPMAM. 2022. Note: Transmission lines > 100 kV.

Transmission completion times. While projects less than 150 miles have been completed in 5-10 years, projects more than 400 miles (e.g., from Wichita KS to St Louis MO) may require 15-20 years to complete.

US transmission lines: length vs time to completion
Years, estimated or actual completion time

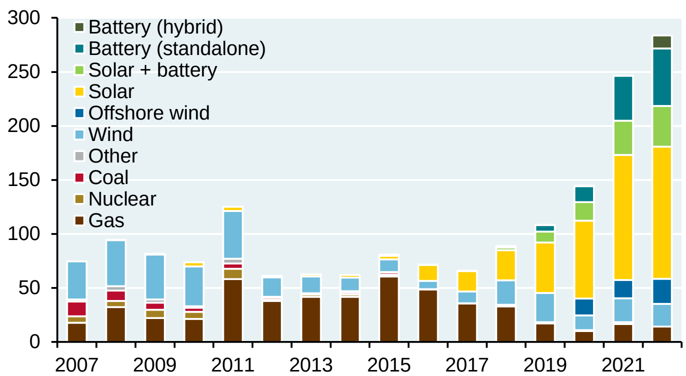


Source: "*The Challenges of Decarbonizing the U.S. Electric Grid by 2035*", Moch & Lee (Harvard). February 2022.

On Transwest Express, designed to transmit Wyoming wind power to the Nevada/California border. A single family in Northwest Colorado secured a sage grouse and elk conservation easement that blocked transmission on its 56,000 acre ranch. The easement also blocked the Gateway South transmission project running parallel to Transwest. The impasse has been resolved and construction can begin, but the project is now in year 18. Since 1990, the use of conservation easements in Colorado has risen from 100,000 acres to 2.7 mm acres. Of 7 large transmission projects fast-tracked by the Obama administration in 2011, 2 have been completed, 4 are pending and 1 has been cancelled.

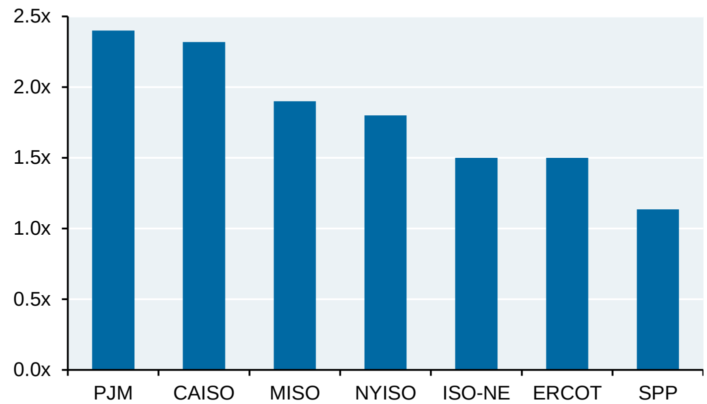
An update on clogged US interconnection queues. The PJM queue has grown by 2.4x since 2019 as solar, storage, wind and hybrid projects overwhelm the ability of grid managers to integrate them. Other ISO queue growth multiples are shown in the second chart. The third chart shows average years between interconnection request and project commissioning, and the table shows wind and solar power in the queue vs installed wind and solar capacity. Be careful regarding what queues mean and what they don't, which we explain next.

The clogged PJM interconnection queue
Cumulative gigawatts of capacity in the queue



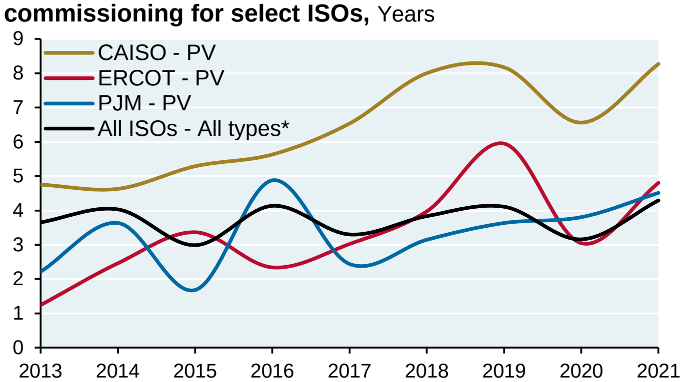
Source: LBNL, JPMAM. 2023.

Increase in interconnection queue from 2019 to 2021



Source: LBNL, JPMAM. 2022.

Median time between interconnection request and plant commissioning for select ISOs, Years



Source: IEA, LBNL. 2022. *Note: All types includes gas, solar and wind for CAISO, ERCOT, PJM and NYISO.

Wind and solar interconnection queues as a % of installed wind and solar capacity, 2021

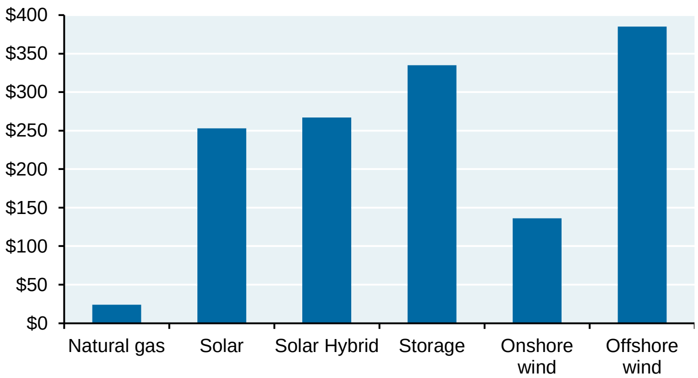
ISO	Queue/Cap %	Excl. offshore wind
CAISO	421%	392%
ERCOT	224%	224%
ISO-NE	628%	134%
MISO	415%	415%
NYISO	1914%	705%
PJM	1078%	980%
SPP	289%	289%

Source: LBNL, JPMAM. 2022

However, be careful when interpreting the meaning of "a project being in the queue". These projects by definition have not been approved for interconnection, may not have raised much capital other than for filing fees, and may not have been evaluated by developers as to whether they will serve the merchant or fixed power purchase agreement marketplace. The completion rates of projects in the queue are very low, and should not be interpreted as representing the generation potential of future wind and solar development. According to LBNL, wind and solar projects entering the queue from 2000 to 2017 only had completion rates of 16% and 10%. As stated earlier in the LCOE section, the largest ISO (PJM) cites a wind/solar completion rate of just 5%.

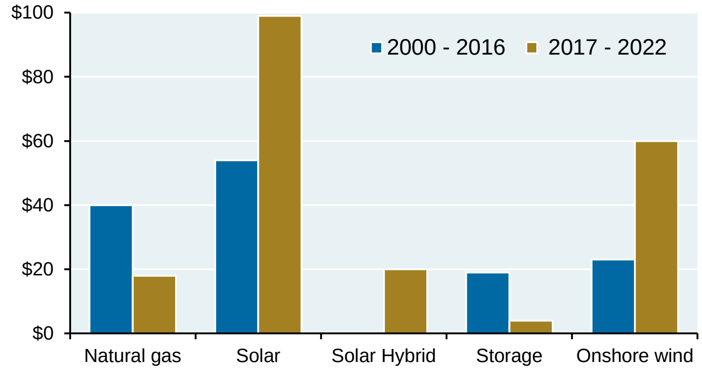
The next two charts show how renewable interconnection costs dwarf those of natural gas, and how solar and wind interconnection costs have been rising while gas and storage interconnection costs are falling. **Bottom line: interconnection delays and costs are a source of friction in the renewable transition.**

Interconnection costs by fuel type for all projects
US$ per kW, 2017-2022 average



Source: LBNL. 2023. Note: includes completed, active and withdrawn projects.

Interconnection costs over time for completed projects
US$ per kW



Source: LBNL. 2023.

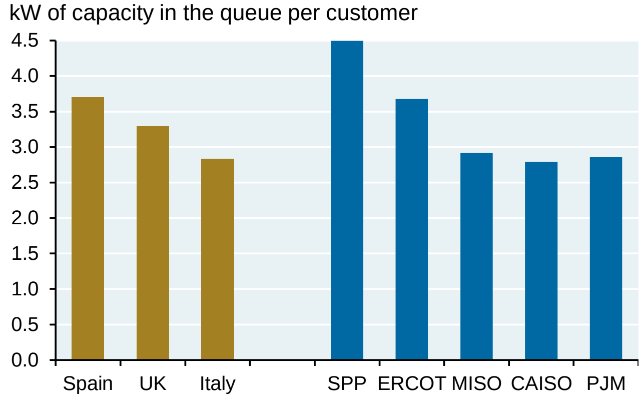
Delays and rising costs result in rising wind/solar curtailment and congestion, as illustrated below. This is not just a problem in the US; the Wind Europe association warned last year of 2,000 wind projects awaiting permission from Spanish authorities, with 19 GW of projects in need of full environmental impact assessments without which developers would need to start from scratch. The German Wind Association alerted investors of similar risks. The chart on the right shows that wind and solar queues in Europe are similar to those in the US.

Curtailment and congestion costs by ISO, 2019-2021

ISO	2019 curtailment	2021 curtailment	2019 congestion cost (mm US$)	2021 congestion cost (mm US$)	Interconnection queue capacity (GW)
Curtailment figures in GWh directly from ISO reports					
CAISO	961	1,505	$152	$164	93
ERCOT	2,370	6,617	$110	$1,400	137
MISO	245	301	$900	$2,800	314
SPP	1,191	6,351	$457	$1,200	94
Curtailment figures in % of generation from LBNL Wind Report, wind curtailment only					
ISO-NE	1.9%	1.8%	$33	$50	461
NYISO	1.5%	2.0%	$462	$624	28
PJM	0.0%	1.8%	$583	$995	105

Source: S&P Global. September 1, 2022.

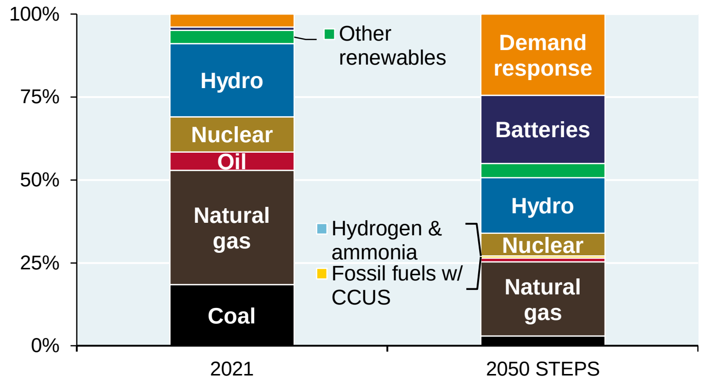
European queues similar to US
kW of capacity in the queue per customer



Source: BNEF, World Bank, JPMAM. 2023.

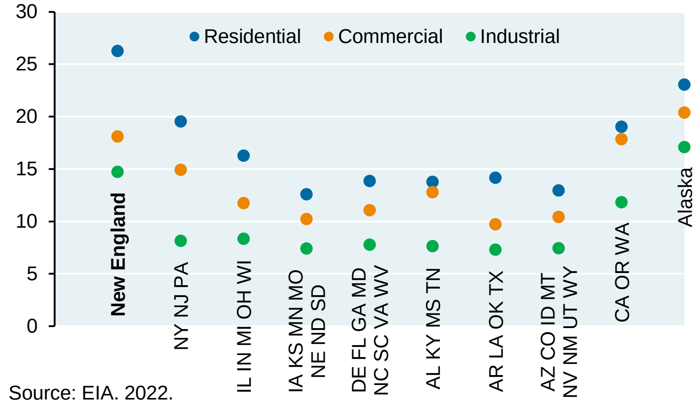
Most decarbonization plans entail the need to build transmission and integrate large amounts of intermittent power. I thought it was interesting that the IEA assumes these challenges will be met in the long run by (i) a substantial increase in battery use which is negligible today, and (ii) a lot of "**demand response**", which is a nice way of saying that electricity consumers will shift their load demand to match electricity supply, perhaps with economic incentives. Both changes would be major departures from today's energy systems.

Where will grid flexibility come from in the future?
Percent



Source: IEA. 2022.

New England: same electricity prices as Alaska
Cents per kWh, November 2022



Source: EIA. 2022.

Let's conclude with New England, a region known for progressive thinking, environmental activism, university divestment policies, think tanks and legions of people focused on energy policy. It's also an electricity albatross for the average citizen and small business, with the highest electricity prices in the US. Electricity prices in Massachusetts are not that different than Alaska, even though Massachusetts is only 200 miles from ample natural gas and low electricity prices in the Marcellus shale region. New England faces the following challenges, none of which its stakeholders have been able to solve:

- no expansion of existing 5-pipeline network despite reliance on natural gas rising from 12% of generation in 2000 to 46% in 2022. New York State blocked the Constitution Pipeline which could have alleviated the gas supply/demand situation in New England; other pipeline projects were shelved when this took place
- when it's cold and heating demand spikes, local gas distribution companies with firm service contracts to provide gas for residential and commercial space heating take precedence over power companies with interruptible service contracts, driving up electricity prices
- not enough storage capacity in the region to store more gas even if they obtained it; lack of adequate natural gas capacity resulted last winter in fuel oil used for 30% of electricity generation, and insufficient electricity peaking capacity to allow for large-scale additions of new customers
- HVDC transmission projects for more Canadian hydropower blocked by Maine and New Hampshire. There's also a possible shift in Canadian policy (after the resignation of the HydroQuebec CEO) to lure more industrial companies to Quebec, reducing its capacity for hydropower exports
- while rooftop solar takes the edge off of peak summer demand, no such luck in the winter
- supplementing pipeline gas with LNG imports from other parts of the US is not an option due to the Jones Act, which stipulates that only US ships can transport goods between US ports. Unfortunately, there are not enough spare US LNG tankers
- offshore wind delay as cost increases prompt developers to renegotiate PPA contracts (Avangrid/Mass.)

All of this is taking place before the next wave of electrification of cars and winter heating. As mentioned earlier, New England didn't land new EV battery factory projects. **Electricity costs may be one major reason as to why.**

Addendum: EV and heat pump related challenges for transmission grids

Some grid challenges from EV and heat pump adoption are often related to local infrastructure. In some jurisdictions, a 37.5 kilovolt-ampere transformer will support 15 households, each of which would be expected to draw around 2 kW of power. But converting a gas furnace to a heat pump could draw 4 to 6 kW, while a Level 2 charger for EVs could draw 3 to 19 kW. As a result, it might not take much of a cluster of uncoordinated EV or heating demand to overwhelm a local grid or possibly blow out a transformer. One study in Palo Alto found that more than **95% of residential transformers would be overloaded** if the city hit its 2030 electrification targets for EVs and household appliances[19].

Another challenge relates to the transformers themselves, which are designed to be cooled at night when usage typically drops. A neighborhood cluster adding several Level 2 EV chargers means that the transformers won't have as much of a chance to cool down. **Multiple Level 2 chargers on one transformer can actually reduce its life from an expected 30-40 years to just 3 years**[20]. Supplies for distributed transformers have already risen from $3-$4k to $20k, and the increase in their weight to support EVs might require some of the 180 million power poles in the US to be replaced as well. Advanced Metering Infrastructure is designed to provide visibility and control into local electricity consumption and voltage, but most utilities do not have these capabilities yet[21].

As for EV charging capabilities required, forecasts vary as shown below. Regardless of which one you pick, the infrastructure needs are large; DC fast charging stations can cost $470k-$725k. National Grid analyzed demand growth at 71 highway charging sites in NY and Massachusetts[22]. By 2030-2035, power capacity needs at passenger and mixed use charging plazas could reach 5-10 MW (as much as a football stadium), and 20 MW at a truck stop, which is similar to the power capacity of a small town. This compares to just 0.6 MW required by four 150 kW fast chargers present in many charging locations today.

US EV charging infrastructure assumptions for 2030

	EVs in the fleet, mm	Workplace chargers	Public Level 2 chargers	Dir. Current Fast Charging ports
Current data	3.5	10,000	104,483	30,551
Required by 2030				
International Council on Clean Transportation	26.0	1,300,000	900,000	180,000
Edison Electric Institute	26.4	1,200,000	2,000,000	140,000
McKinsey/Biden goal	48.0	530,000	675,000	533,000

Source: US DoE; Argonne National Labs; IEEE Spectrum, "EV Transition Explained" (Chap. 4). March 2023.

Charger	Power supply	Power, kW	EV range per hour in miles	BEV hours to charge	PHEV hours to charge
Level 1	120-volt AC	1.3-2.4	3-5	40-50	5-6
Level 2	208 volt (commercial) 240 volt (residential)	3-19	18-28	4-10	1-2
Level 3	Direct current	50-350	NA	1.0-1.5	NA

Source: US Department of Transportation. 2023.

