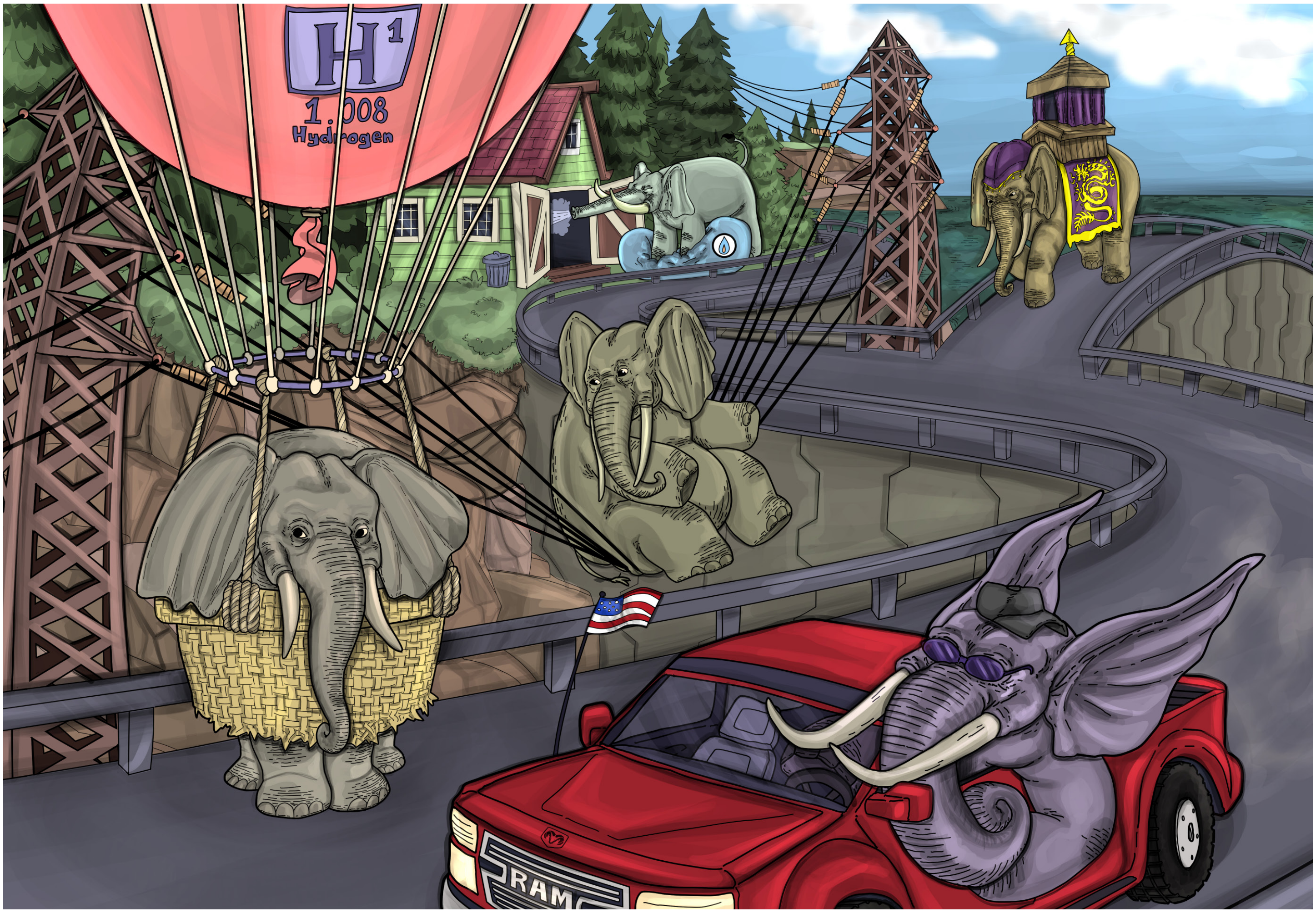
J.P.Morgan



EYE ON THE MARKET | 12TH EDITION

2022 Annual Energy Paper

The Elephants in the Room. We start with a summary of the energy landscape, including the energy crisis in Europe, the recovery in the oil & gas sector and a warning label on industrial electrification and carbon sequestration forecasts. We continue with three topics on electrification, which is the foundation of many deep decarbonization plans: electric vehicle adoption by gasoline super-users, the transmission quagmire and bans on combustion of fossil fuels for heating in favor of electric heat pumps. We then conduct a detailed review of the hydrogen economy, whose liftoff is still many years away. We conclude with deep decarbonization plans for China, whose carbon intensity and emissions levels are the highest in the world.

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

MARY CALLAHAN ERDOES
Chief Executive Officer
J.P. Morgan Asset & Wealth Management

My investment partner Michael Cembalest has released his 12th annual energy paper. It examines the current energy landscape and considers the challenges posed by the transition to a deeply decarbonized world at a time of both worsening climate signals and the increasing need for energy independence. Michael's approach, as always, is focused on the details: the physical, chemical and geological factors that affect how energy is derived and how we use and store it, and the human behaviors that affect energy consumption and distribution. Michael's direct and forensic approach may strike some as signifying acceptance of the status quo. On the contrary: To get where we want to go, we *must* distinguish between promising energy innovations and expensive, unviable or unscalable distractions. We also *must* diagnose the roadblocks that we as citizens are putting in the way. This year's paper, titled *The Elephants in the Room*, is designed to do exactly that: provide a detailed roadmap of the most important challenges ahead. We have much to lose by ignoring the realities of the world we live in, and much to gain by addressing them head on.

Helping you position your portfolios for the future is our top priority, as always. We hope you find this paper insightful, and we look forward to continuing our dialogue with you.

Mary C. Erdoes

Michael Cembalest
Chairman of Market and Investment Strategy
JP Morgan Asset Management

2022 Eye on the Market Energy Paper

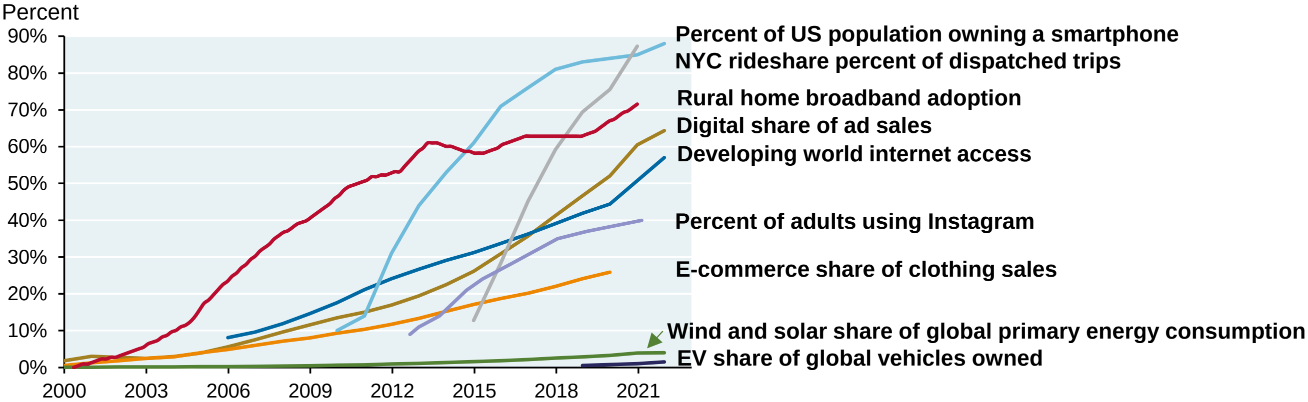
The events in Europe underscore the three unifying principles of our annual energy paper since its inception 12 years ago:

- energy transitions differ sharply from transitions in technology, healthcare and other sectors
- decarbonization of electricity is underway but decarbonization of industrial production, transport and heating lag much further behind
- countries that reduce production of fossil fuels under the assumption that renewables can quickly replace them face substantial economic and geopolitical risks

The bottom chart shows performance of fossil fuel companies and their reportedly stranded assets vs renewable energy companies. To quote Mark Twain: "Reports of my death are greatly exaggerated". We review many of the reasons why in this year's paper. My recommendation as you think about energy issues: ignore all the hype, hyperbole and hockey stick forecasts and focus on the actual trends in the energy transition.

Speed of disruption: some of these things are not like the others

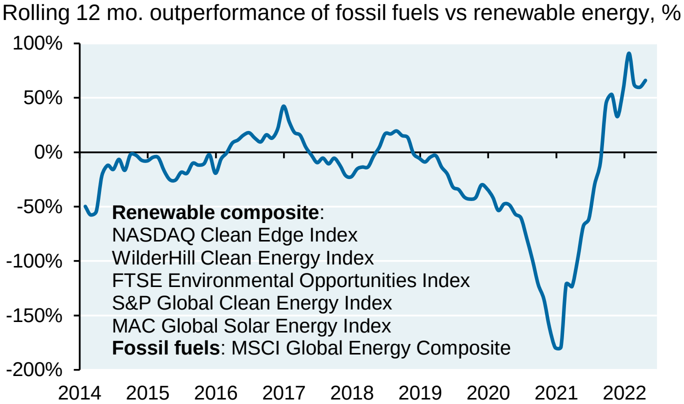
Percent



Source: GroupM, Census, BP, IEA, FHV, Pew Research, NYC Taxi & Limousine Commission, JPMAM. 2021.

Reports of my death are greatly exaggerated

Rolling 12 mo. outperformance of fossil fuels vs renewable energy, %



Source: Bloomberg, MSCI, JPMAM. April 29, 2022.

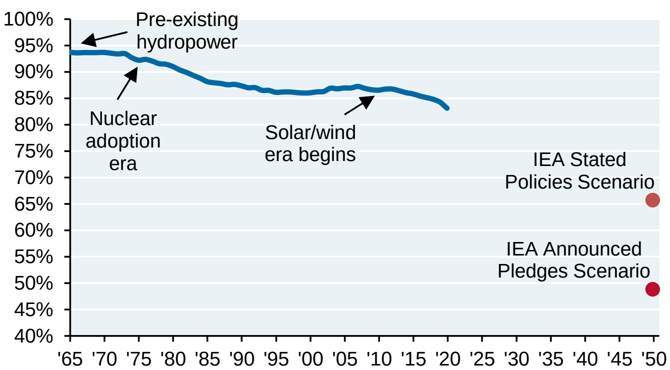
Executive Summary

The fossil fuel share of global primary energy[1] is declining at a slightly more rapid pace now, mostly a result of large investments in wind and solar power used for electricity generation. The market price to procure wind and solar power plummeted over the last decade, a consequence of scale and productivity gains[2]. Even so, fossil fuel reliance across the developed and developing world is still high (70% even in Europe) and the International Energy Agency projects that the world may still be 66% reliant on fossil fuels in 2050. What gives?

First, "levelized costs" comparing wind and solar power to fossil fuels are misleading barometers of the pace of change. Levelized cost estimates rarely include actual costs that high renewable grid penetration requires: (a) investment in transmission to create larger renewable coverage areas, (b) backup thermal power required for times when renewable generation is low, and (c) capital costs and maintenance of utility-scale battery storage. I am amazed at how much time is spent on this frankly questionable levelized cost statistic.

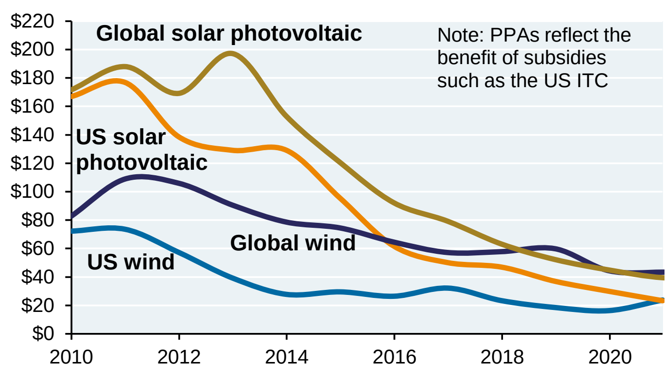
Second, the benefits of grid decarbonization are limited by low electrification of industrial energy use, heating and transportation. While electricity is used for some space/water heating, industrial motors and process heat, electricity is mostly used for space cooling, refrigeration, ventilation, computers and other electronic devices.

The world uses fossil fuels for ~83% of its energy
% of global primary energy consumption from coal, oil and nat gas



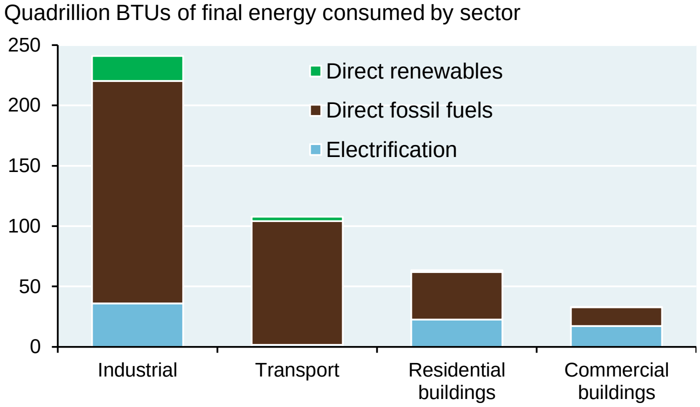
Source: BP Statistical Review of World Energy, IEA, JPMAM. 2021.

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



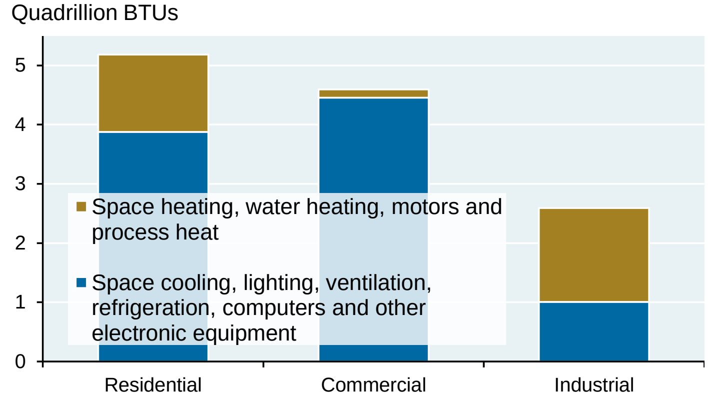
Source: Lawrence Berkeley National Laboratory, IRENA. 2021.

Low levels of electrification in global industry and transport
Quadrillion BTUs of final energy consumed by sector



Source: Energy Information Administration, JPMAM. 2021.

US electricity uses
Quadrillion BTUs



Source: EIA, JPMAM. 2021. Transport too small to plot at 0.04 quads

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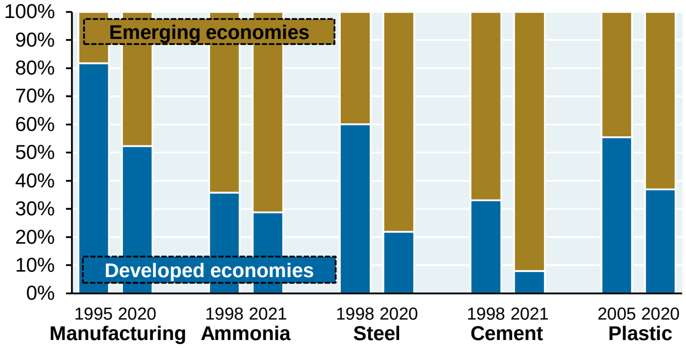
[1] **Primary energy** refers to thermal energy contained in fossil and biomass fuels, and to thermal equivalents of primary electricity generated from nuclear, wind and solar power. Converting primary electricity to primary energy is generally done by dividing the former by an assumed annual heat rate of fossil fuel plants (40% efficiency, equal to 9 MJ/kWh). **Final energy consumption** is primary energy less (a) energy lost in oil refining and natural gas processing, (b) energy lost in conversion of fossil fuels to electricity, (c) power plant consumption of electricity and (d) grid transmission losses.

[2] In the US and Europe, **wind and solar power purchase agreement levels are rising** due to higher interest rates and inflation in industrial metals and other inputs. There are more PPA increases in the pipeline: wind turbine manufacturers just raised prices to the highest levels since 2015, and some are still unprofitable (GE, Siemens).

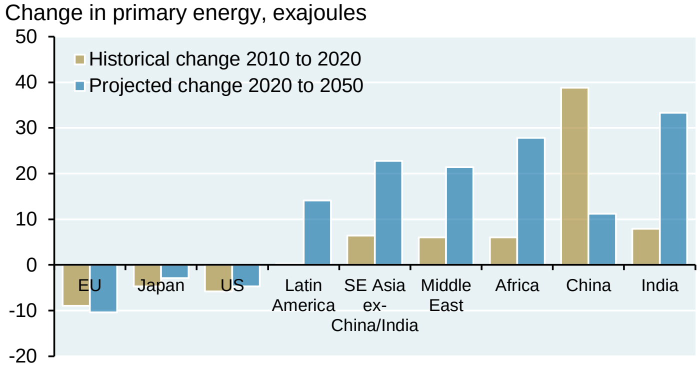
The third critical issue: the energy divide between the developed and developing world. Over the last 25 years, the developed world shifted much of its carbon-intensive manufacturing of steel, cement, ammonia and plastics to the developing world. While the developed world is projected to continue reducing its energy consumption, developing world energy consumption is projected to keep rising (second chart). And as a reminder, coal is still widely relied upon in many developing countries, and also Japan (fourth chart).

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



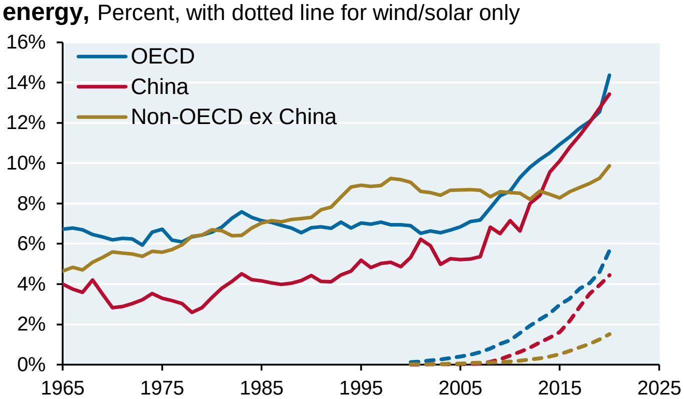
Source: UN Dept. of Social and Economic Affairs, Worldsteel, Plastics*Europe*, USGS. 2021.

China is the only EM country projected to slow primary energy consumption growth over the next three decades
Change in primary energy, exajoules



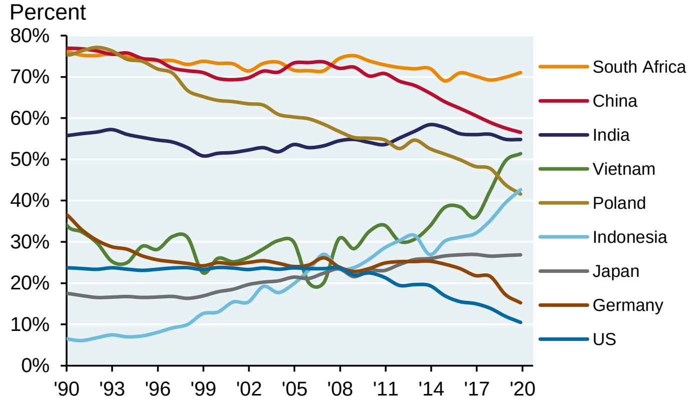
Source: International Energy Agency Stated Policies Scenario. 2021.

Wind, solar, hydro and other renewables share of primary energy, Percent, with dotted line for wind/solar only



Source: BP Statistical Review of World Energy, JPMAM. 2021.

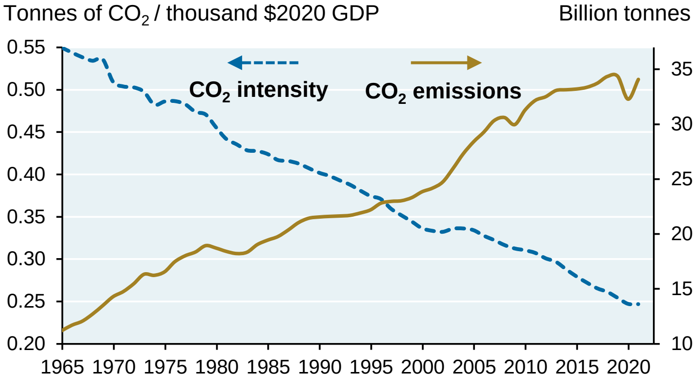
Coal share of primary energy consumption
Percent



Source: BP Statistical Review of World Energy, JPMAM. 2021.

The world gets more energy *efficient* every year, but emissions *levels* keep rising. That's why most deep decarbonization ideas rely on replacement of fossil fuels rather than on reducing fossil fuel consumption per capita or per unit of performance.

Global CO_2 intensity declining, CO_2 emissions rising
Tonnes of CO_2 / thousand \$2020 GDP
Billion tonnes



Source: BP Statistical Review of World Energy, Conference Board, IHS Markit, JPMAM. 2021.

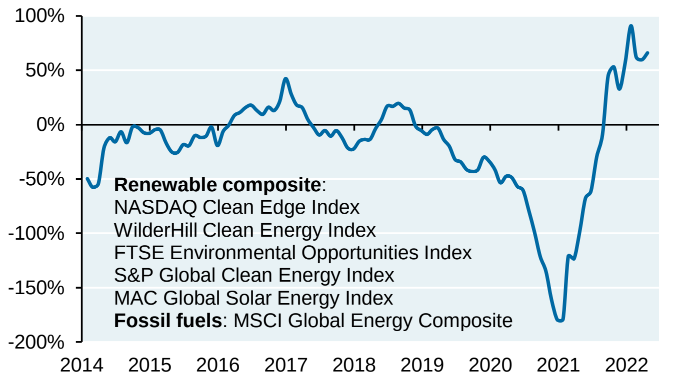
"Reports of my death are greatly exaggerated"

Some of the most ill-advised things I've ever heard about energy were said during the spike in renewable energy stocks in 2020. The short version: "fossil fuel stocks are dead money since the renewable transition is irreversible, ready to power large economies and rapidly displacing the former." Irreversible, yes; the rest of it, not so much. In our 2020 and 2021 energy papers, we argued that stars were aligning for a substantial rebound in oil and gas profitability. The reason: poor oil & gas stock price performance was the result of management decisions to focus on market share and revenue rather than profits, and *not* because of imminent displacement by renewable energy. As shown below, oil & gas industry cash flow and oil demand rebounded sharply in 2021.

The big picture: global gas and coal consumption in 2021 were already above pre-COVID levels, and global oil consumption should surpass pre-COVID levels sometime next year. Looking further out, some forecasts of oil demand in 2030 and 2040 are not that different from today. We also estimate that the US might need almost as much natural gas in the year 2035 as it consumes today, based on assumptions we made on wind and solar growth, EV and heat pump adoption and the decommissioning of coal and nuclear plants[3]. With energy demand still in excess of supply, I believe the MSCI Global Energy Composite will outperform both renewable energy stocks[4] and the broad equity market again over the next year.

Reports of my death are greatly exaggerated

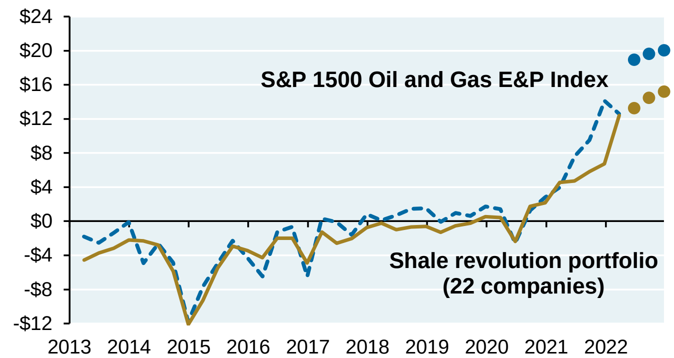
Rolling 12 mo. outperformance of fossil fuels vs renewable energy, %



Source: Bloomberg, MSCI, JPMAM. April 29, 2022.

Oil and gas industry finally turns a profit

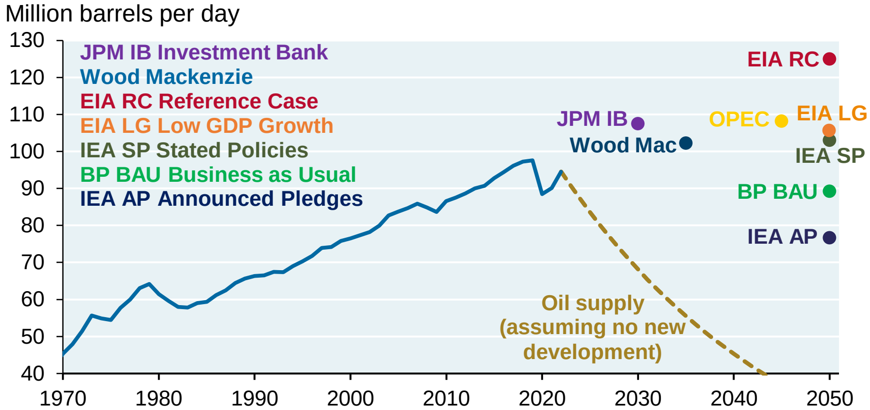
Free cash flow, $ billions



Source: Bloomberg. Q1 2022. Dots represent consensus estimates.

Oil demand, supply from existing fields and demand projections

Million barrels per day



Source: BP, EIA, IEA, OPEC, Wood Mackenzie, JP Morgan Investment Bank, JPMAM. 2021.

Energy sector highlights

- Earnings estimates still do not reflect higher energy prices, rising domestic production and operating leverage
- Energy sector still trades at 9.5x fwd earnings vs 16.5x avg since 1990
- Energy sector trades at 1x book value and is an inflation hedge; also capital intensive and less sensitive to wages
- Energy sector only 4% of S&P market cap vs 20 year avg of 8%
- Some asset manager ESG filters may be relaxed after recent performance

Source: JP Morgan Global Equity Strategy

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[3] See 2021 *Eye on the Market* energy paper, pages 32-33.

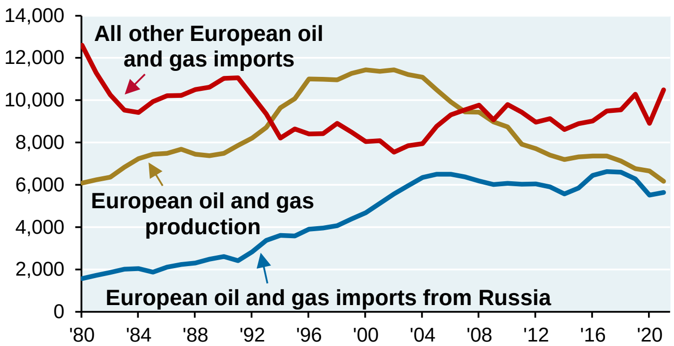
[4] **Renewable energy profitability, or lack thereof**. From 40%-60% of the companies in the Renewable Energy indices shown above are not expected to have positive free cash flow in 2023. Furthermore, most indices include large industrial companies with subsidiary renewable energy businesses (Con Ed, ON semiconductors, the Indian conglomerate Adani, Quanta Services infrastructure, Linde and Air Liquide industrial gases, Wolfspeed semiconductors, etc). In other words, "pure play" renewable companies have an even higher rate of negative free cash flow if we strip out the big industrial companies.

Europe is paying a steep price for its reliance on Russian energy

Europe miscalculated by reducing its *production* of fossil fuels much faster than it reduced its own *consumption* of fossil fuels, and is caught in the vice of Russian energy reliance. **Ramifications for Europe include**: a likely recession; energy consumption displacing non-energy goods and services; a lower rate of growth and a decline in competitiveness of exported energy intensive goods; risks that "cold turkey" withdrawal from Russian energy will require curtailment of industrial production (steel, fertilizer, cement etc) and related employment; higher food prices; and domestic political tensions as anti-establishment candidates take advantage of distress. **Latest news**: Russia cut off Poland and Bulgaria from natural gas shipments since they refused to pay in Rubles.

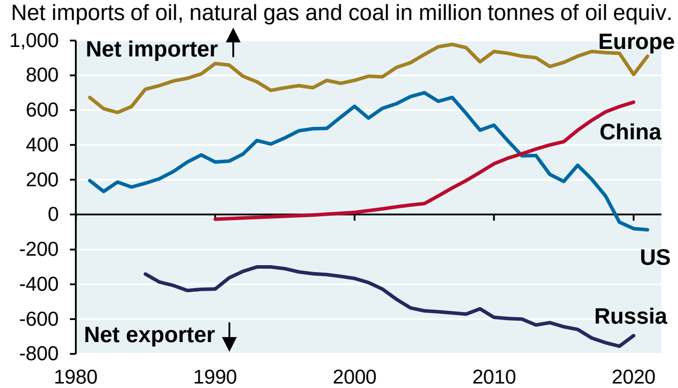
For the record: Mitt Romney warned everyone about Russia during the 2012 Presidential election. He was mocked by Democrats for doing so in 2012, and then ignored by Republicans in 2016.

Europe curtails oil & gas production while keeping imports unchanged, Thousand barrels per day of oil equivalent



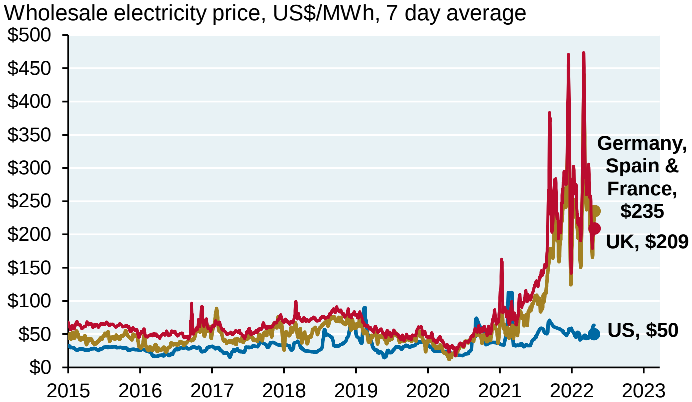
Source: BP, Gazprom, Eurostat, Perovic et al, Russia Federal Customs Service, JPMAM calculations. 2021.

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



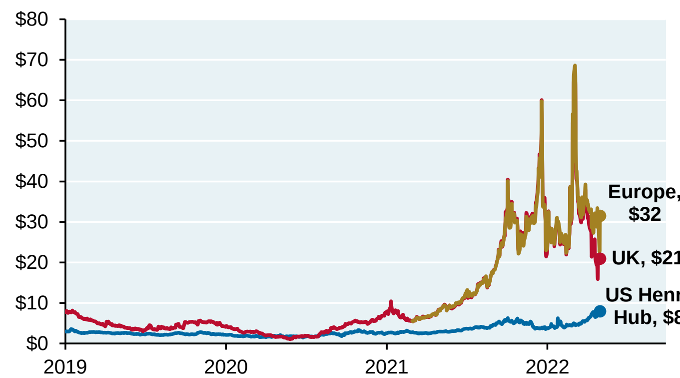
Source: BP Statistical Review, NBS China, JPMAM. 2021.

The US-Europe electricity gap
Wholesale electricity price, US$/MWh, 7 day average



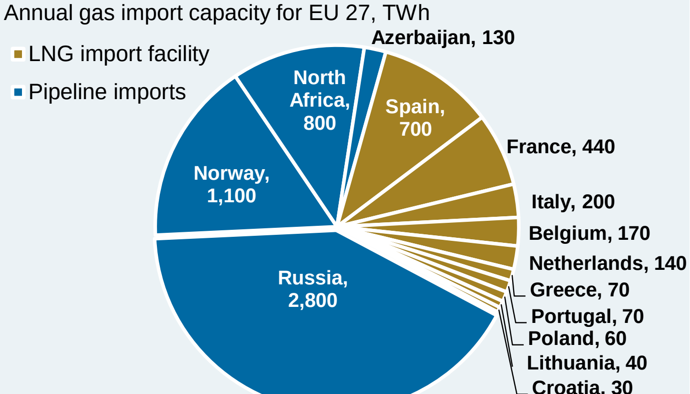
Source: Bloomberg. May 3, 2022. Dots represent latest daily price.

The US-Europe natural gas gap
Wholesale natural gas price, US$ per MMBTU



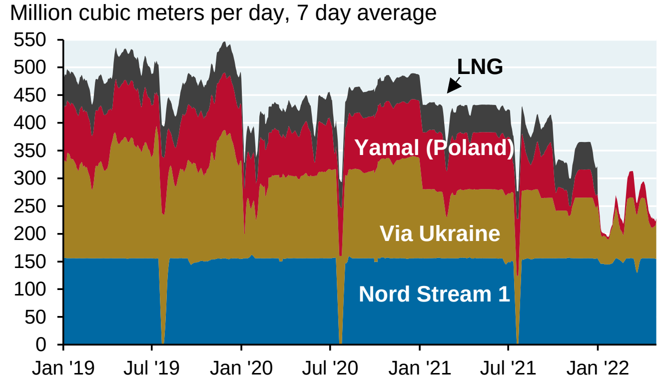
Source: Bloomberg. May 3, 2022.