Power distribution of existing Direct Current Fast Charging Ports

< 51 kW	51-149 kW	150-249 kW	250-349 kW	>349 kW
23%	15%	19%	37%	7%

Source: US Department of Energy/NREL, Q3 2022

[19] City of Palo Alto Utilities Advisory Commission Staff Report, 11/4/2020, Table 1

[20] Deepak Divan, Director of the Center for distributed Energy at Georgia Tech

[21] "*The EV Transition Explained*", IEEE Spectrum, March 2023, Chapter 3

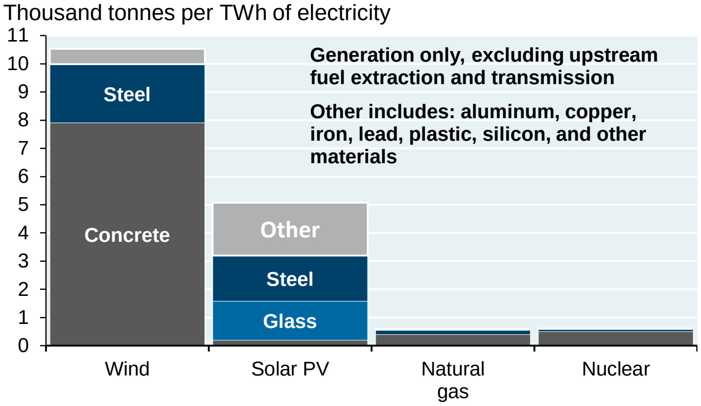
[22] "*Electric Highways*", National Grid, November 2022

[4] Resource nationalism in, globalization out: the scramble to reshore production and processing of minerals used in the renewable transition; nuclear power/SMR update

You need certain minerals to *build* wind and solar capacity one time, while you need oil, gas and coal to run thermal capacity *all* the time. Renewables entail intermittency and energy density issues discussed elsewhere, but on paper their mineral needs would be less of a constraint than fossil fuels…if a country can produce or buy them on a reliable basis. However, the distribution of many minerals is just as geographically concentrated as it is for fossil fuels, and some regions are not well endowed with them.

Let's start with the basics: what will it take to build a renewable future? A lot of industrial materials, for one thing. The next chart looks at the mass of **construction materials per terawatt hour of electricity**. Concrete, steel and glass requirements per TWh for renewables are much larger than for natural gas or nuclear power.

Construction materials by generation source
Thousand tonnes per TWh of electricity



Source: Argonne National Laboratory, Dept. of Energy, JPMAM. 2022.

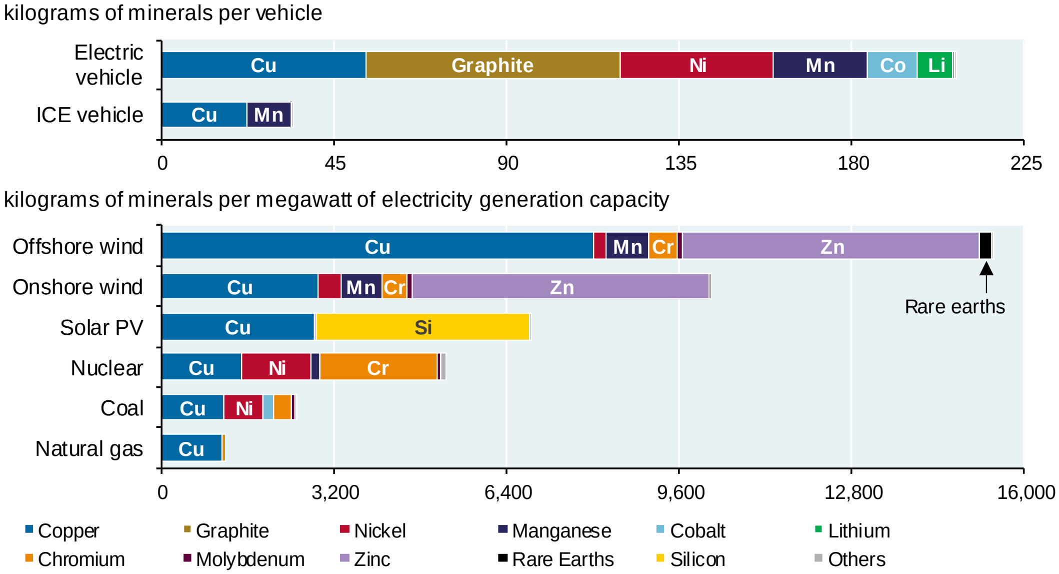
In case you were wondering…

Cement is made from abundant limestone, clay and gypsum, heated to 2,700°F and ground into a powder. The issue with cement is not scarcity of the minerals but the energy required to utilize them.

Concrete is the world's most-used material after water, and is a composite of cement, water, sand and stone aggregates.

The renewable transition also requires a lot of basic and critical minerals. The next chart compares the mineral requirements of electric cars to internal combustion engine (ICE) vehicles, and also compares the mineral requirements of wind and solar to nuclear, coal and natural gas powered electricity generation.

Minerals used in wind / solar / EVs vs legacy energy systems
kilograms of minerals per vehicle



Source: IEA, JPMAM. 2022.

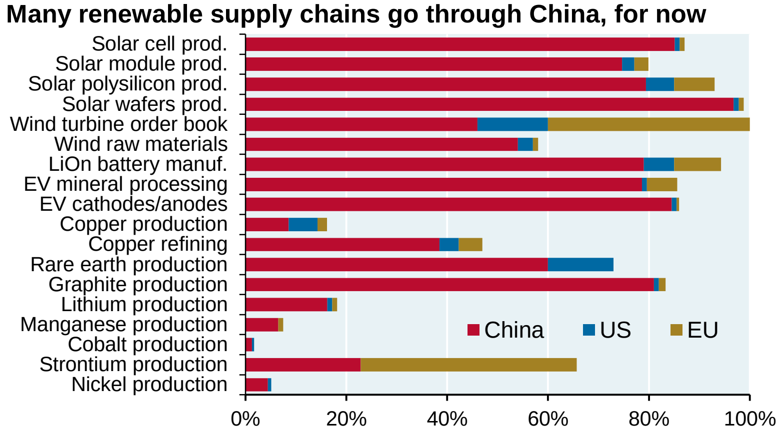
However, the issue at hand is not the abundance of transition minerals. As shown in the table, proven reserves are high relative to current production (> 40 years for most minerals), and global resources are even higher. **The challenges:** *reliability* of supply, particularly when minerals are sourced from countries with higher geopolitical risks; rising resource nationalism; the cost associated with increasing (and arguably belated) surveillance of environmental impacts as in Chile/Peru; and both the cost and time required for these minerals to be mined and processed elsewhere.

Transition minerals are generally abundant

figures in kilotons	Global production	Global reserves	Global resources
Lithium	130	26,000	98,000
Copper	22,000	890,000	2,100,000
Cobalt	190	8,300	25,000
Nickel	3,300	100,000	300,000
Manganese	20,000	1,700,000	NA
Chromium	41,000	560,000	12,000,000
Zinc	13,000	210,000	1,900,000
Rare earths	300	130,000	NA
Iron ore	1,600,000	85,000,000	230,000,000
Platinum grp	0.40	70	100
Graphite	1,300	330,000	800,000
Molybdenum	250	16,000	25,400

The table excludes silicon, which is the second most abundant element in the earth's crust. World resources of limestone and dolomite are also plentiful. Iron ore data refers to iron content rather than crude ore. Platinum group refers to palladium and platinum. Source: USGS, JPMAM. 2022

Many renewable supply chains go through China, for now

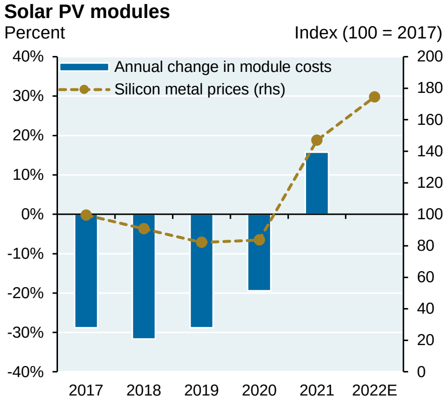


Source: Benchmark Mineral Intelligence, BNEF, EC, IEA, S&P, USGS, JPMAM. 2022.

As shown on the right, **China** dominates many renewable energy production and processing supply chains. It's not going to be cheap to reshore them: even with China as the world's low-cost producer, prices for solar modules and wind turbines rose in 2021 for the first time in several years, and battery cost declines slowed. Inflation has affected other projects as well: developers of the Saudi Neom green hydrogen[23] facility announced that its original budget of $5.0 bn had already risen to $8.5 bn due to cost increases for spare parts, land and interest. We've been acclimated to steady declines in unit pricing due to economies of scale, but at some point, price declines may level out and intermittently rise with demand and/or materials scarcity. Some good news on solar: polysilicon prices have declined by ~50% since their peak last year.

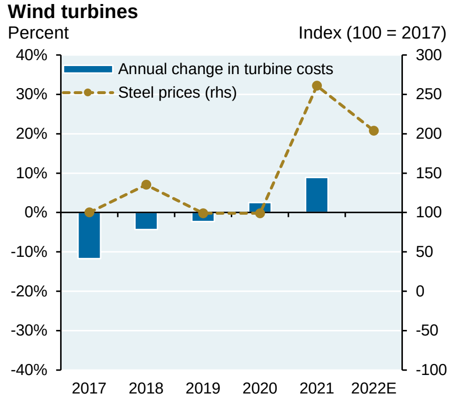
PV module, wind turbine and EV battery prices as a function of select input costs:

Solar PV modules



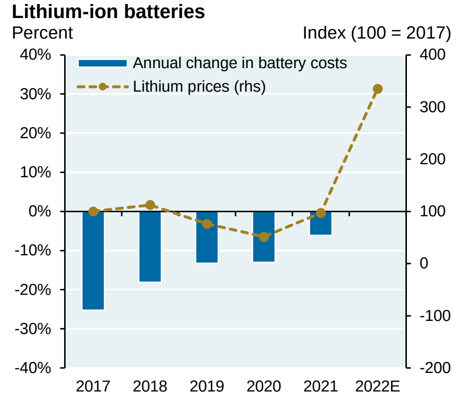
Source: IEA. 2022.

Wind turbines



Source: IEA. 2022.

Lithium-ion batteries



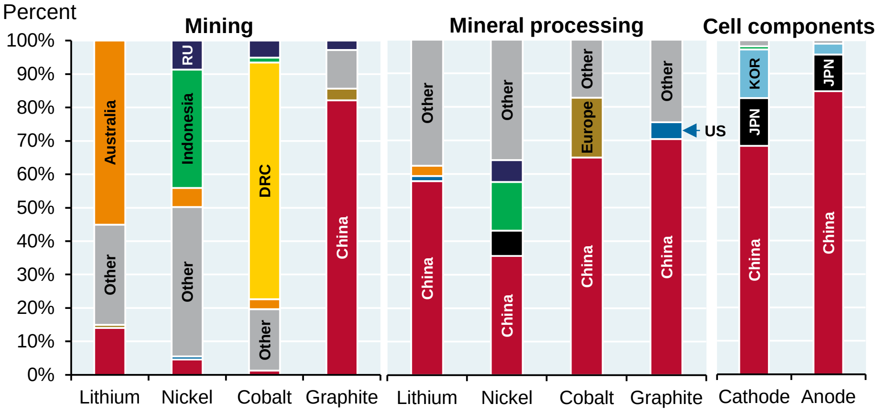
Source: IEA. 2022.

[23] In polymer electrolyte fuel cells, hydrogen and oxygen are converted into electricity and water. Platinum and palladium catalysts are typically used given how well they bind with hydrogen gas to produce protons and electrons via oxidation. **As an example of stability risks rather than mineral abundance risks,** both production and proven reserves of platinum group minerals are concentrated in South Africa, Zimbabwe and Russia.

Battery supply chains

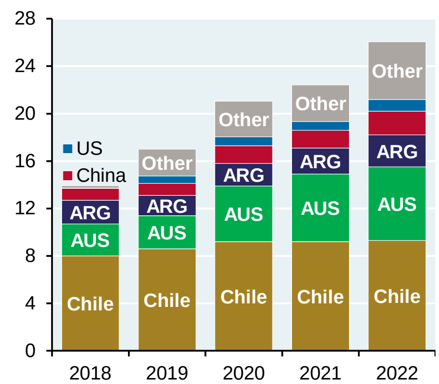
Battery minerals like lithium, nickel and cobalt are mined in several countries. China dominates the mining of graphite which is used in battery anodes, the production of cell components like cathodes and anodes, and the *processing* of battery minerals. China has now matched Germany's passenger car exports at ~2.6 mm units, enabled in part by its EV supply chain strength, and appears poised to surpass Japan in the next few years.

Battery supply chains: mining, processing and components
Percent



Source: IEA. 2022.

Global reserves of lithium by country
Million metric tons



Source: USGS, JPMAM. 2023.

The increase in battery mineral prices (see p.13) may reinforce the recent shift to lithium iron phosphate (LFP) batteries from nickel-based chemistry[24]. Almost half of Tesla's production in 2022 used LFP chemistry, which is being incorporated in future plants in the US and Europe. On lithium:

- The IEA projects lithium needs of 320 kt by 2030, up from 130 kt in 2022. That sounds like a large increase, but the world has plenty of lithium: from 2018 to 2022, global lithium reserve estimates doubled from 13 to 26 mm tonnes. Higher prices accelerate exploration: Iran announced what could be the world's second largest lithium deposit at 8.5 mm tonnes, and India announced a potential 6 mm tonne find as well
- Chinese lithium carbonate prices have declined ~50% from peak 2022 levels, but are still ~4x 2020 levels
- Western lithium mines can require from 7 to 19 years from feasibility study to actual production[25]
- Given low margins from recycling of iron and phosphates, the IEA expects just 1%-3% of battery demand in 2030 to be met from recycled cobalt, nickel and lithium

One possible option for batteries that don't require lithium: **sodium ion batteries (Na-Ion)**, made from sodium, nitrogen, iron and carbon. They may entail only a 20% energy density deficit vs LFP batteries, and might be well suited for urban EVs (shorter travel distances) and grid-scale energy storage. The Chinese battery manufacturer CATL introduced its first Na-Ion battery in 2021. But to be clear, they barely register in the light duty EV fleet today, and will probably have less than a 10% share by 2030 given production lead times required.

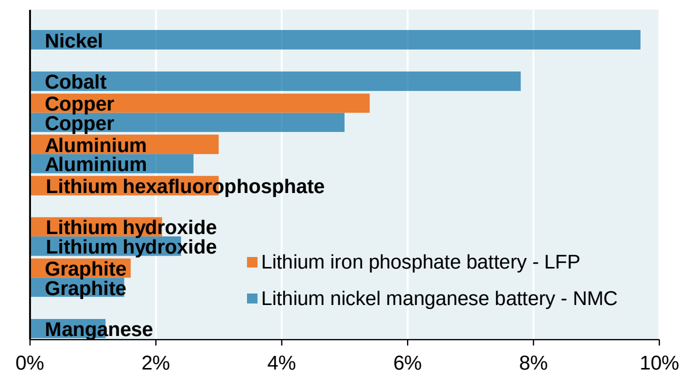
Solid state lithium-air batteries could theoretically entail 2x-4x higher energy density than current batteries that use liquid electrolyte solutions. As per Argonne National Labs, liquid solutions yield lithium peroxide or superoxide with 1-2 electrons per oxygen molecule, while a solid state approach could yield lithium oxide with 4 electrons. They tested a prototype for 1,000 cycles at room temperature, but it has not been commercialized yet. There has been an avalanche of new battery ideas over the last decade; it generally pays to wait for proof of concept based on actual production and adoption before making any projections.

[24] While nickel-based chemistries such as NMC (lithium, nickel, manganese) and NCA (lithium, nickel, cobalt, aluminum) dominated the EV market with 85% share in 2021, **LFP batteries rapidly gained share** despite lower energy density/range, mostly due to LFP batteries not requiring any cobalt or nickel, less risk of catching fire and longer operating lives. China's BYD has improved LFP density by reducing deadweight housing requirements.

[25] IEA, "*Global Supply Chains of EV Batteries*", July 2022

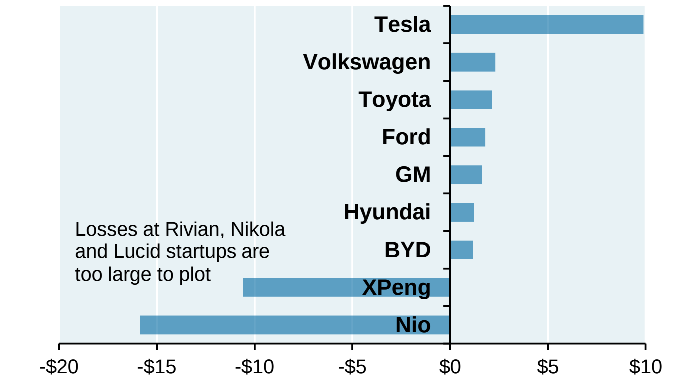
While battery mineral supplies are a critical issue, the sensitivity of battery prices to changing mineral prices is sometimes overstated. Battery prices include costs of production, shipping, labor etc. One study[26] cited increases of just 2%-5% for LFP batteries and 2%-10% for NMC batteries if one of their component mineral prices were to *double* (next chart). And when battery prices do rise, EV makers might still decide to compete on price. That's what Tesla did recently, cutting prices on its Model Y by 20% and Model 3 by 14%, forcing Ford[27] to cut prices as well by 8%-19%. Tesla's price cuts originate from a position of much higher per unit margins.