Russia dominates European gas import capacity
Annual gas import capacity for EU 27, TWh



Source: Bruegel, JPMAM. 2022.

Russian natural gas exports to Europe
Million cubic meters per day, 7 day average



Source: Bloomberg, EIA, JPMAM. May 1, 2022. Excludes pipelines to and through Turkey. Annual LNG data amortized daily; no LNG data for 2022.

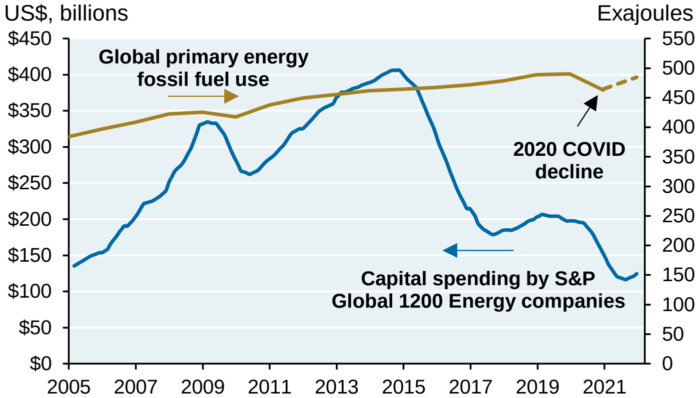
Can Europe quickly change course? They will try to. One plan we have seen entails replacing 2.6 mm bpd of Russian crude oil imports via the US (0.8 mm) and increased production from Canada, Norway, UK and Denmark (0.8 mm). Anything else could require a deal with Iran which still exports 1.3 mm bpd less than in 2018. Gas substitution is a lot harder: Europe imports 174 bcm per year from Russia, and our understanding is that there is not a lot of spare LNG regasification capacity. Spanish LNG regasification utilization rates were only 45% in January but it has limited pipeline connections with the rest of Europe. My guess is that Europe gets part of the way this year through diversification and then has to rely on longer term adjustments. Faster wind and solar? Installations are often constrained by transmission delays and local factors. Electrification of residential heating? So far, mostly confined to Scandinavia (see Section 3). More LNG regasification capacity? Expensive and time consuming. Greater use of nuclear power? The region has been abandoning it other than in France.

Europe is not the only region at risk: on a global basis, capital spending on oil and gas production is declining while oil and gas consumption is not. Many countries are now faced with three broad choices: ramp up their domestic production of fossil fuels to avoid a geopolitical and economic trap; rely on the countries in the table below for imported energy; or confront the obstacles to a faster renewable transition head-on.

The last option is not something that can be accomplished by increasing the cost of capital for fossil fuel companies or by university divestment. A faster transition requires a lot more than that: policymakers would have to curtail community delays and cancellation of renewable energy/transmission projects, and build consensus for some kind of price on carbon. Without these efforts, decarbonization will remain stuck in the slow lane despite all the corporate disclosure rules, shareholder resolutions, ESG policies, etc. A revival of the US "Build Back Better" bill could speed up the US transition a little[5], but there is no news to report yet.

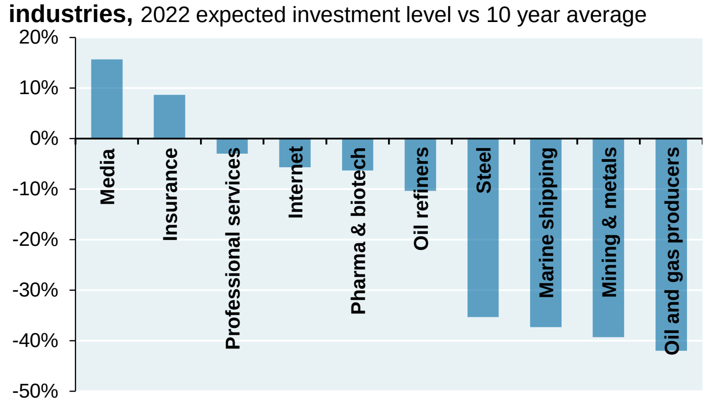
By the way, which country benefits most from renewable energy adoption from a production standpoint? China, of course (see table).

Fossil fuel capex falling despite no change in consumption



Source: BP, Bloomberg, IEA, JPMAM. Dec 2021. Dotted lines = estimates.

Collapse in global investment in energy-intensive industries, 2022 expected investment level vs 10 year average



Source: GS, JPMAM. November 10, 2021.

Largest proven reserves of oil and natural gas

	Natural gas (tr cu ft)			Oil (billion barrels)	
1	Russia	1,320	1	Venezuela	304
2	Iran	1,134	2	Saudi Arabia	298
3	Qatar	871	3	Canada	168
4	Turkmenistan	480	4	Iran	158
5	US	446	5	Iraq	145
6	China	297	6	Russia	108
7	Venezuela	221	7	Kuwait	102
8	Saudi Arabia	213	8	UAE	98
9	UAE	210	9	US	69
10	Nigeria	193	10	Libya	48
11	Iraq	125	11	Nigeria	37
12	Azerbaijan	88	12	Kazakhstan	30

Source: BP Statistical Review of World Energy. 2020.

Renewable production global market share

	China	US	EU
Solar PV module shipments, 2019	63%	<5%	<5%
Wind capacity order book, 2019	46%	14%	40%
Lithium ion battery manuf. capacity, 2021	79%	6%	9%
EV mineral processing/refining (Nickel, Cobalt, Graphite, Lithium, Manganese avg)	79%	1%	6%
EV cathode/anode production	85%	1%	1%

Sources: IEA, BNEF, S&P, Benchmark Mineral Intelligence, 2021.

[5] Most of the bill's proposed spending is reportedly focused on energy efficiency in buildings, tax credits for wind/solar, raising EV tax credits from $7k to $12k, EV infrastructure, air pollution mitigation and reforestation. Proposed spending on hydrogen, CCS, nuclear power, transmission and renewable fuels is smaller.

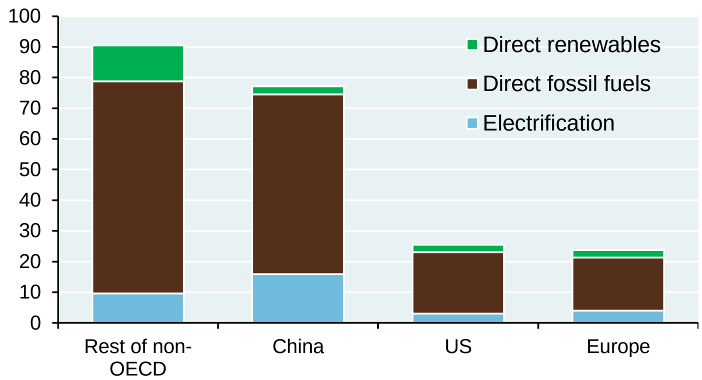
Before getting started: beware of industrial decarbonization and carbon capture fairy tales

We covered two topics last year that are critical parts of the decarbonization challenge: the real-world difficulty in electrifying industrial energy use, and the massive cost/scope required for geologic carbon sequestration to make a material impact. Beware of hockey stock forecasts on these topics; progress has been and will likely remain very slow. You can read more about them via the links below to last year's sections.

Challenges of industrial electrification and decarbonization

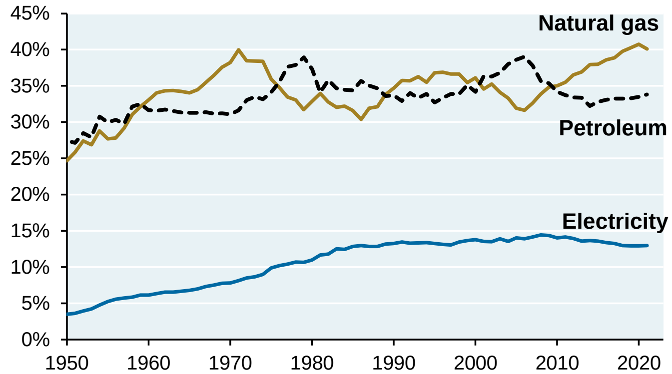
Plastics, cement, steel, ammonia and other industrial materials form the building blocks of the modern world. Electricity is a small share of the energy used to create them; in the US, the electrification share has been unchanged for decades, a testament to the difficulty in increasing it. The primary challenges: (a) industrial production often relies on waste-to-heat energy which is lost during electrification, and (b) many industrial products are non-metallic which makes electrification harder. Natural gas and petroleum remain the dominant energy sources for industrial products. You can learn more at the link above.

Electricity a small share of industrial energy use
Quadrillion BTUs of industrial energy consumed



Source: Energy Information Administration, JPMAM. 2021.

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



Source: EIA. October 2021.

The challenging energy math of geologic carbon sequestration and direct air carbon capture

One of the highest ratios in the world of energy science: the number of academic papers *written* on carbon sequestration divided by the actual *amount* of carbon sequestration (~0.1% of global emissions at last count). The infrastructure required for meaningful geologic carbon sequestration would be enormous. In addition, the energy and materials requirements for direct air carbon capture are essentially unworkable. Here's a quick summary of our conclusions on the topic from last year.

- To sequester just 15%-20% of US CO_2 emissions via traditional carbon capture and storage, the volume of US carbon sequestration (1.2 billion cubic meters) would need to exceed the volume of all US oil production in 2019 (858 billion cubic meters). That's a LOT of infrastructure that does not exist
- Gathering and storing 25% of global CO_2 through direct air carbon capture could require 40% or more of global electricity generation, even when assuming the presence of waste heat to power the carbon capture, requiring ~1,200 TWh per Gt of CO_2. This is clearly an absurd proposition. To quote one of the researchers we worked with, "direct air carbon capture is unfortunately an energetically and financially costly distraction in effective mitigation of climate changes at a meaningful scale"

Other efforts are based on "letting nature do the carbon capture work". One involves conversion of agricultural waste into low-energy, high-carbon oil using pyrolysis, after which the oil is injected underground. Another involves fast growing ocean kelp absorbing carbon, after which it sinks to low temperature depths which may limit the kelp's decomposition. Some profitable tech companies are reportedly paying $600 to $2,000 per ton of carbon to such start-ups. While these ideas might help individual companies hit their carbon footprint targets at a very high price, they are highly unlikely to move the sequestration needle on any meaningful scale.

This year's energy paper: the Elephants in the Room

The phrase "elephants in the room" refers to glaringly obvious issues that need to be resolved. This year's paper covers some of the elephants in the room regarding the energy transition.

We start with three topics on electrification, which is the foundation of many deep decarbonization plans. First, the morass of the US **transmission grid**, clogged interconnection queues and the growing number of renewable transmission projects rejected by landowners and environmental groups. After all, without a robust grid, electrification will be more difficult. Then, the latest on **electric vehicle** adoption, what policies might be needed to get **US gasoline "super-users"** to switch and how rising metals prices affect battery costs. We conclude the electrification section with a look at home heating. Replacing on-site combustion of natural gas, propane and fuel oil with **electric heat pumps** has been mentioned by the IEA as a critical step for the OECD to reduce its GHG footprint. But so far, residential heat pump adoption is mostly a Scandinavian phenomenon.

Next, a deep dive into the so-called **hydrogen economy**, which is still in its infancy. Ultimate hydrogen use cases may be narrower than advertised once costs, round-trip efficiency, materials handling and competition from direct electrification are factored in. The final section is on **China,** whose carbon intensity of energy consumption and emissions are the highest in the world. The IEA sees a path for deep decarbonization in China, but this path is highly reliant on a lot of very aggressive assumptions. We take a closer look.

Closing remarks: for some people who write about wind and dead birds, I made you a new name badge.

<u>Table of Contents</u>

What am I *not* writing about? The GHG benefits of natural gas vs coal, since it's not totally clear what they are

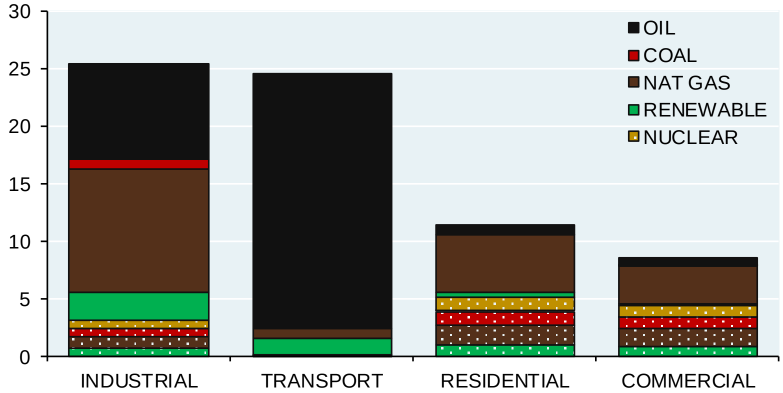
If you accept EPA data at face value, methane "leakage" rates from natural gas have fallen to ~1%, down from 2% in 1990. These rates include leakage from exploration, production, gathering, processing, transmission, storage and distribution. However, EPA emissions data is usually provided by the oil & gas industry and may not reflect variations in utilization or operating performance. As a result, climate scientists conduct their own measurements. Based on aerial, satellite and other surveillance methods, some believe that the EPA underestimates methane leakage rates by 50%-100% (some estimates are even higher). This would offset part of the very large GHG benefits normally associated with coal to gas switching; on a pure CO_2 basis, gas has a 60% lower emissions rate than coal per MWh.

To be clear, coal mining has other highly negative environmental impacts: sulfur dioxide and nitrogen oxide emissions (though they have fallen sharply since the 2005 Clean Air Interstate Rule), mercury emissions and the aftermath from sludge, slurry and fly ash ponds that contain a variety of toxins. In any case, the real-world GHG impact of coal to gas switching may be quite different than the optimal version often assumed.

Sources include Robert Howarth (Cornell), the Harvard School of Public Health and the following studies:
"*Analysis of Oil and Gas Ethane and Methane Emissions in the Southcentral and Eastern US Using Four Seasons of Continuous Aircraft Ethane Measurements*", Barkley et al, JGR Atmospheres, May 2021
"*Assessment of methane emissions from the U.S. oil and gas supply chain*", Alvarez et al, Science, June 2018
"Quantifying methane emissions from the largest oil-producing basin from space", Zhang et al, Science Advances, April 2020

Executive summary exhibits 1-3: Energy use by country, sector and fuel, and energy acronyms

US energy consumed by end-use sector and fuel type
Quadrillion BTUs of final energy consumed; dotted segments = electricity consumed

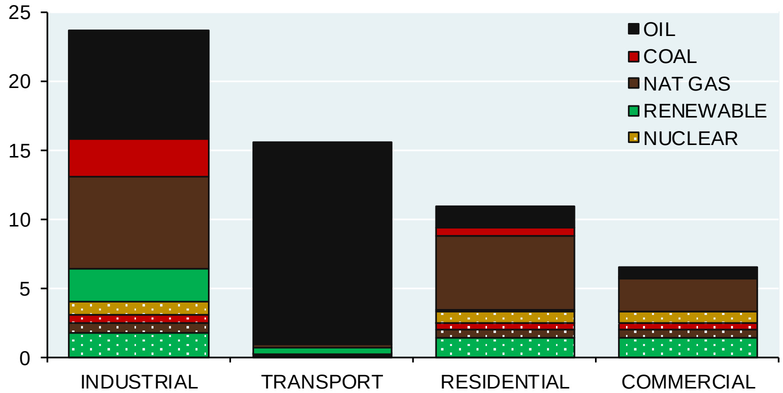


Key stats

Quads of primary energy consumption	93.3
Quads of final energy consumption	70.1
Electricity % of energy consumed	18%
Electricity % of industrial energy consumed	12%
Electricity % of transport energy consumed	0%
Electricity % of residential energy consumed	44%
Fossil fuels % of primary energy	79%
Passenger car energy % of transport energy	60%
Industrial fossil fuels % of primary energy	27%
Renewable % of electricity generation	20%
Renewable energy % of primary energy	13%
Low carbon % of electricity generation	43%
Low carbon energy % of primary energy	21%
Coal % of primary energy	10%
Coal to natural gas ratio in primary energy	0.3
Hydropower share of renewable electricity	37%

Source: Energy Information Administration, JP Morgan Asset Management. 2021. Electricity generation segments are net of thermal conversion, power plant consumption and transmission losses. "Low carbon" refers to renewable generation plus nuclear generation.