Change in battery prices assuming 100% increase in each component mineral price, Percent



Source: *"Monetizing Energy Storage"*, Schmidt and Staffell. 2023.

Net profit per vehicle, 2022, excluding extraordinary items
US$, thousands, all vehicles sold



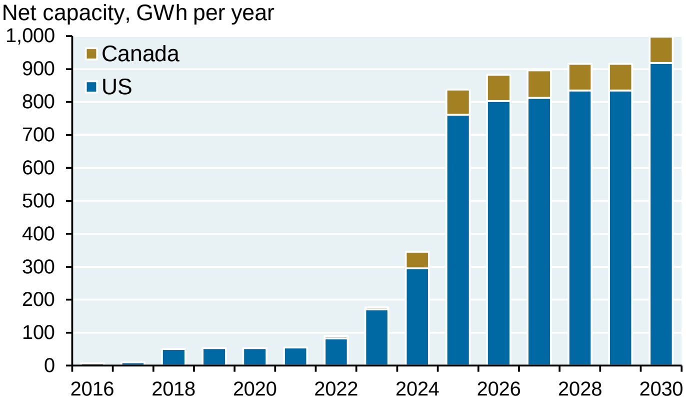
Source: Bloomberg, JPMAM. Q3 2022.

The US battery supply chain build-out

Rivian's CEO said last year that 90%-95% of the battery supply chain does not exist, and that the battery shortage will make the semiconductor shortage look like a "small appetizer". That said, substantial investments have been announced in US battery supply chain assembly which is projected to rise from 55 GWh per year of capacity in 2021 to 1,000 GWh by 2030[28]. Key states: Georgia, Tennessee, Kentucky, Michigan, Ohio, North Carolina and Nebraska (New England may have lost out due to its higher industrial electricity prices; see page 23). Assuming 50-70 kWh per car battery, 1,000 GWh of battery capacity could supply the US with all the batteries it needs for projected 2030 EV passenger car sales of ~8 mm units.

The US is minimally exposed to China on production of EV cells, packs and vehicles. The table shows how the US was reliant on itself and its allies in 2021 for these materials. However: while the US is expanding its ability to manufacture cells, packs and vehicles, **it will probably remain highly dependent on the rest of the world for mining and processing of minerals *used* in these batteries**, and components like cathodes and anodes.

Announced battery plant capacity
Net capacity, GWh per year



Source: Argonne National Laboratory. November 2022.

Country of origin for lithium ion cells, battery packs and electric vehicles sold in the US, 2021
numbers in thousands

	Cells		Packs		Vehicles	
Country of origin	#	Share	#	Share	#	Share
US	362	57%	402	63%	406	64%
Europe	96	15%	109	17%	50	8%
Japan/South Korea	162	26%	119	19%	92	14%
Canada/Mexico	0	0%	0	0%	62	10%
China	12	2%	4	1%	4	1%
Other	0	0%	0	0%	21	3%

Source: ANL, JPMAM. 2022.

[26] "*Monetizing energy storage*", Schmidt and Staffell, Imperial College of London, 2023

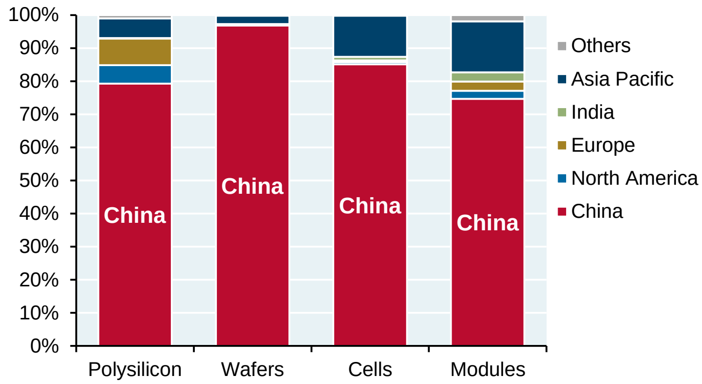
[27] Ford announced an expected $3 bn loss in its EV division in 2023, subsidized by profits in the rest of its business

[28] Investments from Hyundai/SK, Honda/LG, Toyota, Panasonic, Redwood, LG Chem.

Solar power supply chains

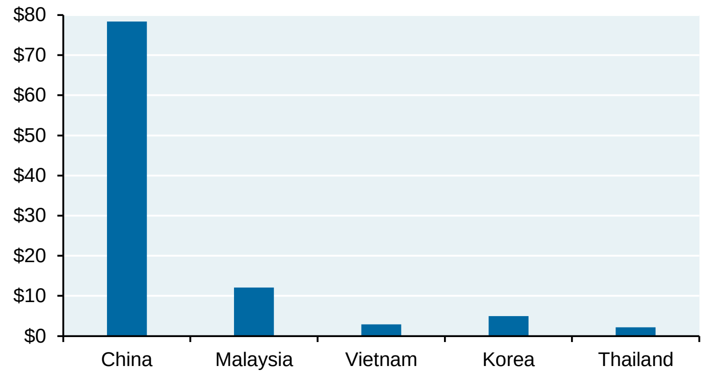
China dominates solar supply chains after a decade of support for its solar industry in the form of low-cost loans, cheap land and electricity, and perhaps mostly importantly the imposition of import tariffs in 2013. **Solar resource nationalism is still rising:** since 2011, the number of antidumping, countervailing and import duties levied against PV supply chains increased from 1 to 16, with 8 more under consideration. China announced that its Ministries of Commerce, Science and Technology are seeking public comment on adding advanced solar ingots and wafers to its list of **prohibited exports**. If China did so, it would mirror US restrictions on exports of advanced semiconductors to China.

Solar PV manufacturing capacity by country and region
Percent



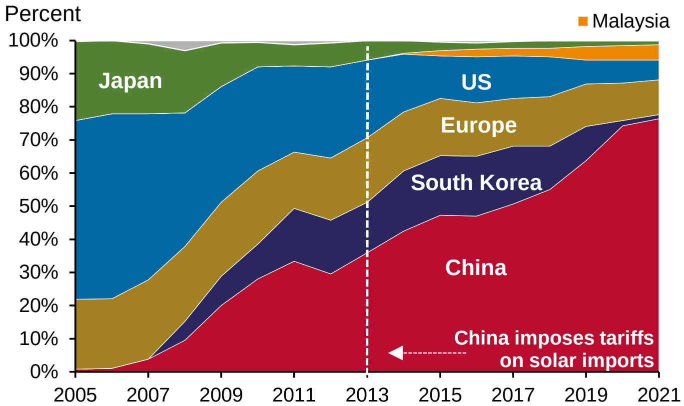
Source: IEA. 2022.

Cumulative PV-grade polysilicon, wafer, cell and module trade balances, 2017-2021, US$, billions



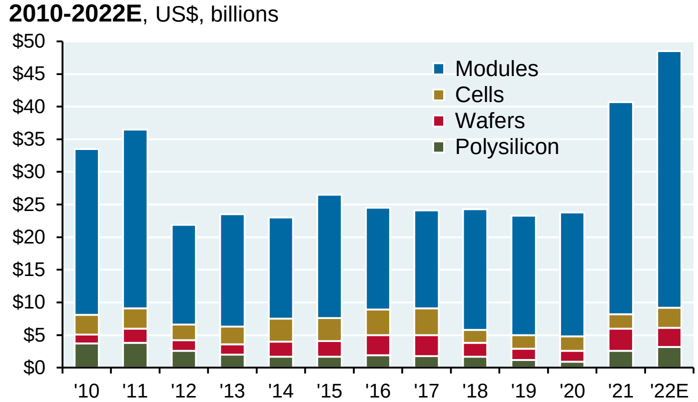
Source: IEA. 2022.

Market shares in global polysilicon production
Percent



Source: Bernreuter Research. 2022.

PV-grade polysilicon, wafer, cell and module trade value, 2010-2022E, US$, billions



Source: IEA. 2022.

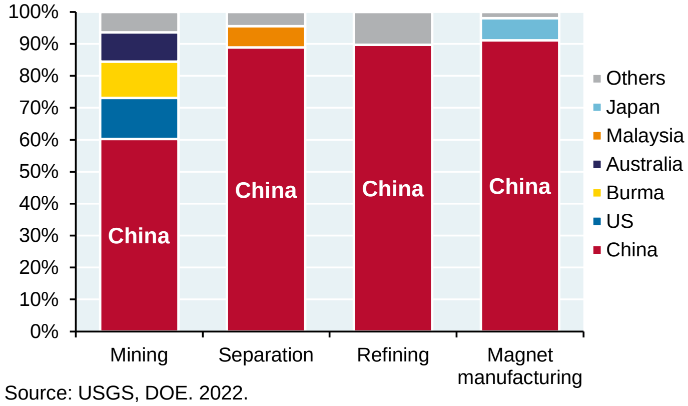
On solar power and US reliance on Asia:

- PV panels are made by extracting high-grade silicon from quartz and forming it into cylindrical ingots which are sliced into thin wafers and chemically treated to create cells capable of converting sunlight into energy
- Last year, most US polysilicon factories were repurposed to supply the semiconductor industry. The US had no active ingot, wafer or cell capacity; the dozen US factories producing them as recently as 2014 were gone. The US now imports enough solar panels to meet 90%-95% of its annual demand
- The US Dep't of Commerce concluded that certain Chinese manufacturers moved operations to Vietnam, Malaysia, Cambodia and Thailand to circumvent tariffs, so they will now be subject to tariffs as well. A decade of tariffs on US solar imports was supposed to jump-start US domestic production, but haven't done much; tariffs simply increase installed costs of US solar power (according to solar project developers)
- The US energy bill has jump-started new US solar supply chain capacity (Hanwha, SPI Energy, Convalt Energy, First Solar); it will be interesting to see the all-in cost per MWh of US production

Wind and magnet supply chains

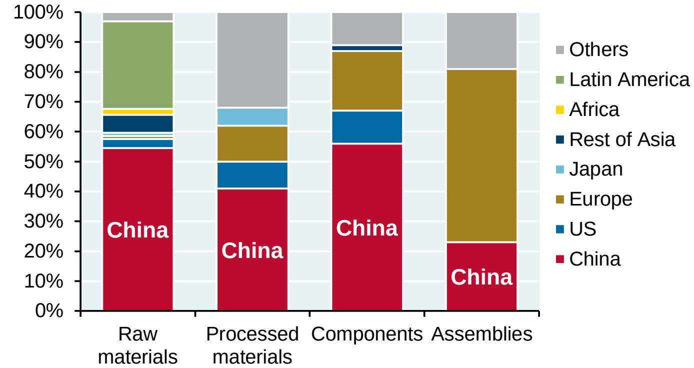
These charts cover supply chains for neodymium magnets[29] and wind power. China is the only country with a fully integrated permanent magnet supply chain. Neodymium is a rare earth element, which we discuss next.

Neodymium NIB magnet supply chains
Percent



Source: USGS, DOE. 2022.

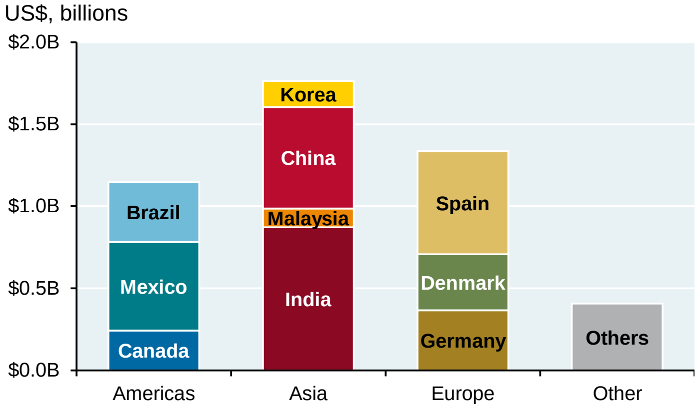
Wind turbine supply chains
Percent



Source: European Commission. 2020.

There are four main wind turbine technology types, illustrated below on the right. I know there's a lot of jargon here, but I included it since I want to illustrate something about offshore wind. In addition to requiring **more copper** than onshore wind, offshore wind mostly relies on "direct drive permanent magnet" generators which require **more rare earth metals** as well. Offshore wind turbines are taller, lighter, more efficient and equipped with larger blades to generate higher capacity factors. At the end of 2022, there were 65-70 GW of offshore wind installed globally, ~7% of global wind capacity.

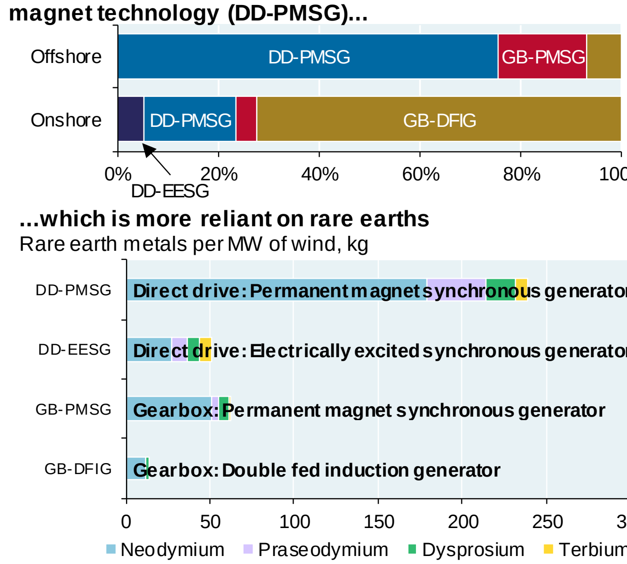
US wind component imports
US$, billions



Source: US Department of Energy. 2021.

The US is less exposed to China regarding wind supply chains when compared to solar power, rare earths and EV battery minerals mining/processing.

Offshore wind is more reliant on direct drive permanent magnet technology (DD-PMSG)...



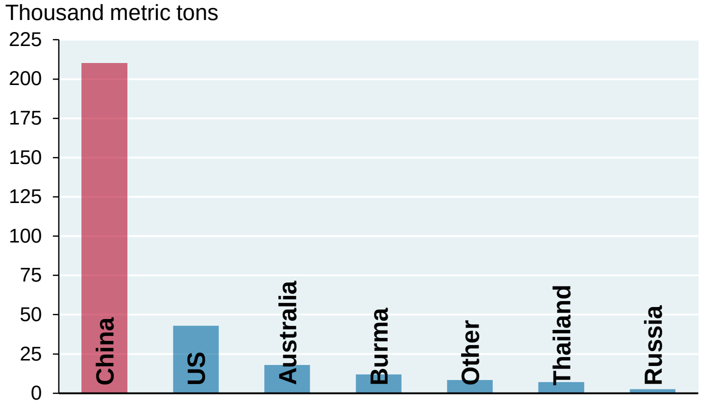
Source: IEA, JPMAM. 2022

[29] **Neodymium magnets** require a lot of work: mining, processing and refining of rare earths; alloying to enhance magnetic properties; melting, strip-casting and rapid cooling; hydrogen decrepitation to disintegrate the magnet material; jet milling to grind neodymium metal into powder; high pressure magnetization; cold isostatic pressing to remove air gaps; sintering in furnaces at temperatures over 1000°C to enhance magnetic properties; all before the cutting, machining, grinding and electroplating to make the final magnets that are used in EVs, wind turbines, marine propulsion systems, cell phones etc.

The supply of rare earth elements (REE) is another key issue in the renewable transition.