OECD Europe energy consumed by end-use sector and fuel type
Quadrillion BTUs of final energy consumed; dotted segments = electricity consumed

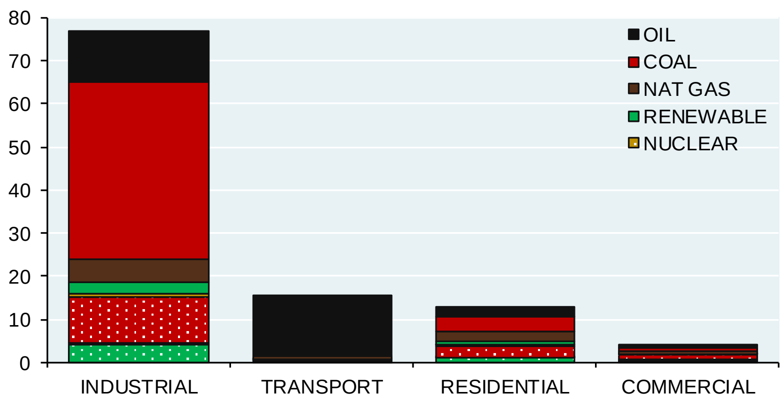


Key stats

Quads of primary energy consumption	76.8
Quads of final energy consumption	56.7
Electricity % of energy consumed	19%
Electricity % of industrial energy consumed	17%
Electricity % of transport energy consumed	2%
Electricity % of residential energy consumed	30%
Fossil fuels % of primary energy	69%
Passenger car energy % of transport energy	50%
Industrial fossil fuels % of primary energy	27%
Renewable % of electricity generation	44%
Renewable energy % of primary energy	22%
Low carbon % of electricity generation	69%
Low carbon energy % of primary energy	31%
Coal % of primary energy	10%
Coal to natural gas ratio in primary energy	0.4
Hydropower share of renewable electricity	43%

Source: Energy Information Administration, JP Morgan Asset Management. 2021. Electricity generation segments are net of thermal conversion, power plant consumption and transmission losses. "Low carbon" refers to renewable generation plus nuclear generation.

China energy consumed by end-use sector and fuel type
Quadrillion BTUs of final energy consumed; dotted segments = electricity consumed



Key stats

Quads of primary energy consumption	160.2
Quads of final energy consumption	109.6
Electricity % of energy consumed	20%
Electricity % of industrial energy consumed	21%
Electricity % of transport energy consumed	4%
Electricity % of residential energy consumed	32%
Fossil fuels % of primary energy	84%
Passenger car energy % of transport energy	25%
Industrial fossil fuels % of primary energy	59%
Renewable % of electricity generation	25%
Renewable energy % of primary energy	14%
Low carbon % of electricity generation	30%
Low carbon energy % of primary energy	16%
Coal % of primary energy	59%
Coal to natural gas ratio in primary energy	7.9
Hydropower share of renewable electricity	57%

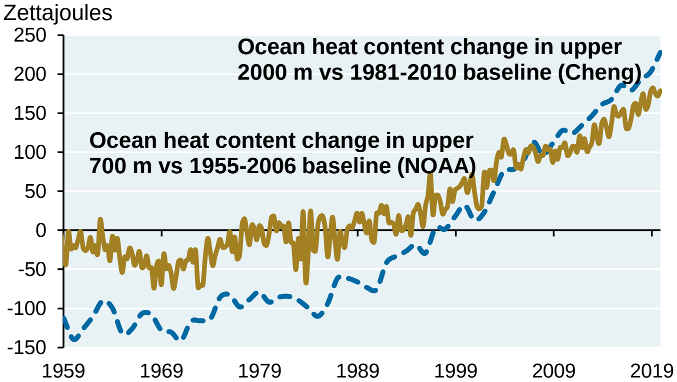
Source: Energy Information Administration, JP Morgan Asset Management. 2021. Electricity generation segments are net of thermal conversion, power plant consumption and transmission losses. "Low carbon" refers to renewable generation plus nuclear generation.

Bcm billion cubic meters; **Bpd** barrels per day; **BTU** British thermal unit; **CCS** carbon capture and storage; **EIA** US Energy Information Agency; **EJ** exajoule; **EOR** enhanced oil recovery; **EPA** Environmental Protection Agency; **GHG** greenhouse gases; **GW** gigawatt; **H_2** hydrogen; **IEA** International Energy Agency; **ISO** independent system operator; **kWh** kilowatt hour; **LNG** liquefied natural gas; **m^3** cubic meter; **MJ** megajoule; **MMT** million metric tons; **MT** metric ton; **Mtoe** million tonnes of oil equivalent; **MWh** megawatt hour; **PPA** power purchase agreement; **Quad** quadrillion BTUs; **TWh** terawatt hour

Executive summary exhibits 4-7: select climate charts

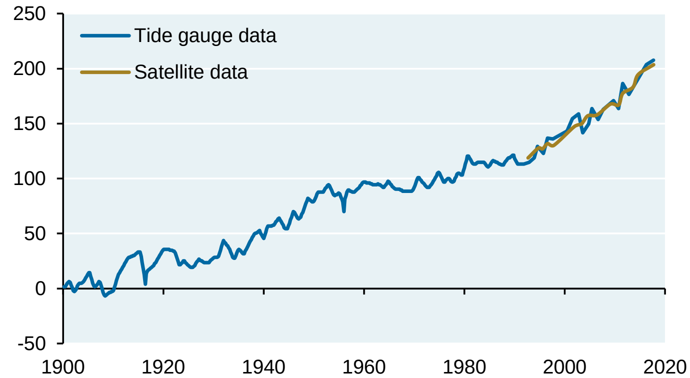
I asked my colleague Sarah Kapnick for exhibits to illustrate the latest climate research she has been following. Sarah is the Senior Climate Scientist and Sustainability Strategist for JP Morgan Asset and Wealth Management. Sarah was previously a climate scientist and Deputy Division Leader at the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory. Sarah is also a member of the American Geophysical Union, the American Meteorological Society and the American Association for the Advancement of Science.

Warming oceans
Zettajoules



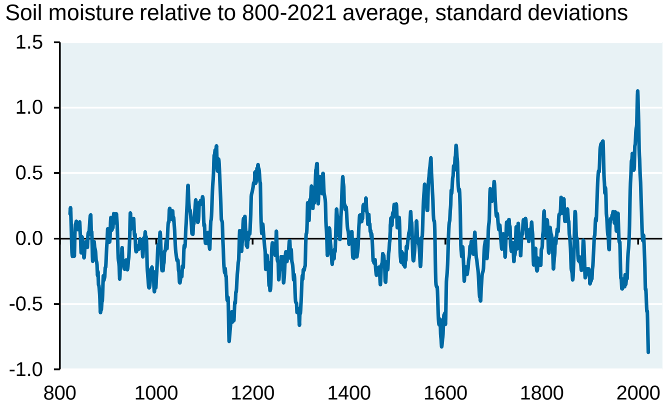
Source: Cheng, L. *et al.*, Advances in Atmospheric Sciences; Dahlman and Lindsey, National Oceanic and Atmospheric Administration. February 2020.

Sea level change (1900-2018)
Millimeters



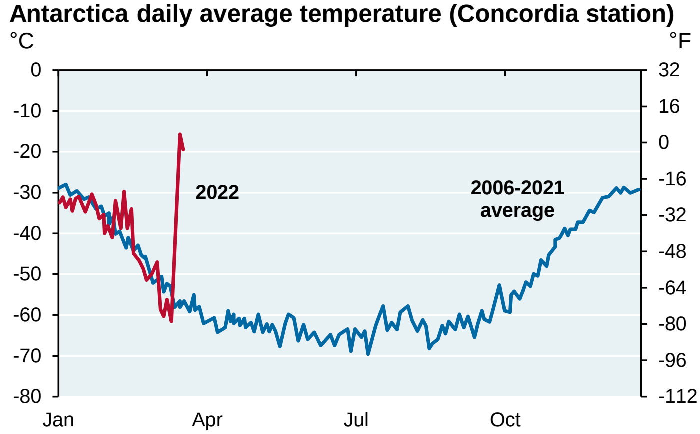
Source: NASA's Goddard Space Flight Center. 2018.

Western drought conditions since 800 AD
Soil moisture relative to 800-2021 average, standard deviations



Source: Nature Climate Change. March 2022.

Antarctica daily average temperature (Concordia station)

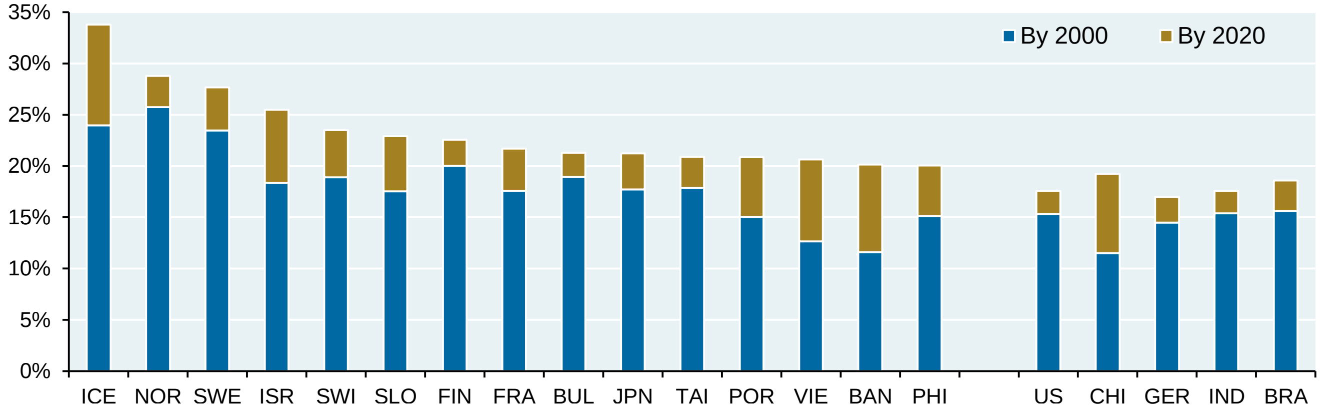


Source: National Oceanic and Atmospheric Administration. March 24, 2022.

Introductory comments on the electrification of everything

Electrification of energy use is at the center of many deep decarbonization plans. Is it possible to electrify large parts of a modern economy? The jury is out. Over the last 20 years, electricity as a share of energy use rose by just 2%-3% in most countries, a *very* slow rate of change. A few countries have reached 25%-30% electrification, but they are typically very small countries with abundant hydro- or geothermal power, and/or they are highly reliant on the outside world. Larger countries still rely on electricity for less than 20% of energy use with small gains since the new millennia began. Remember: a lot of what you read from energy futurists is a blueprint for a world that does not have proof of concept yet.

The slow advance of electrification, 2000 to 2020
Electricity share of primary energy consumption

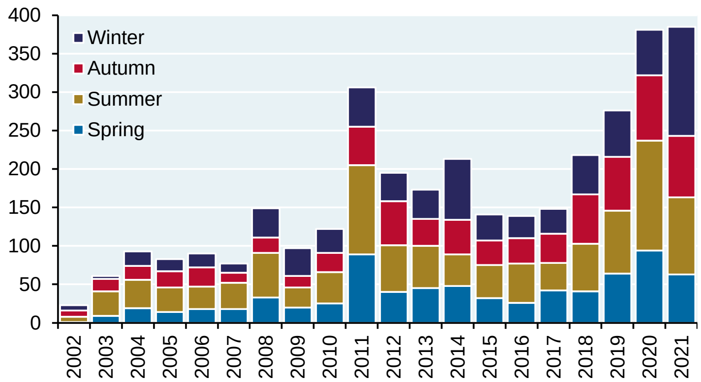


Source: BP Statistical Review of World Energy, JPMAM. 2021.

The next three sections all relate to electrification: the headwinds policymakers face when trying to expand transmission grids to facilitate greater electrification in the first place, and efforts to increase electrification of transportation and residential/commercial heating.

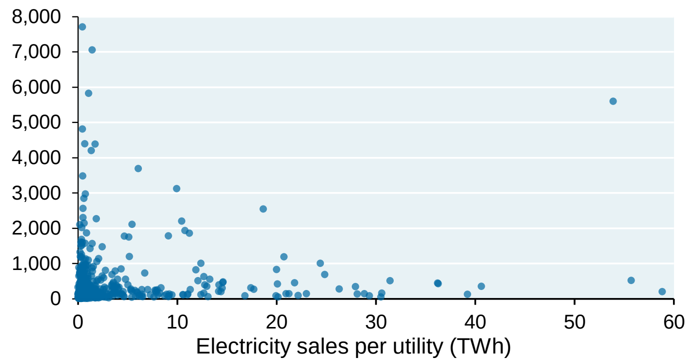
Quick overview of the grid status quo: the US electricity grid has been called the "largest machine in the world", comprising 7,700 power plants, 3,300 utilities and 2.7 million miles of power lines. In the process of electrifying everything, policymakers will need to ensure the stability of this machine. Some US utilities are struggling already with rising grid outages in recent years. Each utility reports average outage minutes per customer per year; some experienced long outages in 2020, although they tended to be the smaller ones.

US reported electric disturbances by season
Number of disturbances



Source: Department of Energy, JPMAM. 2021.

System average interruption duration index (SAIDI)
Outage minutes, annual average per customer, 2020

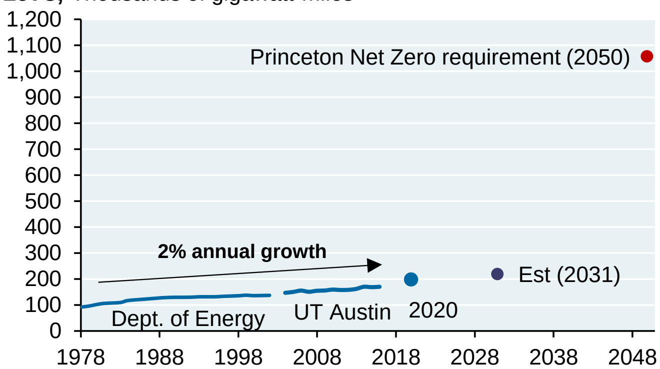


Source: EIA, JPMAM. 2020. Dots represent a given utility's operations within a specific state.

[1] The US transmission quagmire shows little sign of changing

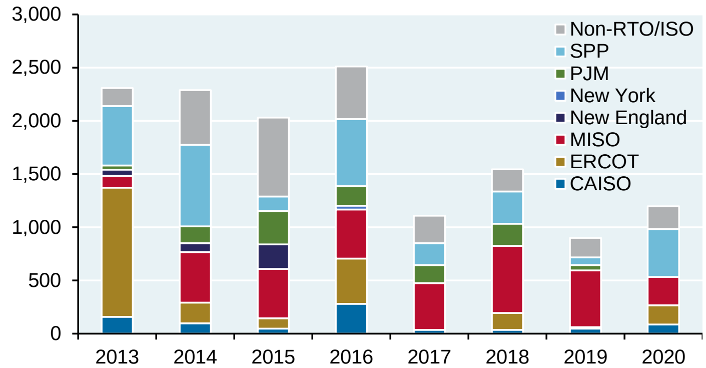
The US plans to electrify a lot of household and commercial energy use over the next ten years. Unfortunately, the US grid is a slowly-changing morass that's already struggling to incorporate more renewables as traditional generation capacity is retired[6]. US transmission infrastructure has been growing at just 2% per year since the late 1970's. More recently, despite the need for more transmission, the grid has been growing even more slowly (second chart). Some projections now estimate just 1% transmission growth to the year 2030. Compare that with the grid expansion required for many Net Zero plans, one example of which is shown in the first chart.

US transmission grid growing at just 2% per year since 1978, Thousands of gigawatt-miles



Source: DOE, UT Austin, *"Net Zero America"*, Larson et al., Princeton. 2020.

Most recent growth has been just 1% per year
Miles of transmission lines added by year and region



Source: S&P Global. 2020.

In last year's paper, we covered the saga of the now-defunct Northern Pass project designed to bring hydropower from Quebec to Massachusetts, blocked by some of the most progressive states in the country. When I speak with Net Zero advocates, if they stare off into space on this topic rather than confronting the NIMBY/state's rights issue head on, it tells me that they are not that serious about addressing real-world obstacles to deeper decarbonization.

Northern Pass is not the exception. **Transmission projects are being blocked across the country by landowners and by conservation groups objecting to the very electrification that they intensely lobby for on paper**. If you want to see people contort themselves into pretzels, read how lawyers at the Illinois Environmental Law and Policy Center explain their litigation to block wind transmission projects in the Midwest[7].

- After New Hampshire blocked Northern Pass, Maine voters blocked the New England Clean Energy Connect project which was also designed to bring Canadian hydropower to Massachusetts. Maine voters approved a referendum by 59% to 41% to block power lines in the Upper Kennebec region, and to require Maine's legislature to approve by a 2/3 majority all large transmission projects on public lands. Conservation efforts to block the project were reportedly financed by NextEra and other utilities in the region. Avangrid, a subsidiary of Iberdrola, had already spent $350 million on the project
- Iowa passed a law preventing the use of state eminent domain for transmission lines. Iowa has one of the highest wind capacity factors in the country at ~40%, but this move effectively shelved a project designed to bring wind power from Iowa to Illinois, and another project to bring wind power to Wisconsin
- Arkansas blocked a wind project from Oklahoma to the Southeastern US
- Missouri blocked a wind project from Kansas to Indiana
- Colorado blocked a wind project from Wyoming to Nevada, Arizona and California
- In California, the state's environmental protection law is often used to delay or stop projects that would have significant benefit to the environment such as solar farms and mass transit
- In Florida, oddly enough, Gov. DeSantis and the state legislature passed laws *preventing* local entities from blocking solar projects and renewable natural gas projects

[6] 39 GW of coal, gas and nuclear capacity have been retired since 2013; another 27 GW to be retired by 2028

[7] "*In aim to expand power grid, Biden faces pushback from conservation allies*", Houston Chronicle, Jan 2022

Some Republicans blame Democrats for the ease with which infrastructure projects are blocked. "*Now with Joe Biden's ambitious climate goals, Democrats are realizing that allowing activist groups to sue over every infrastructure project might not have been their smartest idea. You are lying in the bed you made. It did not have to be this way*" (Rep. Pete Stauber, R-Minn).

Why is it so hard to get transmission projects approved and built?

- **Federal eminent domain** was used over the last 100 years to build railroads, parks, natural gas pipelines, airports, naval stations, interstate highways and fiber optic cables. But eminent domain is *not* being used broadly today by the Federal government to accelerate transmission grid improvements
- **There is no mechanism at the Federal level** to enable national transmission grid planning involving regional integration of renewables across regions and interconnections. The Energy Policy Act of 2005 established a potential pathway to give the Federal government backstop siting authority. However, that authority was challenged in the courts and has been effectively neutralized (see box)
- Even when regional transmission authorities conclude that a given new multi-state line would produce economic benefits for the entire region, **regulators in a state crossed by that line can block it**, and multi-year challenges can be staged by consumer and environmental groups
- The **cost allocation process** for large interregional projects can take years, even when all parties involved agree to proceed with a given project
- **The US Federal Energy Regulatory Commission also does not have jurisdiction** over public power and municipal utilities which serve ~28% of all electricity customers in the US

Then there's the issue of US interconnection queues. Developers of generation capacity have to ensure in advance that their project will be connected to the grid, and how much it will cost since they usually have to pay for the interconnection. The process requires interconnection requests to be handled one at a time in the order they enter the queue. It all worked well when generators added large centralized nuclear and gas plants.

But when hundreds of small renewable projects swarm the queue at the same time, it's an inefficient process that can take up to 4 years. This is particularly true when a given project withdraws from the queue (usually when developers find out that interconnection costs are too high), which then requires the rest of the queue to be re-shuffled and re-evaluated. This is not just a US issue; last year in **Spain**, 40 GW of wind power and 40 GW of solar power had connection permits for the grid but risked losing access due to administrative delays.

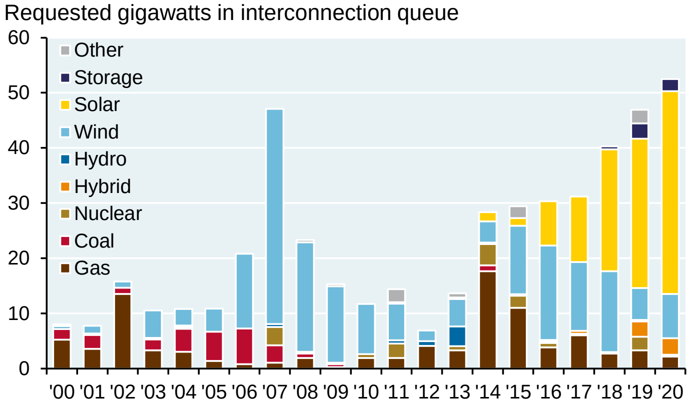
US Courts constrain eminent domain powers granted to FERC in the 2005 Energy Policy Act

The Energy Policy Act of 2005 granted FERC siting and eminent domain authority on transmission line projects if, for example, a state is able to site the project but has not done anything after one year. FERC interpreted this clause as meaning that "a state *could* have sited the project but decided to deny it anyway", and tried to apply eminent domain. States, environmental groups and industry groups all challenged the rule in court. In 2010, the US Court of Appeals for the Fourth Circuit invalidated the rule as being beyond FERC's authority, ruling that FERC can only use its backstop siting authority when a state refuses to even *rule* on the project within a year, or if the state grants a permit but attaches "project killing conditions". See "*Interstate Transmission Challenges for Renewable Energy: A Federalism Mismatch*", Alexandra Klass and Elizabeth Wilson, Vanderbilt Law Review, 2019

The MISO region which spans 15 Midwestern and Southern states is a good example. The first chart below shows the requested GW of generation entering the interconnection queue each year by generation type. On the right, we show the amount that ended up ultimately getting connected: usually much less than 50%, with the remainder withdrawn. **The problem is not just in the MISO region: from 2010-2020, only 24% of projects in interconnection queues reached commercial operation in CAISO, ISO-NE, MISO, NYISO and PJM regions combined[8].** Completion rates were even lower for wind (19%) and solar (16%) projects. Time in the queue almost doubled from 2 years from 2000-2010 to 3.7 years from 2011-2021.

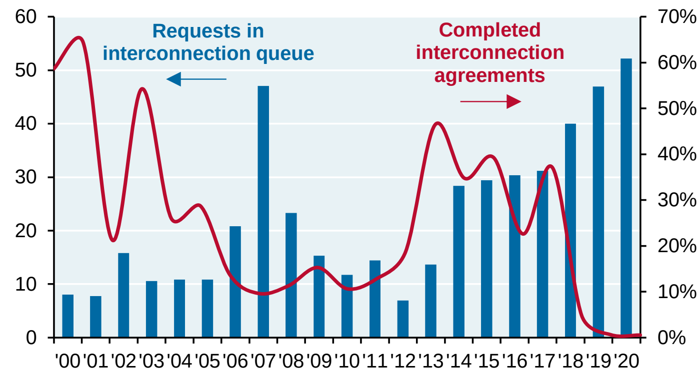
The third chart shows an aggregation of all projects that were in US interconnection queues at the end of 2021. These "in limbo" projects represent multiples of existing wind, solar and storage capacity, but a timetable for their completion is uncertain due to the factors discussed earlier. The last chart shows the growth in the queue on a national level since 2014, broken down by fuel type.

The clogged MISO interconnection queue
Requested gigawatts in interconnection queue



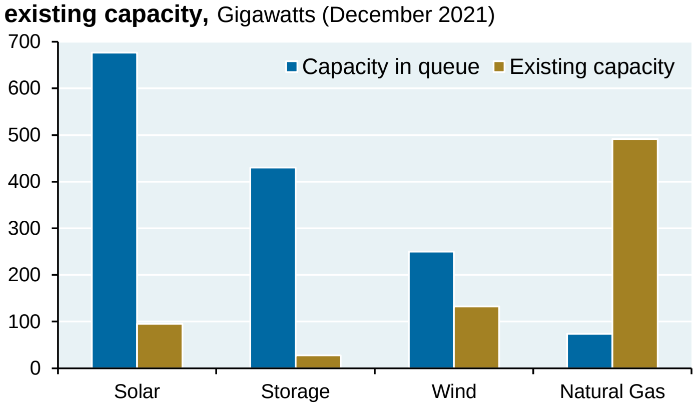
Source: MISO. June 2021.

Less than 50% of MISO queue projects are completed
Gigawatts %, completed requests



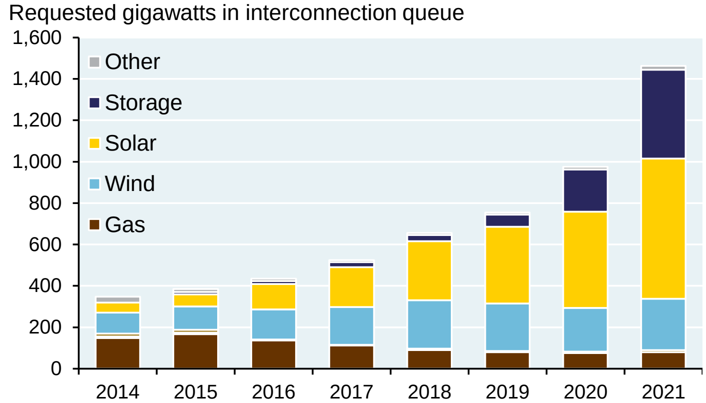
Source: MISO. June 2021.

Renewable capacity in interconnection queues dwarfs existing capacity, Gigawatts (December 2021)



Source: LBNL, EIA, JPMAM. April 2022.

US interconnection queue by fuel type
Requested gigawatts in interconnection queue

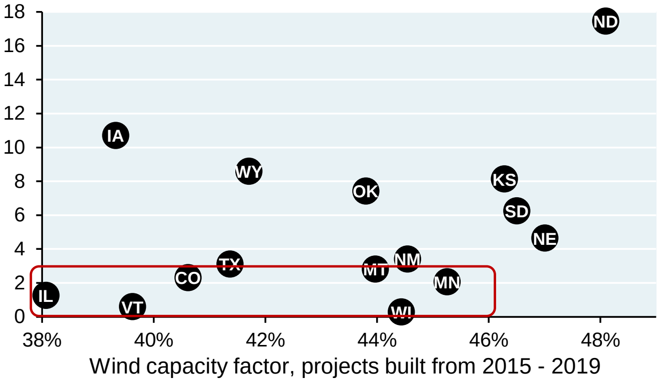


Source: LBNL. 2021.

8 "*Transmission in the United States: What Makes Developing Electric Transmission So Hard?*", Scott Madden Management Consultants, July 2021

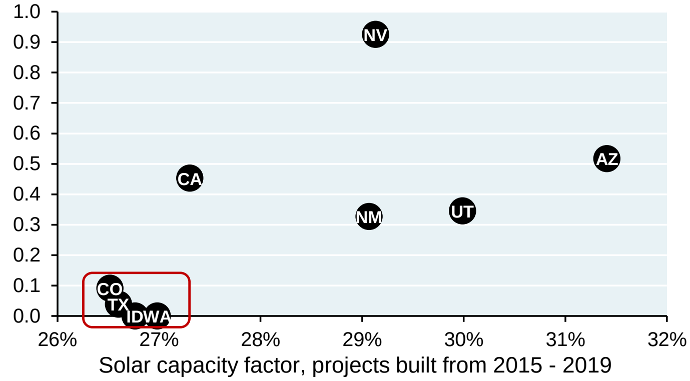
Where might local objections and interconnection queue delays have the largest impacts? One way to think about it: which states are underutilizing their wind and solar natural resources? We measure wind or solar resource potential by looking at capacity factors on recently built facilities, and compare this resource potential to actual generation per capita. Illinois, Colorado, Vermont, Wisconsin and Minnesota have wind capacity factors over 38% but low in-state wind generation per capita. Similarly, Idaho, Texas, Colorado and Washington have underdeveloped solar resources given solar capacity factors on recent projects that exceed 26%.

Wind resource vs generation
Wind MWh per capita, 2020



Source: EIA, JPMAM. 2020.

Solar resource vs generation
Solar MWh per capita, 2020



Source: EIA, JPMAM. 2020.

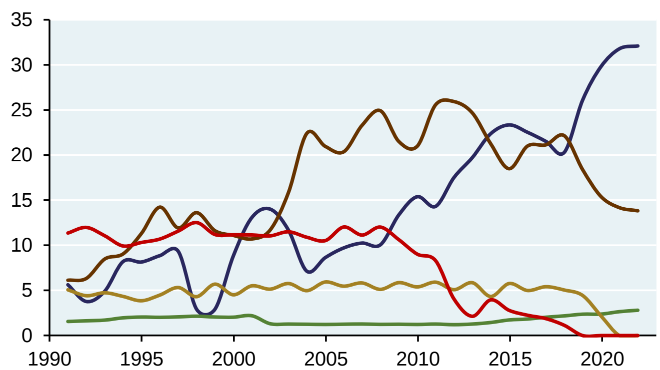
So, where does that leave Massachusetts now that Maine and New Hampshire killed their access to low-cost, clean Canadian hydropower? As shown in the next chart, Massachusetts is increasingly reliant on electricity imports from neighboring states, much of which is not very "green". **Over the long run, many states have given up on Canada and plan to rely on offshore wind instead**. It's not cheap: procurement prices for offshore wind in Massachusetts range from $70 to $100 per MWh for projects expected completed by 2025. That compares to average wholesale electricity prices in Massachusetts of $50 per MWh last year. Massachusetts long term policy commitments for offshore wind add up to almost 50% of the state's electricity consumption**. If so, there may eventually be sticker shock as offshore wind project costs are passed through to residential and industrial electricity consumers.** Around 10 GW of offshore wind are in the advanced permitting stage across the Eastern Seaboard; we will continue to monitor where PPAs and electricity prices end up.

New York is notable as well. Since the shutdown of the Indian Point Nuclear Plant, coal- and gas- powered electricity imports from PJM have closed most of the gap. This fall, construction is set to begin on a 339-mile high voltage transmission line transporting Canadian hydropower. It has taken 17 years to get to this point, and the power line may not be completed until 2025.

To conclude: the disconnect between transmission grid assumptions in Net Zero plans and what's happening on the ground is almost as wide as the chasm between expectations and reality on carbon sequestration.

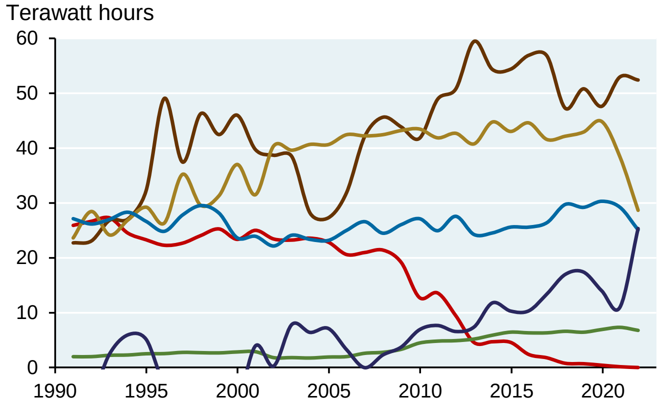
Imports   Natural Gas   Wind & Solar   Nuclear   Coal   Hydro

Massachusetts: electricity generation by source
Terawatt hours



Source: EIA, JPMAM. November 2021.

New York: electricity generation by source
Terawatt hours



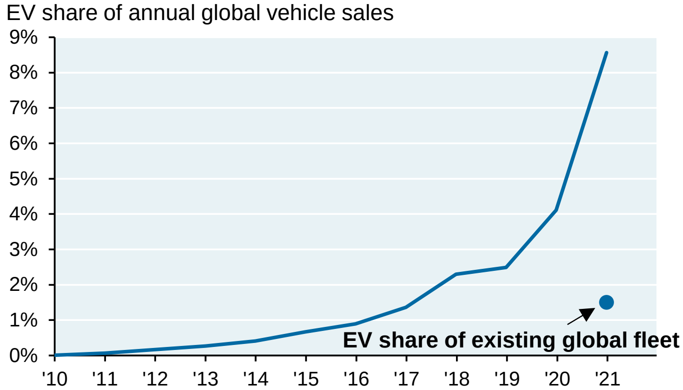
Source: EIA, JPMAM. November 2021.

[2] How should the US deal with gasoline super-users? And what about rising metals prices and battery costs?

Global EV sales gathered steam in 2021, growing to almost 9% of total vehicle sales. That's a meaningful jump from the prior year, although to be clear, EVs are still just 1.5% of the global fleet of vehicles on the road. As discussed last year, the longer useful life of today's automobiles limits the pace of EV adoption absent aggressive subsidies and incentives to switch. The charts on page 21 show projections for EVs as a % of sales for passenger cars and trucks, and how quickly EV sales translate into fleet share gains.