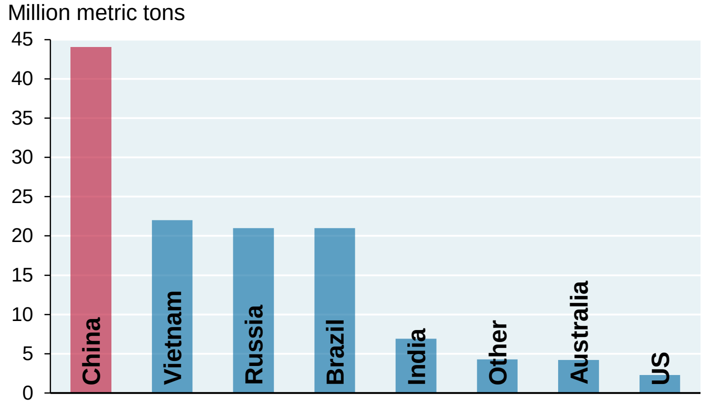
- Despite the name, REE exist abundantly in the Earth's crust. However, they are widely dispersed and found in very low concentrations, making them harder to exploit economically
- REEs are used in EV motors (although there are potential substitutes) and in sintered magnets for wind turbines, as well as for F-35 Lightning Fighter jets, DDG-51 Aegis destroyer warships and mobile phones[30]
- In addition to its dominant 60% share of REE production, China also has the largest amount of REE reserves. To be clear, the geography of actual REE deposits is not entirely known. Sweden for example just announced finding the largest REE deposits in Europe at 1 mm tonnes; they will take 10-15 years to bring online
- China is consolidating control and oversight of its dominant rare earth position. In December 2021, China's State-Owned Assets Supervision and Administration Commission (SASAC) created the China Rare Earth Group, a merger of three of its rare earth state-owned enterprises. The impact: greater pricing power and influence over world supply
- China's dominance in REE supply chains may actually be *understated*. According to a 2022 Petersen Institute study[31], China partners in projects in other countries to secure long term supplies, and exerts control over its own REE production. In contrast, REE production in the US is controlled by investment firms; the Federal government has no direct control over their operations unless it invokes legislation such as the Defense Production Act of 1950
- **If the developed world wants to reshore REE production, it won't be easy**: it will be competing with China's sanctioned REE industry and also **China's unregulated REE operations** which reportedly account for 40% or more of China's total REE output[32]. The latter typically have lower all-in costs given the frequent lack of operational, environmental and labor regulations
- **To reiterate**: the issue here is not REE scarcity, it's the price at which other countries can mine and process them, and how long it would take to do so

Global mined production of rare earths, by country, 2022
Thousand metric tons



Source: USGS. 2023.

Global reserves of rare earths, by country, 2022
Million metric tons



Source: USGS. 2023.

[30] "*What China's Rare Earths Dominance Means for the US*", Baker Institute, Foss & Koelsch, December 18, 2022

[31] "*Green Energy Depends on Critical Minerals. Who Controls the Supply Chains?*", PIIE, August 2022

[32] "*China's public policies toward rare earths, 1975 -2018*", Yuzhou Shen et al in *Mineral Economics*, 2020, and "*The impact of unregulated ionic clay rare earth mining in China*", Packey and Kingsnorth, *Resources Policy*, 2016

- The US relies on China for ~80% of its rare earth metals. Currently, the only US REE producer is MP Materials in its Mountain Pass facility in California, which also sends 30,000 tonnes of the concentrate it produces to China for processing. On magnets, Noveon is the only operational US permanent magnet manufacturer
- The US Dep't of Defense provided $30 mm to Lynas, $45 mm to MP Materials and $30 mm to Noveon. The CHIPs/energy bills also provide tax refunds on production costs, increased funding authority for R&D grants and Defense Production Act funding. Even so, this process will take time, and be contingent on permitting
- How might the US catch up? REE tend to be highly dispersed within the soil, so R&D could lower marginal costs of production. Continuous ion exchange and other techniques beyond traditional solvent extraction could improve efficiency and reduce cost
- **China doesn't just dominate the production and processing of rare earth elements; China is also a large producer of other minerals as well**. The table shows minerals for which China is the largest global producer, along with estimates of each mineral's supply risk and economic importance

Material	Stage	Sup Risk	Eco Imp	China share	Material	Stage	Sup Risk	Eco Imp	China share	Material	Stage	Sup Risk	Eco Imp	China share
Antimony	E	2.9	5.3	74%	Gallium	P	1.8	3.9	80%	Praseodymium	E	7.9	4.8	86%
Baryte	E	1.8	3.6	38%	Germanium	P	5.6	3.9	80%	Samarium	E	8.7	8.1	86%
Bismuth	P	3.2	4.4	80%	Ho, Tm, Lu, Yb	E	8.8	3.7	86%	Scandium	P	4.4	4.9	66%
Cerium	E	8.8	3.9	86%	Indium	P	2.6	3.6	48%	Silicon metal	P	1.7	4.7	66%
Coking Coal	E	1.7	3.4	55%	Lanthanum	E	8.7	1.7	86%	Terbium	E	7.9	4.6	86%
Dysprosium	E	8.9	8.0	86%	Magnesium	P	5.6	7.4	89%	Titanium	P	1.8	5.2	45%
Erbium	E	8.7	3.4	86%	Natural graphite	E	3.2	3.6	69%	Tungsten	P	2.3	9.0	69%
Europium	E	5.2	3.6	86%	Neodymium	E	8.7	5.4	86%	Vanadium	E	2.4	4.9	39%
Fluorspar	E	1.6	3.7	65%	Phosphate rock	E	1.6	6.3	48%	Yttrium	E	6.0	3.9	86%
Gadolinium	E	8.7	5.1	86%	Phosphorus	P	5.2	5.9	74%					

Source: European Commission. 2022. Note: E = Extraction stage, P = Processing stage.

Supply Risk ranges from 0 - 10, with 10 = greatest risk of disruption in supply of a specific material.
Economic Importance ranges from 0 - 10, with 10 = most important for end-use applications.

Heavy Rare Earth Elements

Light Rare Earth Elements

One last minerals comment: on uranium, nuclear power and small modular reactors

Almost half of world uranium production comes from Kazakhstan. The remainder: 12% from Namibia and 5%-10% each from Canada, Australia, Uzbekistan, Russia and Niger. China's share is just 3.5%. While the US was a major uranium producer from 1960-1985, its share has dwindled close to zero despite ample reserves in the Western US. As shown below, the average age of US nuclear power plants is *over 40 years*.

Nuclear power roundup:

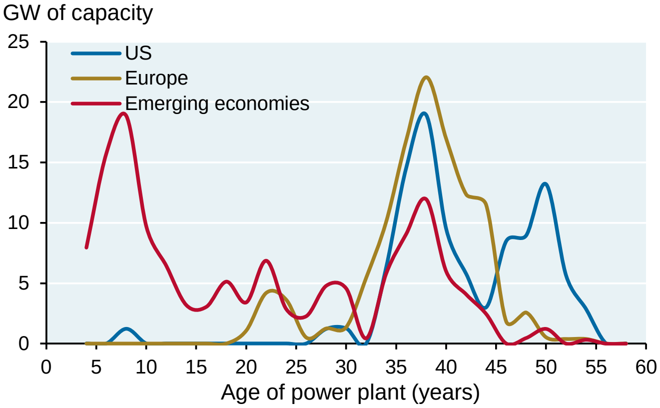
- China, Korea, India, Russia and Turkey are building 34 new nuclear plants, mostly pressurized water reactors
- In the US there are only two being built (in Georgia), both billions of dollars over budget and years behind schedule; they're also the first nuclear plants to be completed in the US in 30 years
- In Europe, France's nuclear output should recover in 2023 after a year plagued by COVID, corrosion shutdowns and low water levels; but that increase may be offset by scheduled decommissioning in Belgium and Germany. While France announced plans to build 14 new reactors by 2050, let's see how that goes: its Flamanville plant has been a planning and execution fiasco. Construction began in 2007; by 2020 it was already 5x over its original budget; and the project managers have had to address structural anomalies, faulty cooling welds and a fire/explosion onsite. Initial operation is now scheduled for early 2024 after additional delays and cost overruns
- Japan has 10 reactors in operation, intends to restart another 7 in 2023 and another 10 by 2030 (out of 33 reactors in total). Japan aims to get back to 20% of generation from nuclear by 2030 (2021 = 7%)

The US Nuclear Regulatory Commission approved construction of demonstration **small modular reactors** (SMR) in Idaho, a 6-reactor 460 MW NuScale project expected to be completed by 2030. The latest cost estimates: $89 per MWh (up 50% from an earlier estimate of $58) and $20,000 per kW. That's much higher than the $13,500 per kW cost of the Georgia nuclear plants even after their cost overruns, and 4x what NuScale estimated just 3 years ago ($4,500 per kW). On nuclear, the cost overrun song remains the same.

There was a very public dispute last year when a former chair of the US Nuclear Regulatory Commission co-authored a study[33] highlighting the ongoing nuclear waste challenge, even with SMRs. The authors concluded that SMRs would produce *more* chemically/physically reactive waste than light water reactors (LWRs), and that the intrinsically higher neutron leakage associated with SMRs suggests that most designs could be worse than LWRs with respect to generation, management and disposal of nuclear waste. The SMR industry disputed this conclusion, arguing that its latest designs were not being taken into account. NuScale's co-founder and Chief Technology Officer reportedly countered that SMR waste streams are similar to LWRs[34]. **Ok; but if that's the case, SMRs have not yet cracked the code on the challenge of nuclear waste**.

Age distribution of existing nuclear reactors

GW of capacity



Source: International Atomic Energy Agency, JPMAM. 2022.

TerraPower update. The completion date for its inaugural Natrium (sodium-cooled) reactor has now been pushed back later than 2028 since Russia is the only current source of high-assay, low-enriched uranium (HALEU) the plant needs. If completed, the Natrium plant would benefit from infrastructure connected to Wyoming coal plants scheduled to be retired in 2025. Congressional bills passed in 2020 and 2022 aim to support domestic HALEU supply chains, and TerraPower announced that it plans to build a Natrium (HALEU) Fuel Facility in North Carolina. Senators Manchin (D-WV), Risch (R-ID) and Barrasso (R-WY) introduced the "Nuclear Fuel Security Act" in Feb 2023 to further this agenda. This will all take many, many years.

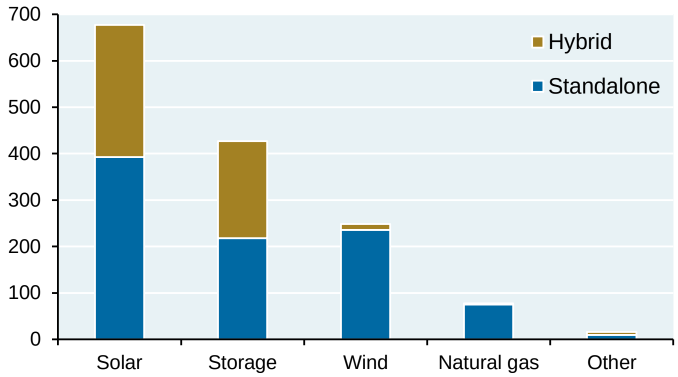
[33] "*Nuclear waste from small modular reactors*", Krall, Macfarlane and Ewing, Environmental Sciences, May 2022

[34] Bloomberglaw.com, Environment & Energy, February 25, 2023

[5] Energy in, most of the energy out: the economics behind the rise in co-located storage and solar power

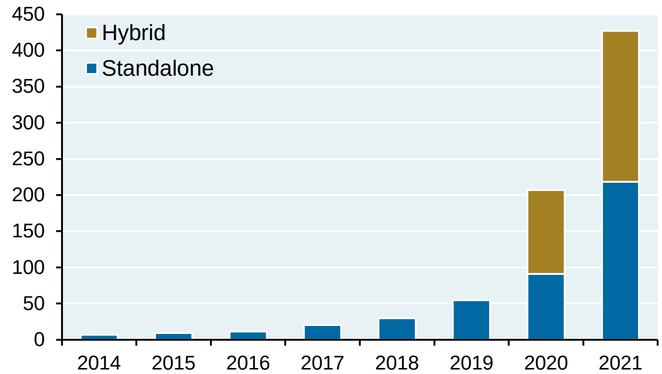
When looking at the US electricity queue, one thing stands out: increasing numbers of hybrid projects involving co-location of solar power[35] with energy storage. Owners of storage can engage in electricity price arbitrage: buy solar power generated in the middle of the day when electricity prices are low, and sell it later in the day when prices are higher. However, more than price arbitrage alone is often required to justify investment. There have been large declines in chemical battery costs, but storage is still relatively expensive to build and operate. In many jurisdictions, storage projects need to derive additional value from "capacity substitution": their ability to stand in as an alternative to power generating capacity or transmission grid capacity for which they are paid a fee, or "capacity payment".

Electricity generation capacity in queues
Capacity, Gigawatts



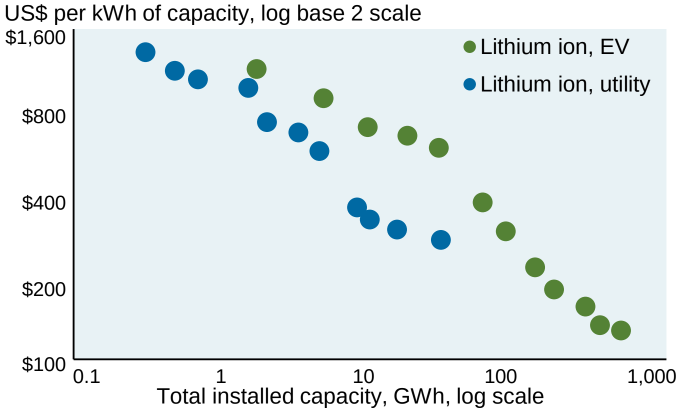
Source: LBNL. 2022.

Storage interconnection queue
Gigawatts



Source: LBNL. 2022.

Battery learning curves
US$ per kWh of capacity, log base 2 scale



Source: "Monetizing energy storage", Schmidt & Staffell (Oxford Press). 2023.

Assumptions for solar+storage model

W. Avg Cost Capital	5.5%				
Storage			*Inverter*		
Capital cost	$284	per kWh	Capital cost	$41	per kW
Operating life	20	years	Operating life	20	years
O&M	$10	per kWh-yr	O&M	$10	per kW-yr
Investment tax credit	30%		Efficiency	95%	
Duration	4	hours			
Charge efficiency	97%				
Discharge efficiency	97%		*Solar*		
Substation			Capital cost	$900	per kW
Capital cost	$77	per kW	Operating life	20	years
Operating life	20	years	O&M	$20	per kW-yr
O&M	$12	per kW-yr	Prod. tax credit	2.75	c per kWh

Source: Decision Solve LLC, JPMAM. 2023.

We asked Jesse Jenkins and his colleagues at Decision Solve LLC, an energy and environmental consulting firm, to help model the economics of energy storage. There are a **lot** of factors involved: intraday electricity price differentials and volatility; capital and O&M costs for storage, solar, inverters and substations; round trip energy efficiency[36]; storage duration; operating life for storage and generation assets; profile of existing renewables on the grid; electricity demand and generation profiles by source; correlation of generation profiles with demand; production/investment tax credits; and the cost of capital. See table above for details.

[35] US solar power is not just growing in utility scale applications. As per BNEF, 33% of existing US solar capacity of 142 GW was installed on residential and commercial buildings as of 2022

[36] **Round trip efficiency**: batteries accept and discharge DC power. So, for wind which generates AC power: wind –> inverter (95%) –> battery charge (97%) –> battery storage –> battery discharge (97%) –> inverter (95%) for total round trip efficiency of 85%. For solar which generates DC power, there is no need for the inverter upfront, increasing round trip efficiency to 89%.

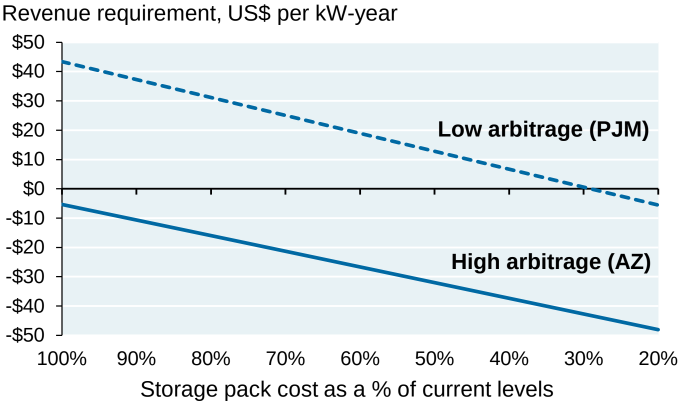
To illustrate storage economics, we modeled two cases: Arizona with high intraday price arbitrage potential and PJM (ISO for mid-Atlantic states) with low intraday arbitrage potential.[37] In the charts below, the X-axis shows storage costs as a % of current levels (of ~$280 per kWh) and the Y-axis shows the additional revenue per kW-year that a storage project must earn to be profitable after earning revenue from price arbitrage.

When the required payment is **positive**, storage would need to earn additional revenue from capacity payments, which are commonly paid by grid operators for helping meet peak electricity demand and displacing the need for peaker plants (usually natural gas turbines used infrequently when demand is greatest). When required payments are **negative**, modeled returns to investors would be sufficient from energy arbitrage alone.

The first chart shows storage on a stand-alone basis, and the second chart shows co-located storage+solar in which case inverter and substation costs can be optimized to reduce capital costs compared to a stand-alone solar project. In other words, storage can effectively smooth out solar generation to reduce interconnection fees and maximize economic value.

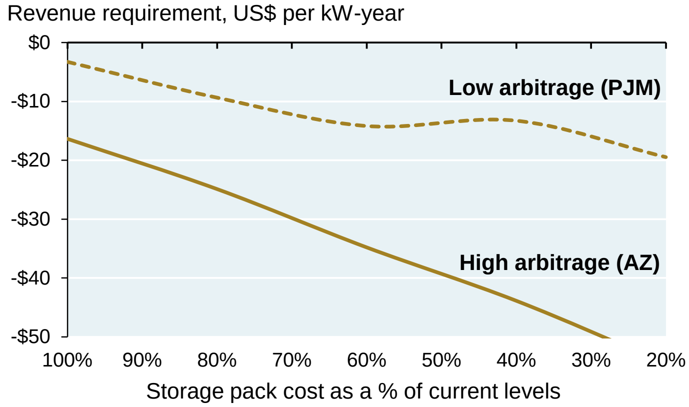
Results: in the low arbitrage location, capacity payments would be needed for stand-alone storage no matter how low your storage cost assumption is. For context, PJM capacity payments per kW-year range from $18 to $73, which explains why some stand-alone storage is built even in such locations. In the high arbitrage location, and in the low arbitrage location when solar and storage are combined, no capacity payments are required according to our set of assumptions (see below on risks of relying on arbitrage as the sole revenue stream). Using a 7.0% cost of capital instead of 5.5% does not change the results very much.

Storage: low arbitrage locations require payments
Revenue requirement, US$ per kW-year



Source: Decision Solve LLC, JPMAM. 2023.

Solar + storage: payments not required in either location
Revenue requirement, US$ per kW-year



Source: Decision Solve LLC, JPMAM. 2023.

To be clear, there are two very big risks for storage investors. The first: other storage investors could crowd into the same market, reducing electricity arbitrage values for everyone (akin to risks in commercial real estate). The second: these models assume "**perfect foresight**" since they use electricity prices, generation and demand patterns from a specific year and assume optimal decisions around when storage is filled and drawn down. In real life this impossible, since storage owners must make decisions regarding utilization without knowing the best time to do so, in which case actual revenues would be lower than what is modeled.

Bottom line: while some locations generate enough revenue from price arbitrage to justify storage investment, others require storage to be paid for its "capacity substitution" value; i.e., eliminating the need for additional grid investment or peaker plants. A few years ago, large capacity payments would have been needed almost everywhere; falling costs of storage have now changed those economics. In 2017, 288 MW of storage was deployed in the US; by 2022 this figure rose to 4.8 GW. Wood Mackenzie estimates that between 2023 and 2027 another 75 GW will be deployed, most of which will be co-located with wind and solar generation.

[37] Average daily price arbitrage per MW assuming perfect foresight and 4 hour storage: Oregon $110, PJM $269, Nevada $316, Arizona $356 and Texas $428

[6] Garbage in, Energy Out: the benefits and limitations of municipal solid waste as a source of energy, and the ongoing dispute over forest biomass in Europe

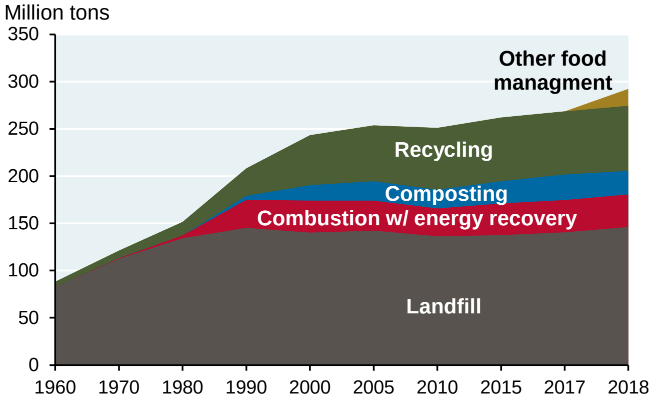
It's important to understand the scope of potential contributions from decarbonization technologies, even when they make economic sense. A good example: conversion of municipal solid waste (MSW) into energy. MSW can be burned to create heat or electricity using a traditional incinerator->boiler->generator. MSW can also be converted into hydrogen via gasification (see next page). As an alternative, landfill gas from MSW occurs naturally due to anaerobic decomposition and can be captured through a system of wells and blowers/vacuums; ~20% of US landfills capture gas for flaring or for energy use as renewable natural gas. Several countries in Europe (Aus, Den, Fin, Ger, Ita, UK) use biogas at amounts above 1 GJ per capita. In 2019, Denmark and Germany biogas use reached 15%-20% of their natural gas consumption.

Converting MSW to heat, electricity or fuel can be worthwhile since the energy and cost required to aggregate it has already been expended, and since landfills would otherwise release methane into the atmosphere as they decompose. But its potential contributions are modest, as we illustrate with two exaggerated scenarios.

Incineration scenario. If ALL recoverable (non-recycled) US solid waste were incinerated to make electricity[38], it could provide ~2.1% of US electricity, 0.8% of primary energy and reduce GHG emissions by 0%-3%, depending on the assumption used for tons of methane produced by each ton of decomposing MSW[39], and depending on the assumption used to convert methane into CO_2 equivalents[40].

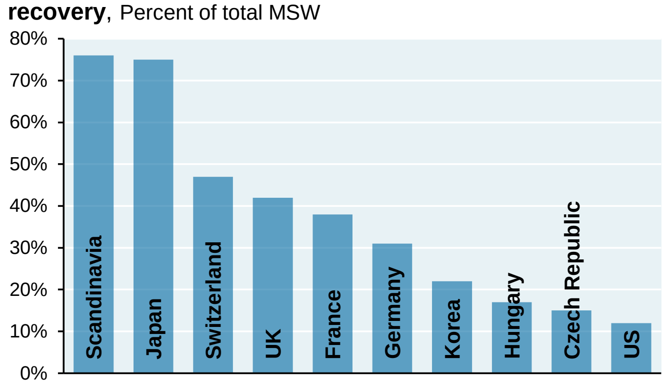
Of course, actual MSW yields from incineration would be **lower** than these figures since this scenario assumes that every ton of non-recycled MSW is converted to power with no frictional losses, impediments or constraints. That's a brave assumption when only ~10% of US MSW is currently incinerated for energy recovery. Countries with higher MSW incineration are often denser with fewer landfill options (Japan, Switzerland). Furthermore, CO_2 in MSW incineration flue gas is dispersed, which can require more than 50% of the power produced to capture if "green" electricity is the goal. MSW incineration also involves substantial hazardous waste issues[41].

US municipal solid waste management
Million tons



Source: EPA, JPMAM. 2018.

Share of municipal solid waste incinerated for energy recovery, Percent of total MSW



Source: EIA. October 31, 2022.

[38] 64 active US MSW incineration plants generate an average of 486 kWh per ton of MSW [Source: EIA, 2021]

[39] The IEA estimates 50 to 100 kg of methane per tonne of decomposing MSW; 70 kg is the median assumption. Estimates derived from EPA data are lower, around 27 kg of methane per tonne of MSW. These two figures account for the emissions reduction range cited above

[40] Methane's higher global warming potential than CO_2 is addressed by applying a multiple to methane emissions to convert them into CO_2 equivalents. We use 25, the multiple cited by the EPA on methane's higher global warming potential over 100 years, and which is cited by the UN Framework Convention on Climate Change

[41] Incineration of 1 tonne of MSW produces 15-40 kg of hazardous waste which requires treatment (dioxins, furans, cadmium, arsenic, mercury), and produces bottom ash as well. Developed countries cleaned up incineration through "extended producer responsibility" rules on E-waste, but that has resulted in **increased export of E-waste** to the developing world [Energy Sustainability and Society, November 2018]

Gasification of MSW. Gasification technology has been around for a long time, but has not been applied widely to MSW. MSW incineration involves high-temperature burning (rapid oxidation) of hydrocarbons, while gasification harnesses hydrocarbons using heat, steam and/or controlled amounts of oxygen. At temperatures exceeding 1000°C in a gasification vessel, MSW can be converted into a syngas rich in hydrocarbons. This gas can be further processed to boost hydrogen yield. In some gasification approaches, metals are not oxidized which makes them easier to recycle, while in others they are separated before the gasification step.

There is no "magic CO_2 bullet": gasification produces hydrogen but also produces the same amount of carbon dioxide per ton as MSW incineration. The difference: carbon from incineration is a combustion by-product, while gasification produces a chemical CO_2 that is separated and captured within the process. This can substantially lower the cost and complexity of carbon retrieval from gasification. To be clear, hydrogen from gasification is only green if carbon byproducts are then sequestered or utilized. In the next section on CCS, we discuss the advantages of concentrated and separated CO_2 streams in flue gas.

Gasification scenario. If ALL recoverable US solid waste were converted into hydrogen using gasification[42], it could replace the hydrogen the US currently obtains via steam methane reformation of natural gas and coal, which is equivalent to ~1.2% of US primary energy. But this is **not a sensible use case** to think about: most hydrogen production via SMR is co-located with the facilities that use hydrogen for oil refining (desulfurization of gasoline), or for ammonia production used in fertilizer. Hydrogen from MSW locations would have to be transported long distances to these industrial facilities, which is expensive. Green ammonia/hydrogen for long haul shipping has its challenges as well[43].

As a result, presumed use cases for hydrogen via gasification of MSW would have to include a range of local demand clusters. This could include local demand for green urea for fertilizer production, green ammonia or methanol, stationary fuel cells for fast charging for EVs (this would require buildout of hydrogen distribution networks through pipelines or trucking) and direct fueling of hydrogen powered long haul trucks, if they ever get commercialized. Hydrogen truck maker Hyzon Motors stopped filing financial statements with the SEC in Q1 2022 (I didn't know that was allowed) after delivering 87 units in 2021, and the former CEO of Nikola Motors was convicted of securities fraud in October 2022 for statements made regarding Nikola's hydrogen truck business. There are 50 hydrogen trucks on the road in Switzerland as part of Hyundai's pilot, and Hyundai plans to deliver another 27 to Germany.

Bottom line: MSW energy recovery makes sense and merits the support it gets in the energy bill[44]. While its contribution to green electricity, heat or hydrogen is likely to be very modest at a national level, it could play a role in boosting local energy security and reduce stress on other energy infrastructure.

In contrast to energy conversion from MSW, solid biomass energy from wood pellets is way more contentious and possibly suspect as a presumed source of renewable energy, as we explain next.

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[42] Assuming 50-60 kg of hydrogen per ton of MSW via gasification on a net basis (net of the hydrogen required to power some of the intermediate processes)

[43] **Green ammonia**: ammonia has a hydrogen content of 17%, an existing distribution network, is liquefied at higher temperatures (-33°C) than hydrogen, has higher volumetric energy density vs other alternatives and lower energy losses when transported over long distances. That's the good news. Hydrogen in ammonia could then be released through catalytic decomposition, or ammonia could be used in a fuel cell designed for it. However, all these conversions carry energy penalties: in transport, round-trip efficiency of liquid ammonia produced from green hydrogen may be just 11%-19%.

[44] Biogas: investment tax credits; renewable natural gas: alternative fuel credits

Europe: not quite as green as it looks

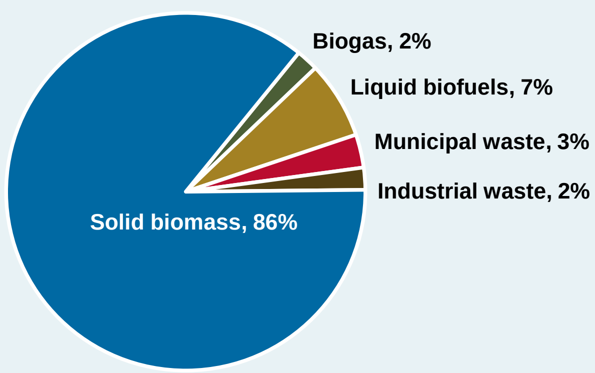
As shown in the first pie chart, MSW is a small portion of global bioenergy utilization. The vast majority is still "**solid biomass**", a category which includes forest residue, wood chips, wood pellets, sawmill residue and construction scrap. **The emissions mitigation and biodiversity impact of solid biomass is a hotly debated topic among climate scientists**. On one end of the spectrum[45], there's some agreement that removal of fine woody debris from deciduous and coniferous trees is a "good" source of solid biomass. At the other end of the spectrum, conversion of naturally regenerating forests to monoculture or polyculture plantations is considered a very "bad" source. In between: stump removal, grassland afforestation and afforestation of agricultural land.

Europe is deploying a lot of wind and solar power, but biomass is still a material part of Europe's renewable energy mix. The numbers are murky since EU/IEA and BP data differ substantially. According to the EU/IEA[46], 63% of the EU28 renewable energy mix in 2019 came from bioenergy, around two thirds of which was solid biomass (the rest was biofuels and MSW). Using BP data, the bioenergy share was 21% in 2019 and 19% in 2022. Either way, the EU28 still uses a lot of solid biomass for electricity, residential and commercial heat and industry energy. Europe produces more than half of the world's wood pellets, and imports even more. As explained above, not all wood pellets are equal regarding climate impact; it depends on the source.

William Schlesinger of Duke University's Nicholas School cites an example of the controversy on wood pellets: a 50-MW power plant burning wood pellets would emit 43,730 tons of CO_2 each year, whereas the same plant burning coal would emit 39,200 tons per year. The difference stems from the lower energy content of wood, so you need to burn more of it.[47] It would then take many years for new tree growth to recapture the difference.

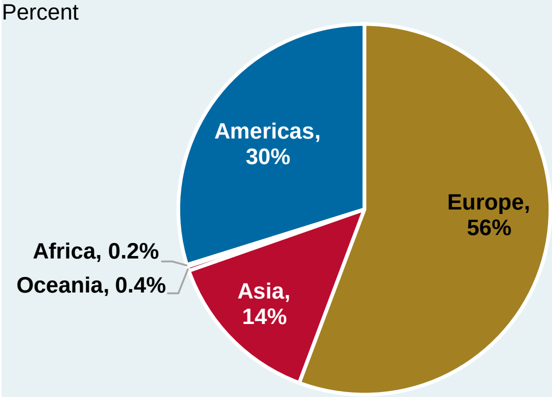
That might be why 500 scientists wrote a letter to the EU Commission in 2021 asking for an end to biomass subsidies[48]. Separately, the European Academies Science Advisory Council believes that replacing coal with wood pellets to generate electricity increases "atmospheric levels of carbon dioxide for substantial periods of time"[49], and a 2018 study from MIT's John Sterman came to similar conclusions. Even so, the European Parliament voted last September to still define woody biomass as renewable. As a result, smokestack CO_2 emissions from burning wood pellets are treated in the EU as if they simply didn't exist.

Global bioenergy supply, 2020
Percent



Source: World Bioenergy Association. 2022.

Wood pellet production, 2021
Percent



Source: World Bioenergy Association. 2022.

[45] "*The use of woody biomass for energy production in the EU*", European Commission, 2021. See page 9 ex.

[46] "*Implementation of bioenergy in the European Union, 2021 update*", IEA Technology Collaboration Program. Part of the reason: EC/IEA data does not use thermal conversion assumptions for renewables and nuclear, as BP does. But there's also a large amount of biomass use in the EU data that BP does not include.

[47] "*Smoke, mirrors and wood pellets*", William Schlesinger (Duke), February 22, 2022

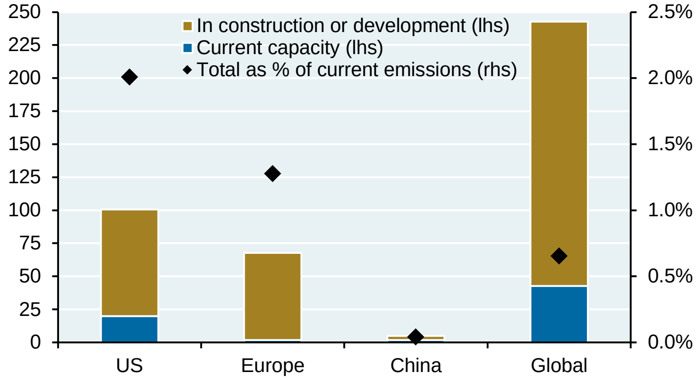
[48] "*Letter regarding use of forests for bioenergy*", February 11, 2021

[49] "*EASAC open letter to IEA Bioenergy*", European Academies Science Advisory Council, May 13, 2020

[7] CCS proposals in, mostly thrown out: the hit rate of planned carbon capture & sequestration projects has been low, but that may change (a little) with new incentives and economies of scale

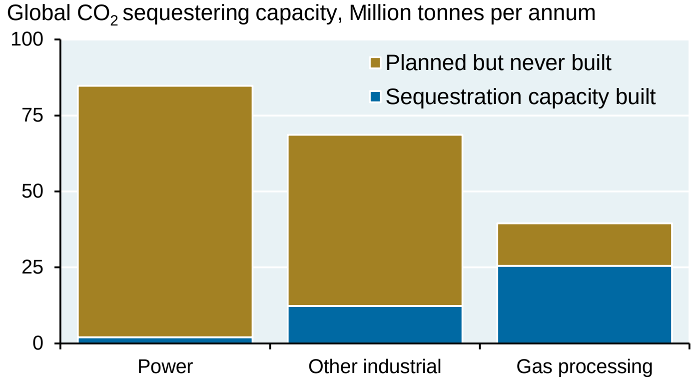
I've written in the past that the highest ratio in the history of science is the number of academic papers written on carbon sequestration divided by actual carbon sequestration. According to Global CCS Institute data compiled in mid-2022, Europe and the US were on track to sequester just 1.5%-2.0% of their current emissions by 2030, and that includes projects still in development. China's CCS targets were even lower.