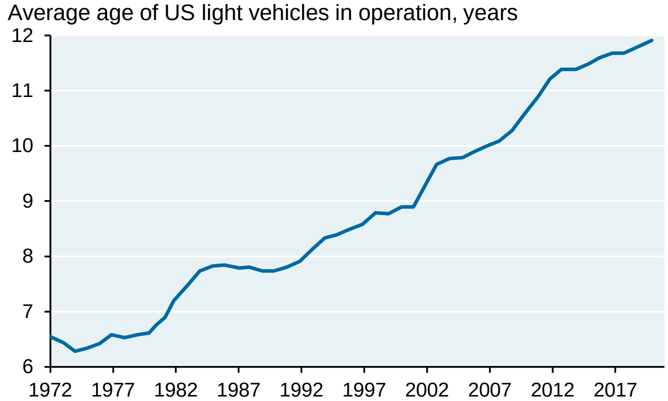
US EV sales trailed many countries in 2021, coming in at just 4.5% of total vehicle sales[9]. Furthermore, lower mpg light trucks and SUVs are still the most popular vehicles in the US market (see third and fourth charts). EVs face a steeper climb in the US, which has the highest share of global transport energy consumption, the highest vehicle share of transport energy, the highest number of vehicles per capita, the longest distances driven per capita, the lowest public transit usage and the lowest gasoline prices as well[10].

Global electric vehicle market share
EV share of annual global vehicle sales



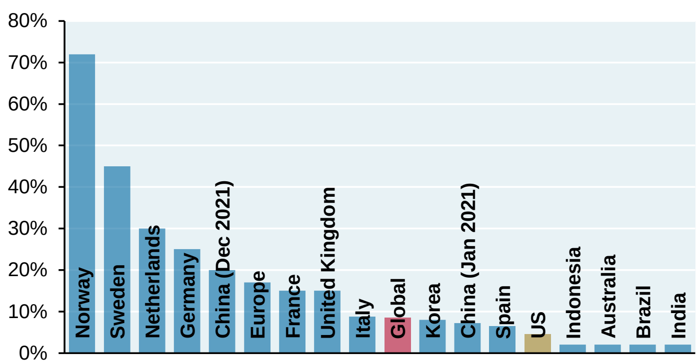
Source: IEA. 2021.

Cars last a lot longer than they used to
Average age of US light vehicles in operation, years



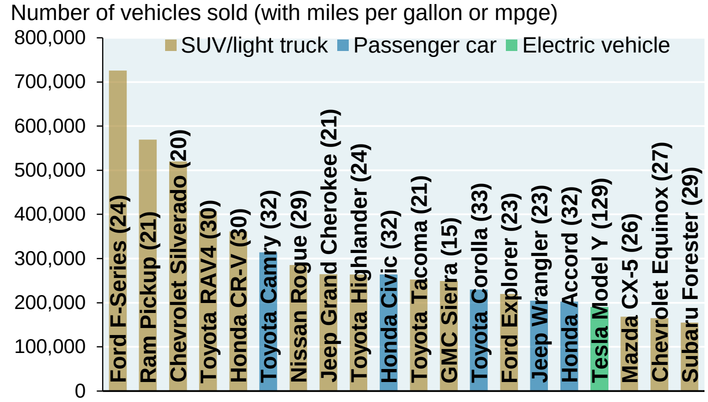
Source: US Bureau of Transportation Statistics, IHS Markit. 2020.

Electric vehicle market shares in 2021
EV share of annual vehicle sales



Source: IEA. 2021.

US: top 20 vehicles sold in 2021
Number of vehicles sold (with miles per gallon or mpge)



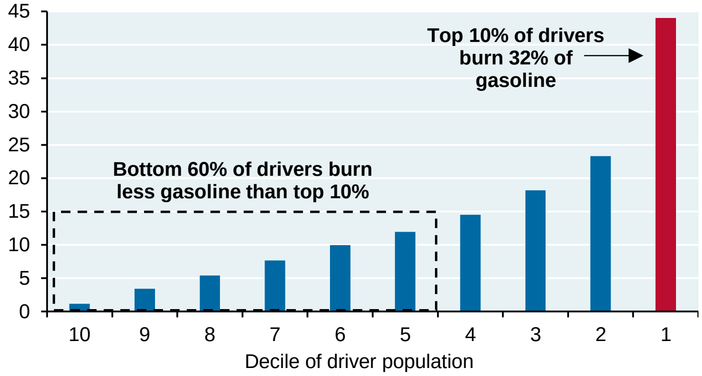
Source: Forbes, fueleconomy.gov. 2021. Mileage = combined city / highway.

[9] I bought my first electric vehicle this year. It's a 4-door 2022 Jeep Wrangler hybrid. It has a 17 kWh lithium ion battery that allows for 21 miles of continuous EV driving. I use it mostly for local kayak fishing. Since I only drive it around 2,000 miles per year, my payback period is 13 years, even with the Federal subsidy.

[10] California State University, EV Volumes; see exhibit in last year's paper on page 14

The prior chart on US vehicle preferences gets at a major issue: what to do about US gasoline "super-users"? As shown below, the top 10% of gasoline consumers in the US account for almost one third of all gasoline consumption, more than the bottom 60% of gasoline consumers combined[11].

The US gasoline super-users
Gasoline consumption, billions of gallons



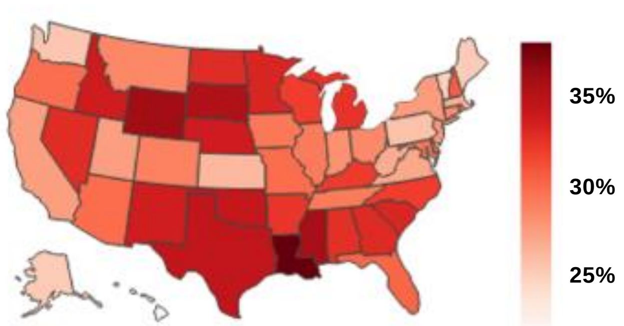
Source: Coltura. July 2021.

Who are these gasoline super-users?

- They drive 3x more miles than the average driver
- They are more likely to drive pickups and SUVs
- They are more likely to live in rural areas
- They have similar income and education levels as the general population
- They spend 8%-13% of their income on gasoline, which is over 2x as much as the average driver

The maps illustrate the challenge. The map on the right shows where the highest concentrations of **EV purchases** are taking place. The shading on this map is almost the inverse of the map on the left, showing where gasoline super-users make up the largest share of gasoline consumption.

Superusers' share of state gasoline consumption



Source: Coltura. July 2021.

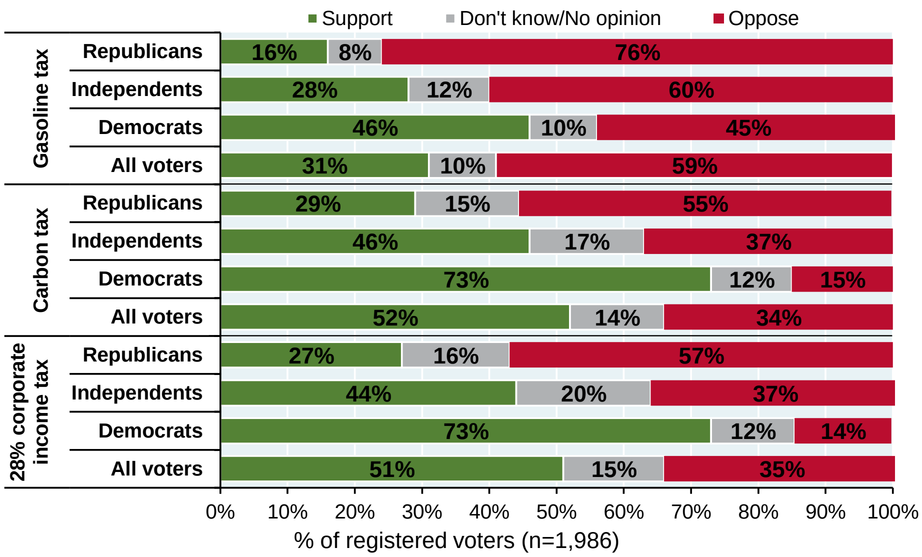
EV registrations by state

Source: Coltura. July 2021.

[11] "*Gasoline Super-users*", Metz, London and Rosler (Coltura), July 2021

How might gasoline super-users be incentivized to adopt EVs more quickly? Many will say "higher gasoline taxes!!", but that is unlikely for political reasons. Even before the Build Back Better bill ran into trouble with resistance in the Senate, polling showed that US voters are less in favor of gasoline taxes than other revenue raising means when paying for infrastructure. A "carbon tax" might sound like it achieves similar objectives as a gasoline tax, but in practice they are different. In Europe for example, the Emissions Trading System carbon tax applies to power generation, manufacturing and aviation but *not* to road or maritime transport.

Gasoline tax has lower support than other options
Voter polling on how to pay for infrastructure, April 2021



Source: Morning Consult. April 2021.

The current US approach is a $7,500 Federal tax credit for eligible EV purchases[12]. **The problem: this incentive delivers a "windfall" to EV buyers who were already driving a fuel efficient internal combustion engine car that they didn't drive much anyway**. In other words, Congress is overpaying them for foregone emissions. On the other hand, Congress is paying gasoline super-users a much lower rate on *their* foregone emissions, and might not be offering them enough to switch. If the goal is emissions reduction, there is another way: **a subsidy per gallon of foregone gasoline consumption rather than a fixed amount per vehicle**.

[12] The $7,500 Federal tax credit is available only for EVs whose battery capacity is beyond a standard minimum size, and for cars whose manufacturer EV unit sales are still below 200,000 vehicle sold to date (Teslas, the GMC Hummer EV and the Chevy Bolt are no longer eligible).

How would a gasoline usage-based incentive work? Here's one option using an incentive of $10 for every gallon of displaced gasoline:

- Driver takes existing gasoline car to dealer
- Dealer obtains car registration history
- Dealer computes average annual miles driven based on initial and current odometer readings
- Dealer obtains EPA mileage rating for that specific vehicle
- Incentive amount = $10 * annual average gallons consumed (miles driven / miles per gallon)
- Driver eligible for incentive if new EV purchased within 30 days of trade-in

The following table uses three examples from lowest to highest gasoline consumption. Driver gallons displaced (C) are 8x higher for the Tacoma driver than for the Accord driver. A usage-based incentive offers the Tacoma driver a powerful incentive to switch: after assumed trade-in values (G), fuel savings (E) and maintenance savings (F), the Tacoma driver ends up *being paid* to swap for an EV (L). Compare that to the current policy which pays the Tacoma driver $6 per gallon of displaced gasoline while paying the Accord driver $73 per gallon.

Bottom line: if the goal is to accelerate the EV transition, the per-gallon incentive might work better given larger incentives for gasoline super-users, and given lower payouts to drivers with less switching benefits. For everyone who believes that a gasoline *tax* per gallon is the right answer, a gasoline *incentive* per gallon might be the second best option given the political realities in the US in 2022 and beyond.

EV incentives: fixed amount per GALLON vs fixed amount per VEHICLE

		2015 Honda Accord 29 mpg	2015 Toyota Highlander 21 mpg	2015 Toyota Tacoma 19 mpg
	Incentive: $10 per gallon			
A	**Location**	New York Metro	Milwaukee Metro	Atlanta Metro
B	**Annual mileage**	3,000	8,000	25,000
C	**Annual gallons displaced**	103	381	1,316
D	**EV incentive @ $10/gallon displaced**	$1,034	$3,810	$13,158
E	**Monthly fuel savings w/ EV**	$26	$105	$327
F	**Monthly maintenance savings w/ EV**	$8	$20	$63
G	**Trade-in value**	$15,848	$18,927	$10,315
H	**EV alternative**	Hyundai Kona EV 3.7 miles/kWh	Tesla Model Y 3.6 miles/kWh	Ford F-150E 2.3 miles/kWh
I	**Price of EV**	$42,500	$65,000	$44,000
J	**Net EV cost after incentive and trade-in**	$25,618	$42,263	$20,527
K	**Monthly car payment on EV (6 years @ 5%)**	$421	$694	$337
L	**Monthly cost to switch to EV**	$387	$569	-$53
	Incentive: $7,500 per vehicle			
M	**Monthly cost to switch to EV**	$281	$508	$40
N	**Taxpayer cost per gallon displaced under existing $7,500 per car tax incentive**	$73	$20	$6

Source: Coltura, Department of Energy, Autoblog, Edmunds, Forbes, JPMAM. April 2022. Assumes: Gasoline = $4.11/gallon; Electricity = 14 cents/kWh. EV cost = lowest available sticker price plus 10%. Assumes existing car is fully paid for.

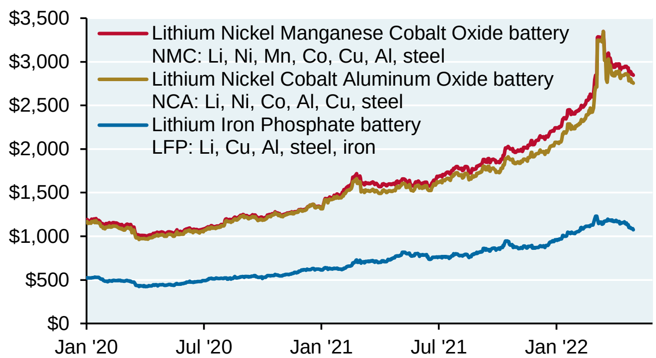
EV special topic: what about rising metals prices and EV battery costs?

Since 2019, cobalt, nickel and aluminum inventory levels relative to demand have reached their lowest levels in many years and their prices surged. What might be the impact on EV battery costs? Using metals composition of EV batteries, we analyzed a hypothetical 60 kWh battery across three chemistry types: Lithium Nickel Manganese Cobalt (NMC), Lithium Nickel Cobalt Aluminum (NCA) and Lithium Iron Phosphate (LFP). The table shows battery chemistry by auto manufacturer; LFP batteries are used by Tesla and Chinese EV makers, while the rest mostly use NMC at least for now. LFP batteries are typically cheaper but have lower energy densities. China manufactures most LFP batteries while Samsung and LG Chem produce most NMC batteries.

Estimated LFP battery costs have risen by ~$500 since Jan 2020, mostly due to rising copper prices; this increase seems manageable as a % of vehicle cost. In contrast, estimated NMC and NCA battery costs increased by ~$1,500 since Jan 2020 with a large part of that increase occurring this year due to rising nickel and cobalt prices. For all EVs, there could be another $500 cost increase due to copper and aluminum for non-battery purposes in excess of amounts needed in gasoline cars. **Bottom line: there may be some sticker shock for EVs reliant on nickel and cobalt**. EV buyers can expect to offset part of this price increase via lower fuel costs if the current gap between gasoline and electricity costs per mile is sustained[13].

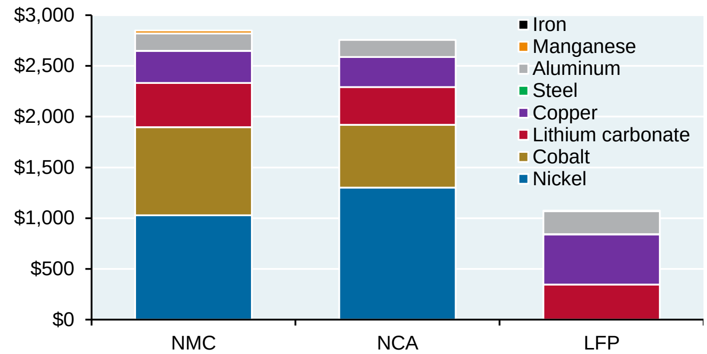
According to Rivian's CEO, EV battery supply chain pressures could surpass the current semiconductor shortage: "All the world's cell production combined represents well under 10% of what we will need in 10 years…**meaning, 90% to 95% of the battery supply chain does not exist**" [WSJ, 4/18/2022]. I doubt that many EV forecasts incorporate these kind of supply chain pressures. The path to higher EV shares may not be that easy.

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



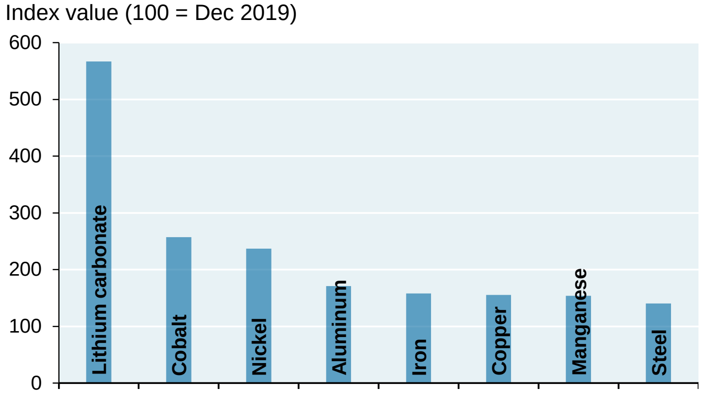
Source: Univ. of Birmingham (UK), Argonne National Lab, Bloomberg, JPMAM. May 2, 2022.