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



Source: Global CCS Institute, OWID, JPMAM. 2022.

CCS ambitions have fallen well short of reality
Global CO_2 sequestering capacity, Million tonnes per annum



Source: *"Explaining successful and failed investments in U.S. carbon capture and storage using empirical and expert assessments",* Abdulla et al., 2021.

The track record of carbon sequestration has been very mixed. A 2022 report from the Institute for Energy Economics and Financial Analysis[50] covered 13 of the world's biggest projects, accounting for more than half of global carbon capture capacity. According to IEEFA, only half the projects met their sequestration targets.

Similarly, a 2020 study found that around half of 39 CCS projects attempted in the US failed to meet targets[51]. Some projects spent resources on front end engineering and design but were terminated before completion; others failed after inception and were abandoned or reconfigured without CCS; and others are in operation but sequester CO_2 below targets. The same study found that **on a global basis, 80% of planned CCS projects were never built.** As shown above (right), only gas processing CCS projects had a high completion rate. Larger projects failed more often, as did first-of-a-kind CCS systems. A success factor in the study: credible revenues in the form of bilateral offtake agreements for CO_2, usually for use in Enhanced Oil Recovery (EOR)[52]. According to Global Data, 74% of active CCS facilities are incentivized by the economic value generated from EOR.

And then there's the forbidding carbon infrastructure math: sequestering just 15% of current US CO_2 emissions would require CCS infrastructure whose throughput volume is greater than the volume of oil flowing through the entire US distribution and refining system[53], a network which took over 100 years to build. Without viable after-markets for CO_2 which face very challenging thermodynamic realities (see page 39), the processing and pipeline requirements needed for CCS to make a dent are staggering.

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[50] "*The Carbon Capture Crux*", IEEFA, Robertson and Mousavian, Sept 2022

[51] *"Explaining successful and failed investments in U.S. carbon capture and storage using empirical and expert assessments",* Abdulla (Carleton) et al., Environmental Research Letters, December 29, 2020

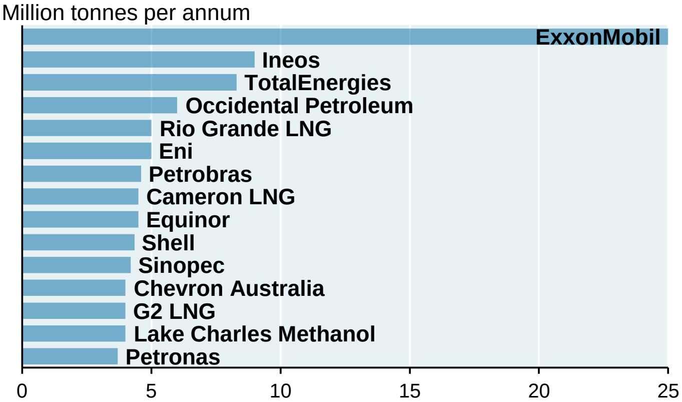
[52] Gas injection using natural gas, nitrogen or CO_2 accounts for 60% of EOR in the US, with thermal (steam) injection accounting for the remainder. Only 20% of CO_2 used for EOR is captured from processing plants or power plants; the majority of CO_2 used for EOR comes from naturally occurring underground reservoirs

[53] 15% of US CO_2 emissions = 0.75 bn tonnes of CO_2 by weight, and **0.94 bcm** of CO_2 by volume assuming 800 kg of CO_2 per m^3 (supercritical treatment). That's more volume than 2021 US distribution and refining of 0.71 bn tonnes of crude oil, whose volume would be **0.82 bcm** assuming oil density of 870 kg/m^3

Some of my colleagues are more optimistic on CCS now that large oil/industrial companies are involved, building sequestration projects as a service. Around 30 US oil, gas and petrochemical projects announced new CCS add-ons and greenfield projects to take advantage of the \$60-\$85 per tonne tax credit for sequestered CO_2 in the energy bill. Rystad Energy projects 3x more global sequestration volume by 2030 than the CCS Institute, although that would still be just 2% of global CO_2 emissions, and they already estimate that one third of the projects will be delayed. Rystad also tracks pilot projects based on *utilization* of CO_2 (for industrial products, concrete, fuel and chemicals) rather than for sequestration or EOR. This is currently a very small market, consuming ~230 million tonnes per year of CO_2, or 0.6% of global emissions.

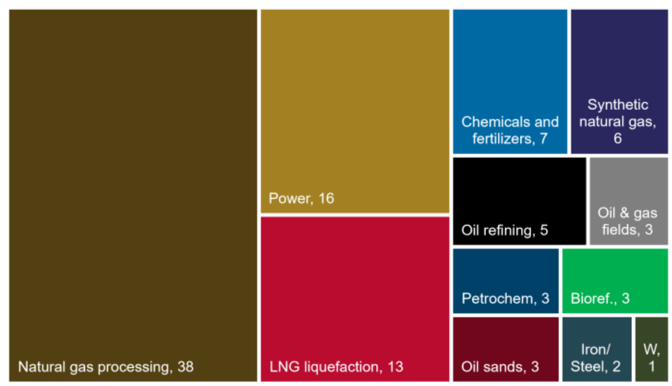
There are possible breakthroughs: Pacific Northwest National Laboratory announced a technique to capture factory emissions at \$39 per tonne vs \$55-\$60 using current state of the art technology (the revised approach needs 2% water rather than 70%, reducing costs by requiring less heat to boil a smaller amount of water). Something to watch: Net Power plans to build natural gas plants with CCS technology to capture 97% of CO_2 generated, using supercritical CO_2 rather than steam to drive the turbine (its funders include Occidental Petroleum, 8 Rivers and Constellation Energy).

Current and projected CCS capacity
Million tonnes per annum



Source: Global Data, EnergyMonitor.AI. 2020.

Active global CCS capacity by industry, %, 2022
Source: Global Data, Energymonitor.ai. W = Waste-to-Energy



Some industrial companies already know how to separate carbon from gas streams since it's required in urea plants, coal-to-chemicals and gas processing. They currently release the CO_2 rather than capturing and storing it permanently. But even if they finance CCS with the help of tax credits, it can take 5-6 years to get Class VI permits for underground sequestration from the EPA. Also: infrastructure and storage capacity required is often much greater than the needs of any single emitter; CCS hubs would be needed so that emitters could share the cost of transport and storage, and creating them is complicated.

Bottom line: CCS project hit rates may rise but their aggregate contribution is likely to be small

There are three critical variables in play:

- Proximity to good sequestration locations such as the US Gulf Coast (high storage density due to shallow, high porosity and high permeability aquifers), bringing down pipeline and injection costs
- High concentration and pressure of CO_2 in flue gas streams, which reduces CO_2 capture costs
- The share of each sector as a % of total industrial emissions, as a measure of materiality

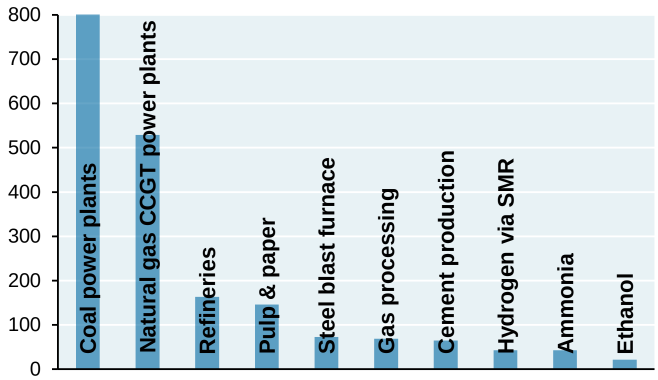
As shown on the following page, ethanol and gas processing plants have very high concentrations of CO_2 in flue gas streams but represent smaller shares of US industrial emissions. The elephants in the room are power plants which account for ~70% of industrial emissions, but they've got among the *lowest* CO_2 concentrations. So, unless there are new commercialized technologies to capture power plant emissions profitably with a subsidy of \$85 per tonne, and unless large numbers of these power plants are located near viable sequestration locations, the US may remain on target to sequester just 2% of its emissions by 2030.

What about synthetic fuels derived from CO_2? There's a lot of research on possible conversion methods, but no major breakthroughs so far. This will be a topic for another year. To summarize: **CO_2 is an inert low-energy molecule that requires a lot of energy to break apart**. This causes poor adsorption of CO_2 on the surface of a catalyst, which is why it's difficult to obtain fuels from chemical conversion and when using enzymes in biological conversion as well. A recent paper summarized many ideas being investigated[54]. Some are chemical (catalytic hydrogenation, photocatalytic and electrochemical conversion) and some are biological (photosynthesis, non-photosynthesis and bio-hybrid conversion). The paper concluded that the search for a highly active, stable and cost-effective catalyst is a work in progress. If anything ever changes, we will write about it here.

CCS Exhibits

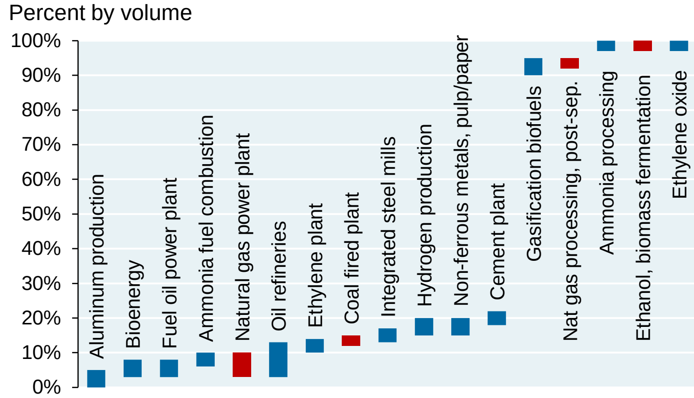
Gas and coal power plants account for the largest share of US industrial emissions but have among the lowest CO_2 concentrations, resulting in higher capture costs per ton. Capturing CO_2 from flues with 15% concentrations can be impaired by contaminants (sulfur, mercury, fly ash, etc) that negatively affect CO_2 capture catalysts.

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



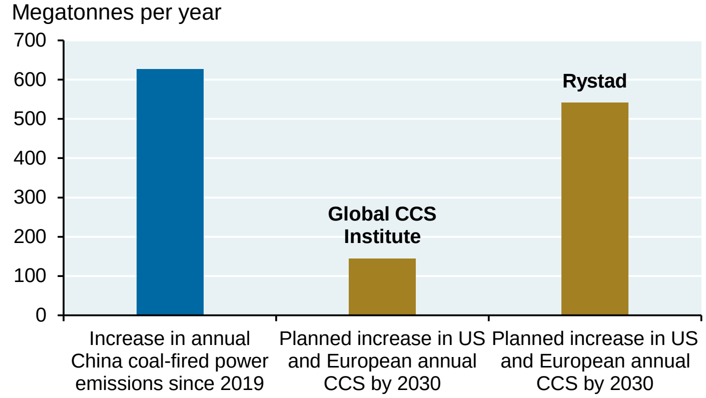
Source: IPCC, Swedish Env. Research Institute, Penn State, JPMAM. 2022.

I can be convinced that learning curves will reduce some CCS costs, and that there could be breakthroughs on solid adsorbents or membranes that react with CO_2. But to reiterate, the US infrastructure math cited earlier suggests that the overall CCS impact will be very modest…and then there's China, whose increase in annual coal-fired power emissions since 2019 is larger than all new US and European annual sequestration planned for 2030.

China: CO_2 emissions from coal fired electricity generation
Gigatonnes per year, rolling 12 months

Source: Ember, JPMAM. December 2022.

US / European CCS ambitions vs China coal emissions
Megatonnes per year



Source: Ember, Global CCS Institute, JPMAM. 2022.

[54] "*Conversion of carbon dioxide into fuels*", Journal of CO_2 utilization, Okoye-Chine (VCU) et al, August 2022

[8] California Dreaming: the improbable reveries of electric planes, nuclear fusion, space-based solar power, direct air carbon capture and fully autonomous car networks

Each idea below has been shown to work in preliminary field testing, in a lab setting or in a conceptual model. My purpose here is not to dispute their technical feasibility; it is to explain why none of them should be expected to make a meaningful contribution to decarbonization in the next decade or more.

Electric planes

Once you factor in energy density and reserve requirements (the need to circle an airport in a delay or fly to another airport 60 miles away in an emergency), electric planes with 20-100 seats would be able to travel for only 6-30 miles[55]. International Council of Clean Transportation analysts found that even with a substantial improvement in battery energy density from today's levels, such a fleet would offset less than ~1% of total aviation emissions; the authors "were surprised by how terrible the range actually was"[56]. Other studies have come to the same conclusion regarding the impact of decarbonizing short trips: **while trips less than 200 miles are plentiful by number of *departures*, they represent less than 5% of aviation *emissions*[57]**.

Even after accounting for the higher efficiency of electric motors, the effective energy density of traditional planes is still 22x higher than electric planes[58]. Safety and certification issues would also have to be met, and delays in Eviation and NASA X-57 prototypes are a sign of how hard this is to achieve. In 1909, the Wright brothers delivered an airplane to the US government capable of carrying 2 people for 70 miles; that's the same capability of certified battery powered planes today (the modern versions are stable in flight with modern controls and safety systems, and are used for training). One analysis cited the ideal use case for small electric planes as remote regions in Norway or the Orkney Islands in Scotland, since there are no land-based alternatives. **Prospects: grounded until further notice.**

Nuclear fusion

A December 2022 fusion experiment generated more energy than it consumed, with 2 MJ of energy in and 3 MJ out. But it took 300 MJ of energy to power the lasers which produced the energy inputs, and even more energy to power cooling systems and computers. Also: the experiment was fired once at a single target, and can only do so once a day; it required equipment housed in a building that's the size of a football field; and it generated enough energy to boil a tea kettle or run a hair dryer for 15 minutes. Other problems: release of fusion energy destroys surrounding instruments and mirrors; commercialized fusion would require multiple pulses per second (not just one per day) and without all the damage; fusion actually depends on fission reactors for tritium fuel; and any fusion energy balance must also account for the energy required to build a 400,000 ton facility, as in the case of ITER in France.[59]

US Energy Secretary Granholm stated a goal of commercial fusion in the next decade. I don't think the Biden administration has any basis for this projection, other than hopium repeated by fusion's true believers and investors. Fusion as a practical source of limitless electricity is at "about the same stage of technology readiness as in 1978"[60]. Fusion appears to be decades away, if it can be done at all. **Prospects: not in my lifetime**.

[55] "*This is what is what's keeping electric planes from taking off*", MIT Technology Review, August 2022

[56] "*Performance analysis of regional electric aircraft*", Mukhopadhaya and Graver, International Council on Clean Transportation, July 2022

[57] "*The potential of full-electric aircraft for civil transportation*", Staack et al (Linkoping University/Sweden), CEAS Aeronautics Journal, 2021, see Figure 4

[58] Assumptions: electric motor efficiency 90% vs jet combustion efficiency 33%; jet fuel energy density 43 MJ/kg vs lithium ion energy density of 0.97 MJ/kg plus 150% improvement; empty plane wt = 54% of take-off wt; cargo+passengers = 21% of take-off wt; electric plane useful load is 70% of jet due to lack of fuel shedding

[59] "*The Quest for Fusion Energy*", Daniel Jassby (Princeton Plasma Physics Laboratory, retired), May 2022 Inference Quarterly Science Review

[60] "*Fusion Mania*", John Deutch (MIT, US Energy Advisory Board), Joule, April 2023 forthcoming

Space based solar power

It's always sunny in space, with 3x-50x more solar energy than on earth. But to harness that solar power: robots would have to assemble solar panels in outer space; multiple costly launches would be needed for each space station, leaving each project with a large emissions deficit upfront; space debris could damage panels requiring space-based repair; panels would be exposed to constant radiation, affecting lifespan and performance in unknown ways; space solar power would have to be converted to microwaves and back at just 40% efficiency; heat shedding is needed, which is difficult in space; all resulting in efficiencies of just 25%-35%. According to one treatise on space solar, its cost could be three orders of magnitude higher than terrestrial equivalents[61].

China aims to have a system operating by 2035, although I think it's fair to wonder if it's an energy system or a weapons system. The UK aims for 2040: a 2,000 pound satellite taking up an entire square mile in space, and a terrestrial antenna that requires a piece of land that is 4 miles by 8 miles. Antenna cost alone: $1 billion for 5 GW. The European Space Agency and NASA are working on this as well, but each satellite would be 10x heavier than the International Space Station, which weighs 450 metric tons and which took three decades to build in low Earth orbit. A paper from the Colorado School of Mines estimated that costs would have to decline by 94% from an original 2012 estimate to make sense. Space solar is not *infeasible* like the fictional transporter system on the USS Enterprise, just really, really *expensive*. **Prospects: cloudy with a chance of failure**.

Direct air carbon capture (DACC)

Two years ago, I cited a DACC paper concluding that it was "an energetically and financially costly distraction in effective mitigation of climate changes at a meaningful scale"[62]. The authors' conclusion was based on the energy required to produce the aqueous hydroxide solution that reacts with CO_2 and the energy needed to regenerate it, plus energy required to compress CO_2 and store it underground.

There are new US DACC subsidies of $180 per ton and lots of startups, but I'm not sure much has changed yet. CO_2 only makes up 0.04% of the atmosphere, requiring more energy to capture than CO_2 from flue gas. If estimates from the World Resources Institute are right, DACC requires ~2,200 kWh per ton of CO_2…so to capture 10% of US emissions, it would take 1.2 trillion kWh, or ~30% of US electricity generation. A 2022 update from UC Riverside[63] found that CO_2 capture using liquid solvents requires 1-13 tons of water per ton of CO_2, and estimated DACC costs at $250-$1,000 per ton. The higher values reflect use of renewable power rather than fossil fuels to source the energy. Howard Herzog (MIT, author of *Carbon Capture*) highlighted last year that even a modestly sized US DACC industry would effectively consume almost all existing capacity of zero carbon energy.

Mass production may bring some DACC costs down. Occidental is building one of the world's largest DACC plants in the Permian Basin to capture 1 mm tons per year, and plans to build 100 by 2035 (100 mtpa = 0.27% of global emissions). Roughly four DACC 1 mm ton plants would have the same annual CO_2 benefit as Tesla's 2022 production compared to ICE cars[64]. But Occidental is still building their first plant, and the project's original budget has already been revised up by 15%. Let's wait and see how this goes before extrapolating too much.

A cynic would say that DACC is a way for companies with very small CO_2 footprints to pay huge premiums to offset them[65], generating taxpayer-funded windfalls for DACC companies whose contributions to emissions reductions will end up being negligible. **Prospects: irrelevant without a sea-change in technology**.

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[61] "*Space based solar is not a thing*", Casey Handmer (Caltech), August 2019. Casey is a polymath who provided valuable guidance, insights and data for this section and others in this year's paper

[62] "*Unrealistic energy and materials requirement for direct air capture in deep mitigation pathways*", Chatterjee and Huang, Nature Communications, 2020

[63] "*Current status and pillars of direct air capture technologies*", Ozkan et al, iScience, April 2022

[64] Assuming 3.0-3.5 tonnes of CO_2 savings per vehicle per year vs an ICE car, and 1.3 mm units sold by Tesla in 2022. Sources: European Federation for Transport & Environment, US EPA

[65] Climeworks does not disclose what it charges Microsoft, Stripe and Shopify per ton of CO_2 via DACC; published reports indicate at least $600 per ton, with the company aiming to reduce it to $500 by 2025

Fully autonomous passenger car networks reducing emissions

According to the MIT-IBM Watson AI Lab, self-driving cars could reduce fuel consumption by 18% and reduce CO_2 emissions by 25%[66]. The benefits would allegedly result from an optimized network that avoids stop-and-go traffic. Intel famously projected a $7 trillion autonomous car market opportunity in 2017, GM projected mass production of fully autonomous vehicles by 2019, Lyft said in 2016 that half its rides would be self-driving by 2021 and Ford also mentioned 2021 as a mass production date.

So, where are all the self-driving cars? After $100 billion spent according to McKinsey, there's little progress so far. Some automakers have scaled back their ambitions, while Ford and VW pulled the plug on their self-driving car efforts completely. Waymo now says it will take decades before autonomous vehicles are widely used, and a basket of LiDAR scanning stocks has collapsed by 80% since its peak.

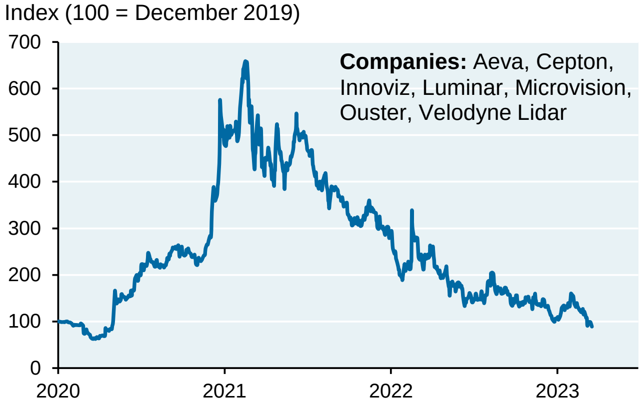
Years of testing reveals there are still too many unpredictable "edge cases" for autonomous cars to figure out. Today, self-driving cars are mostly confined to places in the Sun Belt since they still can't handle adverse weather very well, and struggle with construction, animals, traffic cones, crossing guards and "unprotected left turns" involving oncoming traffic. One video shows a Waymo car so confused by a traffic cone that it drives away from the technician sent to rescue it. One of the industry's earliest advocates scaled down his ambitions to focus on **autonomous trucks for industrial sites**, since that's what the technology can now handle best.

For all their faults, humans are pretty good drivers: one traffic death per 100 million miles driven as per NHTSA data (bus drivers are even better at one fatal crash per 500 million miles). It's also unnerving that some autonomous car companies reportedly run simulations inside data centers and count the results as "road miles driven". The hype on this idea got ahead of itself; vehicle autonomy one can find today is mostly confined to Level 2 features such as emergency braking, traffic warnings and steering assistance (vs Level 5 full autonomy).

What about Tesla? 400,000 Tesla customers pay extra for something Tesla calls "Full Self Driving" features. The California DMV sued Tesla for misleading advertising, claiming that Tesla features are really just Level 2 features such as steering, lane following and break/acceleration support. Whatever their level, these features apparently work well. According to Tesla's self-reported data shown below, its autopilot technology avoids a lot of accidents and appears way ahead of the closest competitor. That said, Tesla has issues too: in Full Self Driving mode, one of its cars encountered a person holding up a stop sign in the middle of a road. The car failed to recognize the person (partly obscured by the stop sign) and the stop sign (out of its usual context on the side of a road); the human driver had to take over since the experience was outside of the training dataset[67].

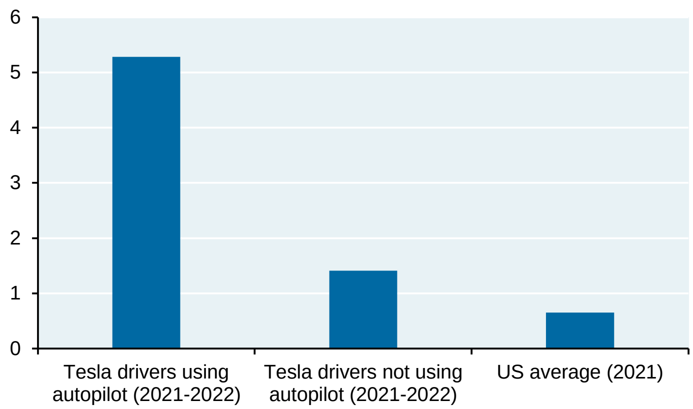
Prospects: optimized large-scale traffic networks governed by self-driving vehicles work great in Disney's Wall-E and the Jetsons, but are not in our near-term future.

LiDAR stock basket
Index (100 = December 2019)



Source: Bloomberg, JPMAM. March 20, 2023.

Million miles driven before a car accident



Source: Tesla, Department of Transportation, JPMAM. Q4 2022.

66 "*On the road to cleaner, greener, and faster driving*", MIT News, May 2022

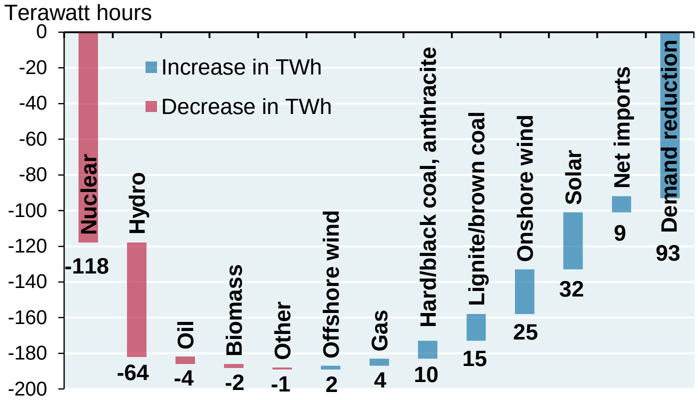
67 "*AI Platforms like ChatGPT Are Easy to Use but Also Potentially Dangerous*", Scientific American, Dec 2022

Epilogue: How Europe survived the winter of 2022 and what comes next for Russia/China

A few months ago, some projections for Europe were dire: a possible €2 trillion energy cost hit to EU consumers. The net cost now looks like €0.5 trillion instead. In this section we look at the details, implications for coal, where Russia/China go from here and the issue of energy subsidies. Primary European survival factors:

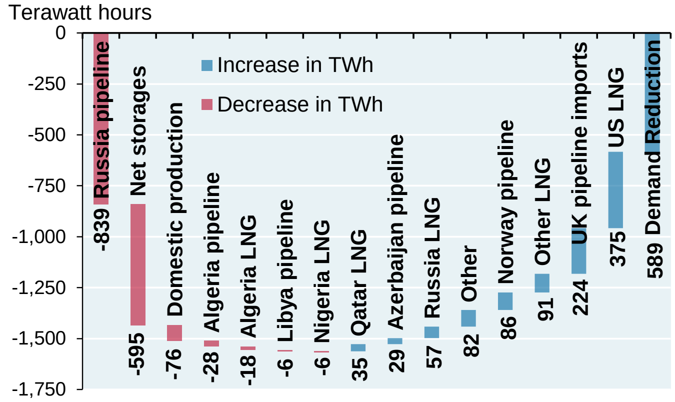
- *Stimulus*. Fiscal stimulus, windfall profits taxes, natural gas price caps and subsidies (see page 44)
- *Weather*. One of the warmest winters in the Northern Hemisphere in the past 50 years
- *Massive demand destruction*, which are the largest bars in both charts below. Is demand destruction sustainable? A lot of articles have been written on "European deindustrialization" since last fall. That's the kind of thing that can only be measured over long periods of time, but it will be something to watch
- *More renewables, increased use of coal and drawing down gas storage*. China's COVID lockdown reduced its LNG demand, which allowed Europe to enter the winter with natural gas storage over 90%+. Germany ended the winter with 70% gas storage instead of its 30% average
- *Electricity pricing policy changes*. Europe altered a pricing mechanism in which wind, solar, hydro, coal and nuclear power producers were paid the same price for electricity as power producers using natural gas. Why the change? Fossil fuel producers set marginal prices most of the time in Europe (see table), and when natural gas input prices soar, the marginal price for electricity was paid to *all* power producers. European countries have now implemented electricity price caps that effectively reduce windfall profits of non-gas electricity producers when gas prices spike

Change in EU electricity generation: 2021 vs 2022
Terawatt hours



Source: ICIS. 2022.

Change in EU natural gas supply mix: 2021 vs 2022
Terawatt hours



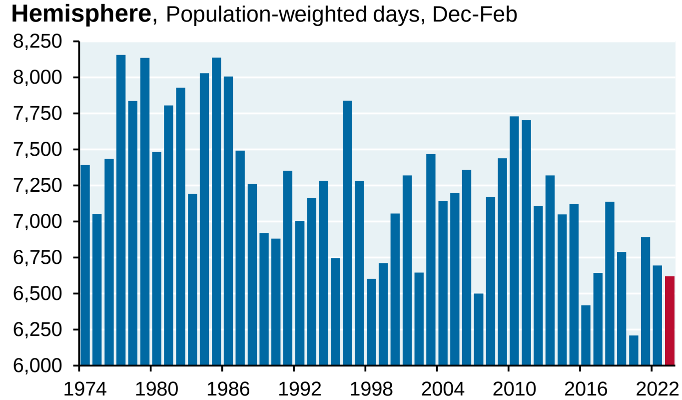
Source: ICIS. 2022.

How marginal electricity prices are set in Europe
% of all hours

Country	Fossil fuel	Non-fossil	Imports
Germany	91%	7%	2%
Denmark	25%	13%	62%
Spain	89%	6%	5%
France	7%	93%	0%
Ireland	61%	1%	38%
Italy	86%	11%	3%
Greece	77%	0%	23%
Portugal	87%	13%	0%
UK	84%	1%	15%

Source: *"Energy Transitions in Europe - Role of Natural Gas in Electricity Prices"*, Zakeri et al. July 23, 2022.

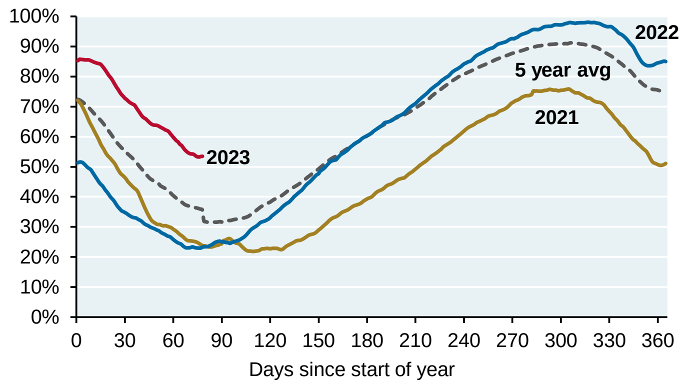
Historical heating degree days in winter for the Northern Hemisphere, Population-weighted days, Dec-Feb



Source: J.P. Morgan Global Commodities Research. February 16, 2023.

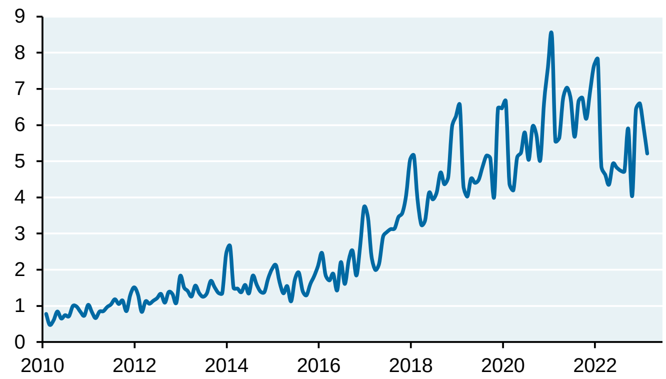
While the worst is probably over for Europe's energy crisis, the region will still emerge as having very high import dependency, higher costs of energy than the US and impediments to industrial activity. Companies such as BASF, Dow, Trinseo, Lanxess and ~50% of all chemical companies still intend to cut jobs and investment in Germany given higher energy costs, with some planning a move to the US. Another example: European aluminum smelter curtailments peaked in late 2022 at 30% of production, and less than 5% have come back online since despite falling gas prices.

Northwestern Europe natural gas storage
Percent full



Source: Bloomberg, AGSI, JPMAM. March 19, 2023.

China liquefied natural gas imports
Tonnes, millions

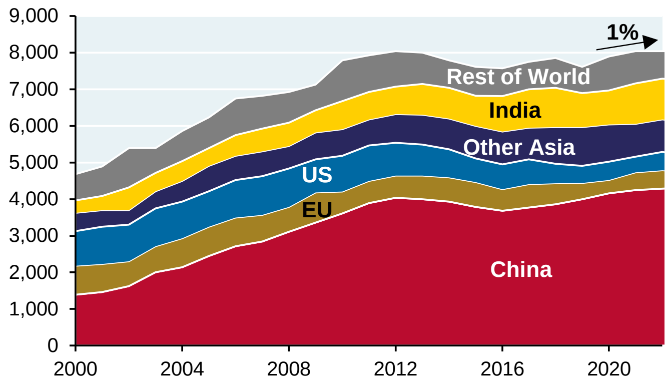


Source: Bloomberg, JPMAM. February 2023.

Global coal consumption is not falling but it's also not soaring

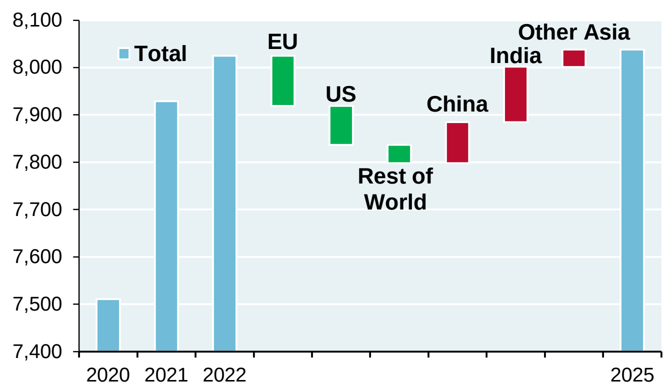
Some analysts cite a ~6% increase in European coal use following its boycott of Russian pipeline gas, and new all-time high levels of global coal use. **Technically, that's true**: global coal use in 2022 rose to an all-time high. **However**, this all-time high was only 1.2% higher than in 2021, and only 1% higher than the prior all-time high in 2013. Coal is no longer in decline (although it still is in the US), but the impact of Russia's invasion on European coal use is sometimes exaggerated. The IEA expects global coal use to be mostly unchanged by 2025, with China and India increases offsetting declines in the US and Europe.