EV battery cost breakdown using current metals prices
US$ per 60 kWh battery



Source: Univ. of Birmingham (UK), Argonne National Lab, Bloomberg, JPMAM. May 2, 2022. Iron and steel values are plotted but are too small to see.

EV metals prices have risen by 50% or more since 2020
Index value (100 = Dec 2019)



Source: Bloomberg, JPMAM. May 2, 2022.

Manufacturer	Vehicle type	Battery type
Audi	Passenger EV	NMC
BMW	Passenger EV	NMC
GM	Passenger EV	NMC
Hyundai	Passenger EV	NMC
Kia	Passenger EV	NMC
Mercedes-Benz	Passenger EV	NMC
Porsche	Passenger EV	NMC
BYD (China)	Passenger EV	LFP
Hongguang	Passenger EV	LFP
Ford	F-150 EV	NMC
Tesla	Short range passenger EV	LFP
Tesla	Long range passenger EV	NCA
Volkswagen (2023)	Entry level passenger EV	LFP
Volkswagen (2023)	High end passenger EV	NMC
Rivian	Electric trucks and SUVs	LFP
Rivian	Delivery vans	LFP
Chinese OEMs	Class 8 truck	NMC

Source: S&P Global, Fitch Solutions, EV manufacturers, JPMAM. March 2022.

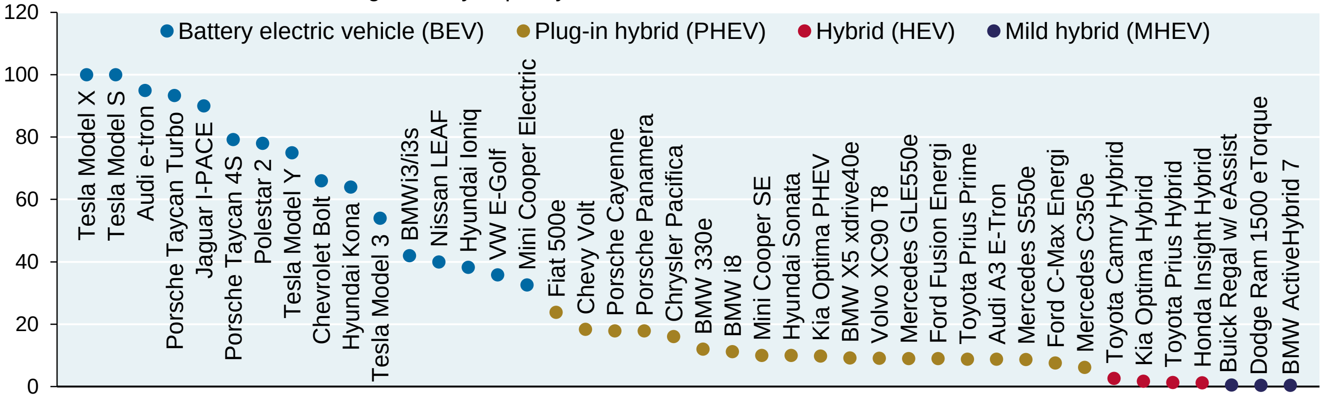
[13] Assuming 25 mpg for a gasoline car, 3 miles per kWh for an EV, $4 gasoline, 14 cents per kWh for electricity and 11,000 miles driven per year, EV owners would save ~$1,250 per year in fuel expenses. Comparing this annual amount to the incremental upfront cost of an EV over a gasoline car yields the payback period.

EV exhibits: penetration as a share of sales and as a share of fleet size

Most EV analyses include battery electric vehicles (BEV) and plug-in hybrid electric vehicles (BHEV) since the prime mover in both cases is the electric motor, even though some PHEVs have large backup fuel tanks. Most do not include hybrid electric vehicles (HEV) since its primary mover is usually an internal combustion engine, although this depends on the length of average trips and other driving behaviors. The first chart shows battery capacity by EV type. The subsequent four charts show BNEF forecasts of how quickly EVs as a % of sales translate into EVs as a % cars on the road. I'm not endorsing their forecasts since BNEF is often overly optimistic on a lot of things; but their modeling is a good illustration of the relationship between the two variables.

Electric vehicle battery capacity by type

Kilowatt hours, sorted in descending order by capacity

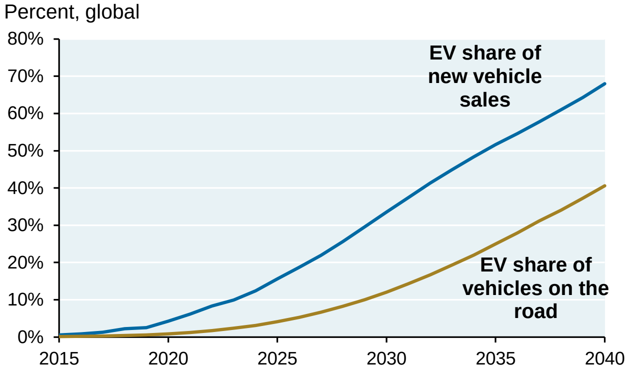


Source: Car and Driver, Automotive World, vehicle manufacturers. February 2021.

Note: light duty vehicles are < 3.5 tons; medium duty 3.5 tons to 15 tons; heavy duty > 15 tons.

Passenger vehicles

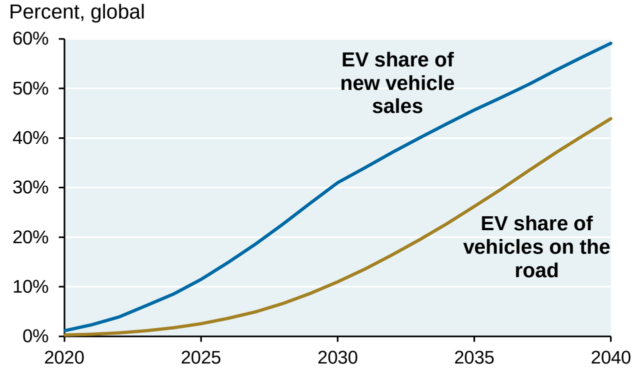
Percent, global



Source: BNEF. 2021.

Light-duty vehicles

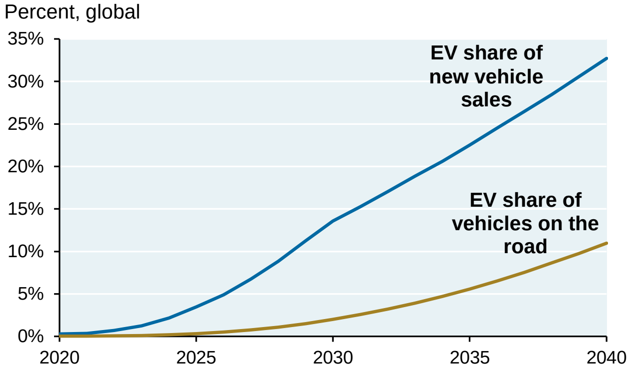
Percent, global



Source: BNEF. 2021.

Medium-duty vehicles

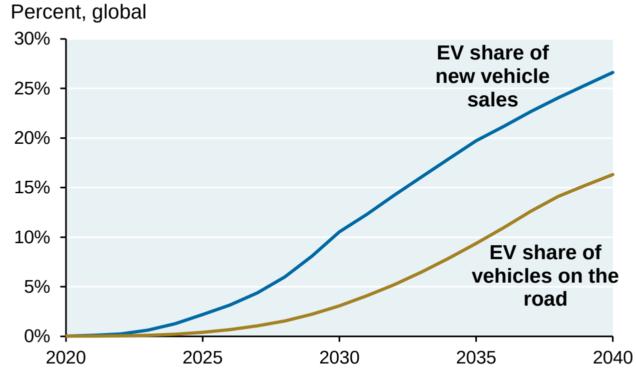
Percent, global



Source: BNEF. 2021.

Heavy-duty vehicles

Percent, global



Source: BNEF. 2021.

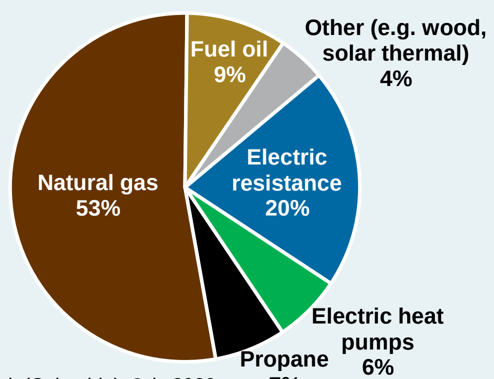
[3] Residential heat pumps and fossil fuel combustion bans: more complicated than it looks

Residential heating in the US and Europe is dominated by on-site combustion of natural gas and other fossil fuels. Some European countries and US cities have banned combustion of fossil fuels in new residences; San Francisco, San Jose, Denver, Seattle and New York City[14] are recent examples and there are more bans on the way (see page 26 on European bans). The goal: require electrification of new residential heating instead, which can reduce CO_2 emissions as more wind/solar are added to the grid.

First, let's review why electrification makes little sense using resistance (traditional baseboard) heating. In areas where grids are reliant on coal and natural gas, emissions would sharply *increase* compared to combusting natural gas on-site. The reason: the energy efficiency of gas and coal-powered electricity generation (including transmission losses) is often less than half the efficiency of on-site gas combustion that can exceed 90%[15].

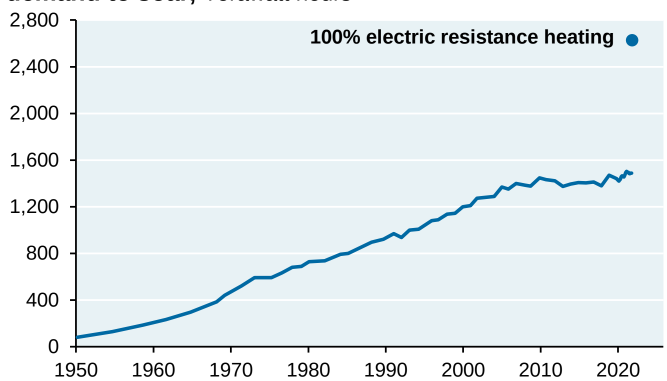
As a result, broad use of resistance heating could cause residential electricity demand to double, and that's not the only problem. As shown in the table, universal resistance heating could also increase peak loads in every Census tract in the US, each of whose peak loads would *more* than double[16]. The result: the need for more transmission and distribution which has to be built for *peak* loads rather than average ones. Given these outcomes, widespread electric resistance heating makes no sense, even in places with high renewable shares of electricity generation.

Natural gas dominates US home heating
% of total residential space heating energy



Source: Waite et al. (Columbia). July 2020.

Universal resistance heating would cause electricity demand to soar, Terawatt hours



Source: EIA, JPMAM. November 2021.

Table 1: Universal resistance heating would also cause peak loads and infrastructure needs to skyrocket

	Space heating shares			Residential emissions from all energy uses (mmt CO_2)			Electricity demand (TWh)		Peak load increases	
Scenario	Resistance heating	Heat pumps	Fossil fuels	Electricity	Fossil fuels	All	Space heating	All energy uses	Tracts w/ increased peak load	Average peak load increase in affected census tracts
Current	20%	6%	69%	250	339	589	368	1,382	NA	NA
All residences use resistance heating	96%	0%	0%	1,084	0	1,084	1,613	2,626	100%	135%

Source: Waite et al. (Columbia). July 2020.

[14] In December 2021, the **New York City Council** banned gas-powered heat and stove appliances in newly constructed buildings. The ban takes effect on December 31, 2023 for new buildings six stories and below. By July 1, 2027, it will include all new construction irrespective of size.

[15] "*Gas, oil and wood pellet fueled residential heating system emissions*", Brookhaven National Labs, Dec 2009

[16] Tables 1, 2 and 3 show output of a model of residential home heating and emissions built at the Census tract level by Michael Waite, Department of Mechanical Engineering at Columbia University. Michael worked with us on specific scenarios we designed after reading his February 2020 article in Joule Magazine, "*Electricity Load Implications of Space Heating: Decarbonization Pathways*" on air-to-air heat pumps in residences.

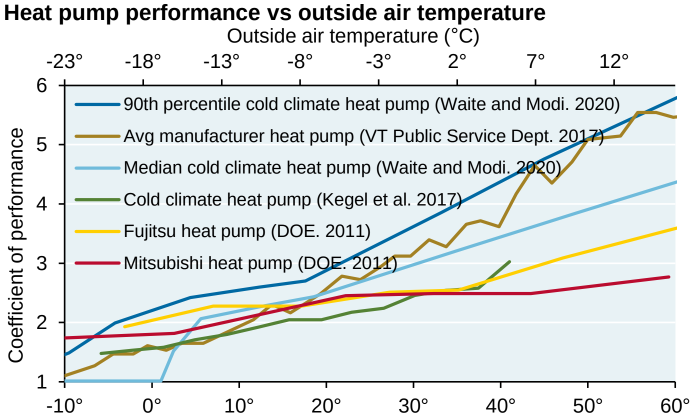
Fortunately, there's a better way: air-to-air electric heat pumps[17] can provide heat much more efficiently than resistance heating. A simplified heat pump explanation:

- Strange as it may seem, there's heat in the air even when the temperature outside is freezing. A heat pump extracts that heat using refrigerants as cold as -60°F (-51°C) that flow through the unit's outside coil. The refrigerant starts as a low temperature liquid, it absorbs heat and turns into a low temperature vapor
- The warmed refrigerant is then circulated to the interior via a compressor that increases its pressure and temperature, readying it to heat the interior air. The compressor is the main electricity-using component and since it's only driving heat transfer, it uses less energy than resistance heating
- The efficiency of a heat pump is defined by its "coefficient of performance" (COP), which refers to the amount of heat it provides per unit of electricity consumed. The higher the outside temperature, the greater the differential between the heat in the air and the unit's refrigerant, and the more efficient the heat pump will be. A COP of 1.0 would mean that the heat pump is only performing in line with resistance heating
- Estimates of heat pump efficiency vary (see below, left), but there's broad acceptance that they provide heat very efficiently at most ambient temperatures. As shown in the chart, heat pump COP might still be around 2.0x at temperatures as cold as 10°F (-12°C)

Heat pumps may need a seasonal average COP of 2.0-2.5 to make sense from a climate perspective, and higher to make sense from an economic perspective. Assume a home whose onsite combustion of natural gas is ~90% efficient, and that its regional utility is highly gas-reliant. Switching to gas-powered electricity would use roughly twice the energy at a COP of 1.0 given ~45% efficiency of modern combined cycle natural gas plants. So, a heat pump COP of 2.0 would be needed to match the energy/emissions of the original onsite natural gas burner.

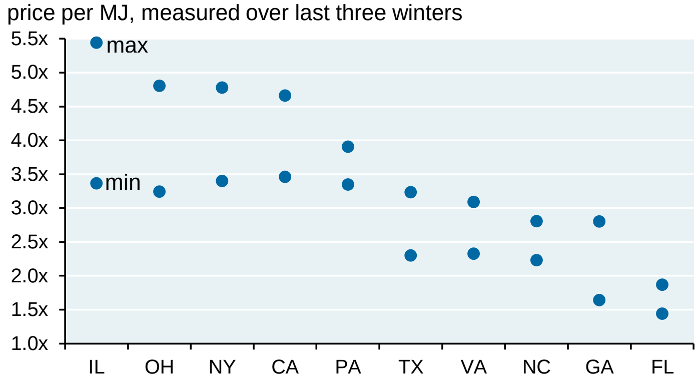
More renewable energy reduces the COP required for heat pumps to make sense from a climate perspective. However, there's still the issue of homeowner economics. Per unit of energy, US electricity was 2x to 5x more expensive than natural gas in many states over the last three winters. **As a result, a heat pump would need a COP of 2x to 5x in these places for fuel cost expenses to break even**. In other words: a heat pump's COP needs to be roughly equal to the multiple of electricity to fuel costs for homeowner fuel costs to break even.

Heat pump performance vs outside air temperature



Source: JPMAM. 2021.

US electricity costs 2x to 5x more than natural gas
Residential electricity price per MJ divided by residential natural gas price per MJ, measured over last three winters



Source: EIA, JPMAM. January 2022. Top 10 states by electricity consumption.

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[17] **I recently installed several Bosch heat pump/air conditioning units in my home**. Assume the temperature outside is 35 degrees and the temperature in the house is 55 degrees since the system is turned off. Assume I then turn on the heating system and set the thermostat to 68 degrees. My particular Bosch system uses the fuel oil system in tandem with the heat pump until the temperature in the house is 3-5 degrees below the thermostat target, at which point the heat pump would work on its own.