Global coal consumption
Million tonnes



Source: IEA. 2022.

Global coal use and projections to 2025
Million tonnes

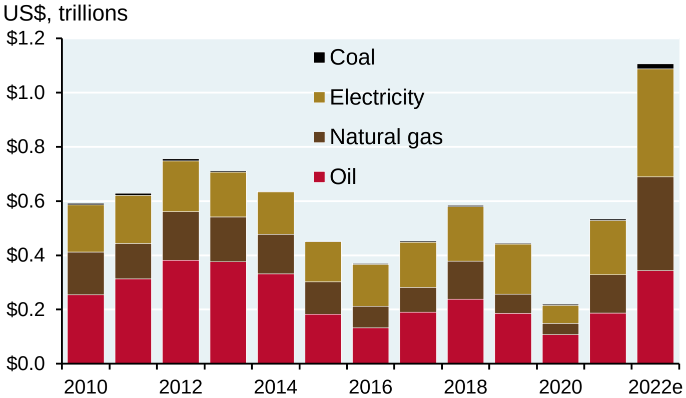


Source: IEA. 2022.

Consumer subsidies provided in Europe are part of a broader discussion on fossil fuel subsidies that are often misunderstood or misinterpreted. When people read headlines such as "Fossil fuel subsidies hit $1 trillion record", they might not know who is providing those subsidies, and to whom. So, I will do that here.

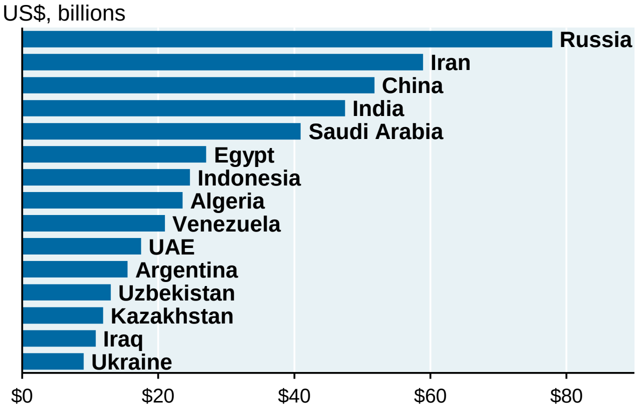
The $1 trillion subsidy figure for 2022 refers to IEA estimates of energy consumption subsidies provided almost exclusively by developing countries to shield citizens from oil, gas, coal and electricity price hikes. The first chart shows the history of these subsidies since 2010, while the second chart shows the largest subsidy providers in 2021. The IEA's methodology: compare prices on international markets to local prices kept artificially low via direct price regulation, pricing formulas, border controls or supply mandates.

Fossil fuel consumption subsidies by type, 2010-2022
US$, trillions



Source: IEA. 2023.

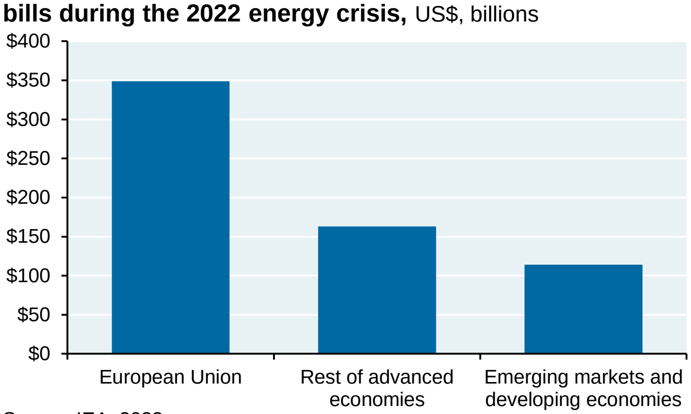
Fossil fuel consumption subsidies by provider, 2021
US$, billions



Source: IEA. 2023.

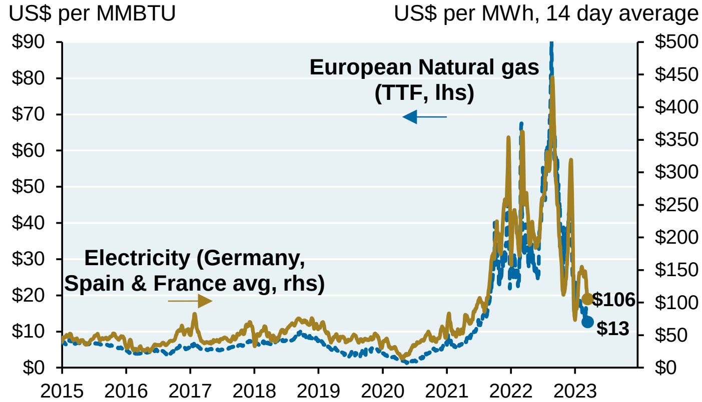
Some emergency spending in 2022 was not captured in the first chart in countries where consumer prices were close to market prices. The IEA estimated these "other consumer measures" at ~$500 billion in 2022, $350 billion of which was spent in Europe whose consumers felt a lot of pain anyway.

Other government consumer measures to reduce energy bills during the 2022 energy crisis, US$, billions



Source: IEA. 2023.

EU gas and electricity prices
US$ per MMBTU
US$ per MWh, 14 day average



Source: Bloomberg, JPMAM. March 20, 2023.

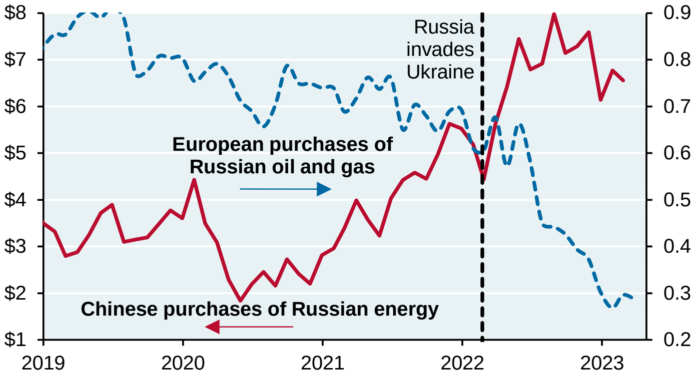
Do consumer subsidies shield energy consumers in developing and developed countries from its true economic cost? Yes. Would removing these subsidies accelerate the renewable transition in a stable and predictable way? Unclear, and the IEA itself states that "**fossil fuel prices are not the best way to drive clean energy transitions**… Imbalanced or poorly sequenced approaches to transitions, in which fuel supply is cut ahead of demand, create clear risks of further price spikes and there is no guarantee that such episodes are unambiguously good for transitions"[68].

[68] "*Fossil fuel consumption subsidies 2022*", IEA, February 2023

A Russia-China partnership "without limits" includes a lot of energy

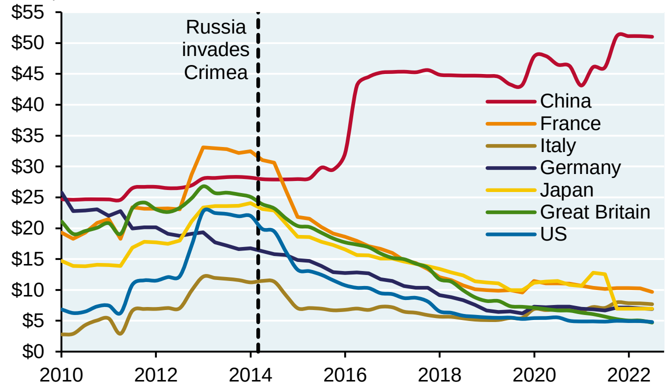
Russia and China announced a "no-limits" partnership before the invasion of Ukraine. Bilateral energy and capital flows are shown below. Other notable trends: a spike in Chinese exports of arms, ammunition, firearm parts and aircraft parts to Russia alongside a collapse in Chinese exports of arms and ammunition to Ukraine.

Chinese vs European purchases of Russian energy
US$, billions Million tonnes of oil equivalent / day



Source: CREA, EIA, GACC, Bloomberg, JPMAM. March 2023.

Cross-border syndicated loans to Russia
US$, billions



Source: BIS. Q3 2022.

Facts and figures on Russia, China and energy:

Natural gas (bcm = billion cubic meters)

- In 2020, Russia sold 175 bcm of gas to Europe and just 4 bcm to China via the Power of Siberia pipeline, which began deliveries in 2019; final phase set for 2025
- China gas imports from Russia are still smaller than from Turkmenistan but are expected to rise. In the first half of 2022, China imports were 7.5 bcm with a 2025 target of 48 bcm and a 2030 target of 88 bcm. Part of the projected long-term increase: Power of Siberia 2, a 50 bcm gas project from Russia to China through Mongolia
- Chinese entities participated as investors, lenders, off-takers and contractors for Russia's Yamal LNG project, allowing Russia to diversify its gas exports

Nuclear and coal

- Russia is participating in construction of 2 nuclear plants in China, and is also China's second largest coal supplier (15% of China imports) after Indonesia

Oil (bpd = barrels per day)

- Russia exported 0.8 mm bpd of oil to China in 2021 and 1.0 mm bpd in 2022, and is China's second largest oil supplier after Saudi Arabia. In 2022, Rosneft agreed to sell an additional 0.2 mm bpd via the Kazakhstan-China pipeline. China and India are part of a shrinking pool of Russian oil buyers; in January 2023, Russian Urals oil was trading at a massive 50% discount to Brent

Appendix: US methane update as more studies show higher leakage rates than reported EPA data

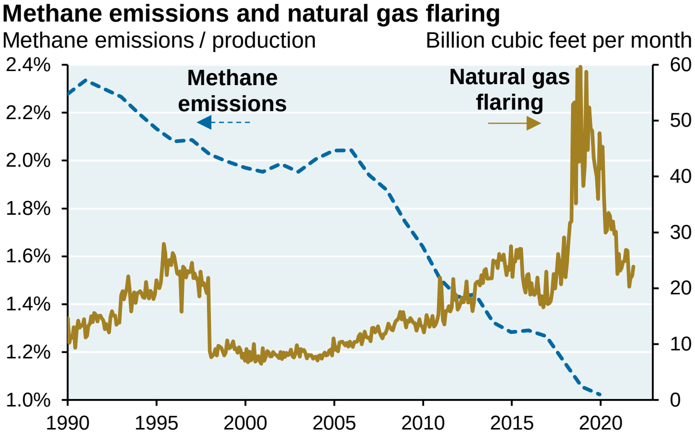
If you accept EPA data at face value, methane leakage from US natural gas operations fell to ~1% in 2020, down from 2.3% in 1990. These rates reportedly include leakage from exploration, production, gathering, processing, transmission, storage and distribution. However, EPA emissions data is usually provided by the oil & gas industry and may not reflect actual operating performance. As a result, climate scientists conduct their own methane leakage measurements. **Their aerial, satellite and other surveillance methods suggest that EPA data underestimates methane leakage rates substantially, with the latest Stanford study showing Permian methane leakage rates that are several times higher than EPA estimates (see table)**.

In a December 2022 Dallas Fed survey, while ~60% of large firms had plans to reduce methane emissions and flaring, only ~40% of smaller firms did. The IEA believes that emission reductions of ~75% are feasible with existing technology, and elevated natural gas prices make methane abatement more economically attractive. A 2023 study in IOP Science concluded that for nearly half of all operators, emissions intensity in the Permian did improve by >50% from 2019 to 2021. Why this is so important: a 2022 study in *Science* found that only 91% of methane is destroyed by flaring rather than the EPA-assumed 98% (a fivefold difference).

I asked Ben Ratner in JP Morgan's Sustainability group for his thoughts on this issue. Ben's comments:

- Reducing methane emissions is the most immediate and cost-effective way oil and gas companies can cut greenhouse gas footprints in this decade, but progress has been uneven and there's low hanging fruit
- Industry leaders have begun to shift from desktop estimation to more accurate measurement (i.e., using sensors on planes/drones), committed to eliminate gas flaring by 2025 and have engaged with regulators
- The US now directly regulates methane as a pollutant under the Clean Air Act and legislates a methane fee, although flaring standards are below what some advocates seek. States like CO, NM and PA instituted tighter requirements for leak detection/repair, flaring minimization and other best practices
- The Oil and Gas Methane Partnership (OGMP) is a collaboration of US and European industry leaders working with civil representatives. Under OGMP's recently defined "2.0" protocols, companies agree to set a methane target, increase methane measurement and report progress annually
- Eliminating natural gas flaring is a common-sense move for companies that want to support energy security and sensibly reduce their carbon footprint, while bringing more product to market. In a 2019 Dallas Fed survey, 70% of respondents cited lack of pipeline capacity as the reason for Permian Basin flaring

Methane emissions and natural gas flaring



Source: EPA, EIA, JPMAM. December 2021.

The gas flaring spike in 2019-2020 appears to be a by-product of an oil drilling boom in regions without adequate gas pipeline capacity, and the frequent practice of granting flaring permits to any developer requesting them. Since 2020, more pipeline capacity has been added and industry operators have been more focused on culling unprofitable operations.

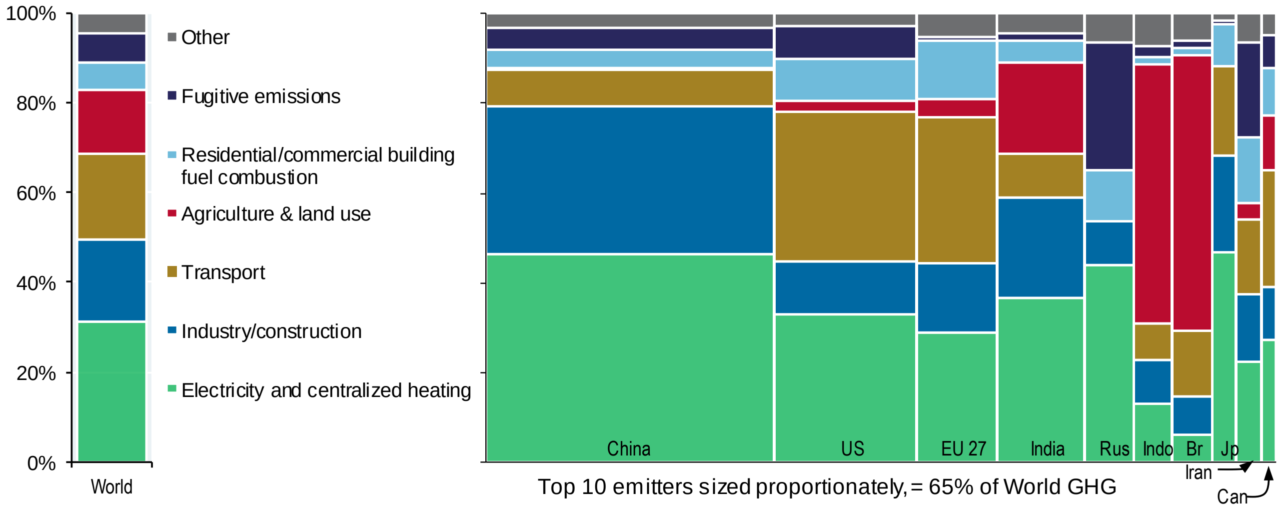
Methane studies (publication, year, lead author)

IOPscience	2023	Hmiel
Half of E&P operators in Permian Basin show > 50% gain in methane emissions intensity from 2019 to 2021		
Stanford	2022	Chen
Permian emissions several times higher than EPA estimates		
IEA	2022	N/A
Methane emissions from the energy sector are 70% higher than the amounts reported by national governments		
Science	2022	Plant
Flaring destroys ~91% of methane not 98%, a 5-fold difference		
ACP	2021	Barkley
Oil/gas methane emissions 48%-76% larger than EPA estimates		
Science	2018	Alvarez
Supply chain emissions are ~60% higher than EPA estimates		
Science	2020	Zhang
Permian Basin methane emissions are over two times higher than inventory-based estimates		

Source: JPMAM. 2023.

Our last chart of the year shows GHG emissions by country and sector, sizing each bar accordingly. The dark blue fugitive emissions bar for the US is one of the larger ones on the page. To the extent that these fugitive emissions are based on EPA-reported methane data and not on higher-frequency empirical measurements cited on the prior page, the US fugitive emissions bar may be substantially understated.

Greenhouse gas emissions by sector & country, % of total



Source: CAIT Climate Data, OWID, JPMAM. 2019.
Global GHG emissions: 76% carbon dioxide, 16% methane, nitrous oxide 6%.

What are fugitive emissions as defined in the chart?

- CO_2 from flaring
- CH_4 from coal mining
- CH_4 from natural gas and oil systems (production, flaring/venting and transmission/distribution)
- CH_4 and N_2O from solid fuels, oil and natural gas, incineration and open burning of waste

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