Broad heat pump adoption would entail large emissions declines, as shown in the third row in the table. But what about electricity distribution capacity which has to be built for PEAK loads, not AVERAGE loads? Broad adoption of heat pumps without backup power could cause peak loads to surge in many parts of the country on very cold winter days, requiring massive grid upgrades. The red zone in the third row shows the results: 2/3 of all Census tracts would experience higher peak loads with average peak load increases of over 100%.

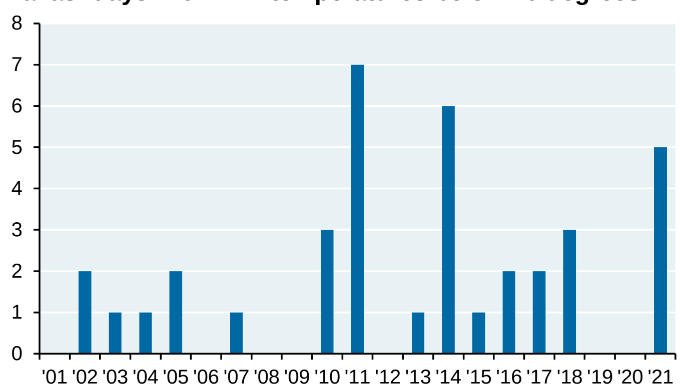
Table 2: Universal heat pump adoption slashes emissions but increases peak loads and infrastructure needs

	Space heating shares			Residential emissions from all energy uses (mmt CO_2)			Electricity demand (TWh)		Peak load increases	
Scenario	Resistance heating	Heat pumps	Fossil fuels	Electricity	Fossil fuels	All	Space heating	All energy uses	Tracts w/ increased peak load	Average peak load increase in affected census tracts
Current	20%	6%	69%	250	339	589	368	1,382	NA	NA
All residences use resistance heating	96%	0%	0%	1,084	0	1,084	1,613	2,626	**100%**	**135%**
All residences use heat pumps, no backup thermal power	0%	96%	0%	282	0	282	415	1,429	**63%**	**109%**

Source: Waite et al. (Columbia). July 2020.

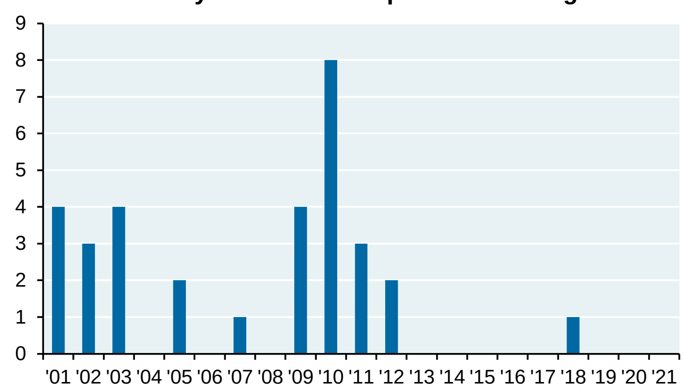
Temperature histories for Dallas and Tallahassee illustrate the issue. It doesn't get very cold that often, but there can be several days a year when minimum temperatures fall below 20°F (-7°C). As a result, any plan needs to account not just for average winter demand but for demand on the coldest days[18] when days demand could surge as illustrated in Table 2. If so, "smart" systems that switch to non-electric backup power on the coldest days could in theory reduce peak grid surges and reduce the need for transmission grid investment.

Dallas: days with min. temperatures below 20 degrees F



Source: NOAA, JPMAM. September 2021.

Tallahassee: days with min. temps below 20 degrees F



Source: NOAA, JPMAM. September 2021.

[18] While grid outages would negatively affect homeowners with electrified heating systems, boilers powered by gas, heating oil and propane also do not work without electricity. The big policy question: **would greater electrification of residential heating increase the frequency or duration of grid outages by overloading the grid with incremental demand?**

"Smart systems" could help…but what kind? Backup non-electric power looks like the right answer: this would still result in large reductions in fossil fuel use and emissions, but does not result in peak load increases anywhere in the US. This seems like a great solution but…**is it economically viable for the natural gas industry to maintain residential infrastructure for backup purposes only?** If not, the last row may not really be a viable outcome. Perhaps residential fuel cells could be used as backup on cold days to reduce grid surges, but now we're talking about even more structural change and higher all-in costs.

Table 3: Non-electric backup power on cold days eliminates peak load increases and grid buildout needs, but from what energy source?

	Space heating shares			Residential emissions from all energy uses (mmt CO_2)			Electricity demand (TWh)		Peak load increases	
Scenario	Resistance heating	Heat pumps	Fossil fuels	Electricity	Fossil fuels	All	Space heating	All energy uses	Tracts w/ increased peak load	Average peak load increase in affected census tracts
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All residences use resistance heating	96%	0%	0%	1,084	0	1,084	1,613	2,626	100%	135%
All residences use heat pumps, no backup thermal power	0%	96%	0%	282	0	282	415	1,429	63%	109%
All residences use heat pumps, backup thermal power in place	0%	93%	3%	268	13	281	405	1,419	0%	0%

Source: Waite et al. (Columbia). July 2020.

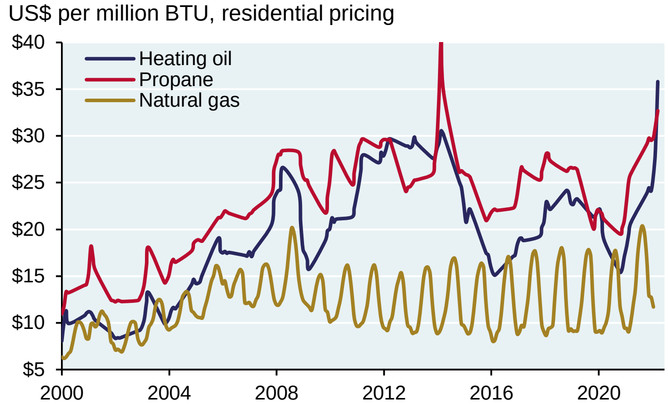
Economic incentives to switch. A separate analysis examined the economic consequences of residential heat pump adoption[19]. As shown in the next table, 40%-80% of homeowners using propane, fuel oil and electric resistance heating have economic incentives to switch to heat pumps. However, natural gas homes are by far the largest share of US residential housing stock, and the share of natural gas homeowners with incentive to switch to heat pumps is estimated at less than 10%. The primary reason for their lower incentives: **natural gas is usually much cheaper than propane and fuel oil**, as shown in the last chart.

Economic incentives to switch to heat pumps are much lower for homes heated by natural gas

Fuel type	Share of housing stock	% with economic incentive to switch
Natural gas	56%	8%
Electric resistance	20%	48%
Fuel oil	8%	40%
Propane	6%	79%

Source: Vaishnav et al (University of Michigan). 2021. Analysis assumes 2018 average fuel and electricity prices.

Natural gas is a lot cheaper than propane or fuel oil
US$ per million BTU, residential pricing



Source: EIA, JPMAM. March 2022.

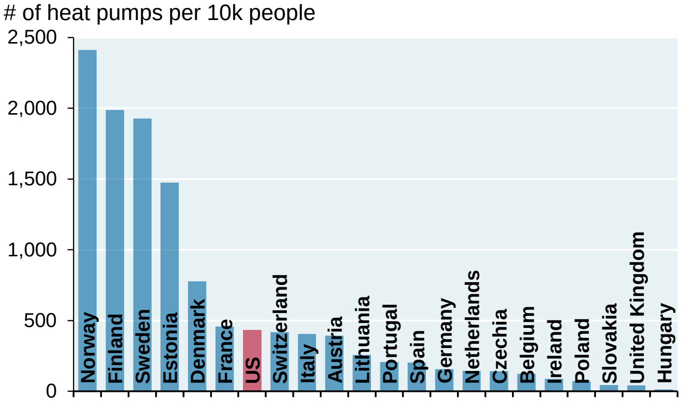
[19] See "*US residential heat pumps: the private economic potential and its emissions, health, and grid impacts*", Deetjen (UT Austin) and Vaishnav (University of Michigan), Environmental Research Letters, July 2021. Assumed heat pump costs: $3,300 (existing central air systems), $3,700 (without central air systems) or $4,800 (homes requiring removal of existing boilers); plus $143 * kW of capacity for purchase and installation; and up to $6,000 depending on need for ductwork

Heat pump adoption without backup thermal power can be done in cold climates. Heat pumps are popular in Scandinavia where they compete favorably with resistance heating, biomass and "district" heating (centralized heating from biomass and waste timber, and from data center excess heat). In addition to air-to-air heat pumps, other heat pump types extract heat from the ground or from groundwater. These heat pumps are often more efficient and have higher capacity since they're drawing from heat sources which are warmer than the ambient air (they also cost more due to installation and materials). As for heat pumps without backup power, homes in Scandinavia are more energy efficient as indicated by their lower energy consumption per dwelling on a climate adjusted basis than the rest of Europe[20]. US homes use ~2x the energy as homes in Europe and even more vs Scandinavia, increasing the difficulty of heating US homes via heat pumps with no backup systems in place.

Norway, for example, provided subsidies to switch, applied high fossil fuel taxes (basic plus carbon taxes are ~$130 per metric ton for fuel oil compared to just $11 in the US), its electricity prices are low and oil boilers were first restricted and now banned. **However, Norway is not a great template for larger, denser countries**. Norway has 5 million people, its population density is 10% of European levels and 97% of its electricity comes from cheap hydropower. The rest of the continent has to deal with larger surges in peak loads: 4x as much electricity can be used on a very cold day compared to a normal one. That might explain why heat pumps are used at lower rates in the rest of Europe: only 6% of Europe's 240 million residences have heat pumps installed.

Heat pump adoption highest in Scandinavia

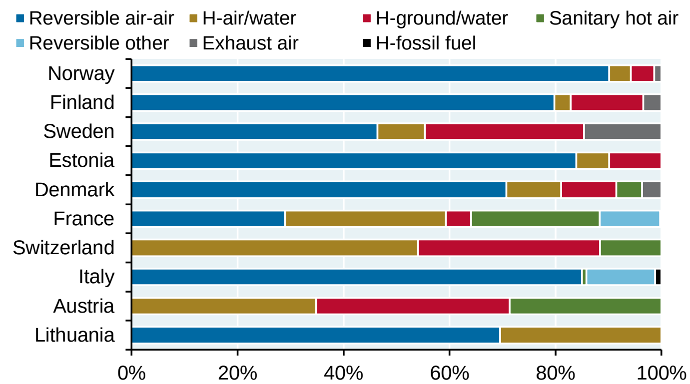
# of heat pumps per 10k people



Source: EHPA, European Statistical Office, Census. 2020.

Europe heat pump types

Percent of stock



Source: European Heat Pump Association. 2018. H = hybrid heat pump.

Europe aims to phase out fossil fuels for residential heating by 2040, and the IEA's 10 point plan for reducing European reliance on Russian energy also calls for a faster pace of heat pump adoption. To get there, 40% of residential and 65% of commercial buildings will need to be electrified by 2030 via 35 million new heat pumps[21]. As with green hydrogen, Europe will be a litmus test for the achievable pace of change in energy production and consumption. Combustion bans have expanded in Europe, which should increase heat pump momentum[22]:

- Denmark (2013) banned the installation of oil and gas boilers in new buildings
- Netherlands (2018) banned connection to the gas grid for new buildings
- Austria (2020) banned the installation of oil and coal boilers in new buildings
- Norway (2020) banned the use of oil for heating new and existing buildings
- France requires new construction after 2022 to meet maximum CO_2 emissions per square meter with different levels depending on the building type, effectively banning all mono-fuel fossil fuel systems
- Belgium's Flemish region introduced a ban on fuel oil boiler installation for new buildings and major energy renovations in residential and non-residential buildings starting in 2022
- Germany banned installation of mono-fuel oil and coal boilers starting in 2026

[20] "*International comparisons of household energy efficiency*", Odyssee-Mure Project, EU Commission

[21] *"How Norway Popularized an Ultra-Sustainable Heating Method"*, Peter Yeung, January 17, 2022

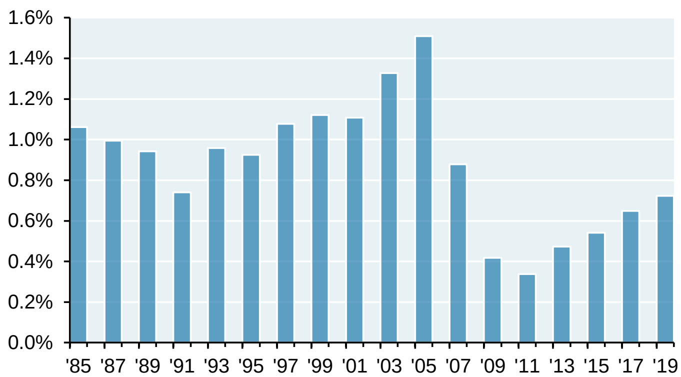
[22] "*Phase out regulations for fossil fuel boilers at EU and national level*", Institute for Applied Ecology, Oct 2021

Wrapping up: heat pump adoption will be slow if it relies mostly on new homes

Both studies we cited analyzed *existing* US homes and the costs and benefits of switching to a heat pump. For *new* homes, all-in costs for heat pumps can be lower given greater energy efficiency of a new home[23] and no need for retrofit ductwork. For new homes, heat pumps may even be cheaper than natural gas in more cases. In the US, heat pumps accounted for 40% of all new single family home heating units in 2020 and almost 50% for multi-family[24].

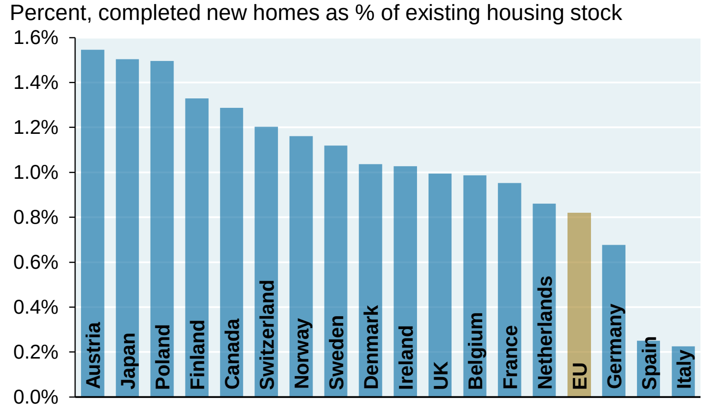
That's good news, but the transition to heat pumps will be slow if it relies mostly on new homes due to changing public policy: **new homes sales in the US and Europe average just 1% or less of the housing stock each year**. Think about it this way: a car can last 10-15 years before having to be replaced, while a house can last 40-50 years or more. Of course, burners and furnaces don't last as long as a house does. But they last a lot longer than cars do: the average life of a natural gas furnace is 15-20 years, and the average life of a fuel oil furnace is 20-25 years. Replacing them with new furnaces when they expire is also simpler than shifting to a new form of home heating. As a result, electrification of residential heating may be a slower process than electrification of transport, unless generous subsidies are provided to promote switching.

US single family home turnover per year
Percent, new single family home sales / single family housing stock



Source: Census, JPMAM. 2019.

European new home turnover per year
Percent, completed new homes as % of existing housing stock



Source: OECD, JPMAM. 2020 or latest year available.

[23] According to Harvard's Joint Center for Housing Studies, the average home built before 1960 consumes 42.5 thousand btu per square foot compared to 27.2 btu per square foot for a home built from 2010 to 2015.

[24] "*Heat Pumps: More Efforts Needed*", IEA, November 2021

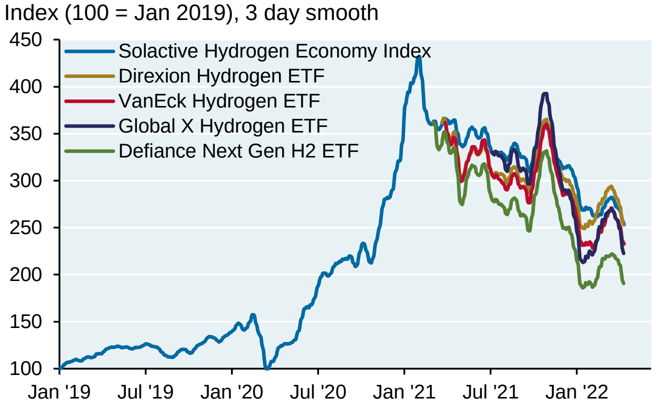
[4] Whydrogen? Use cases may be narrower than advertised, and the timeline is a long one

There's a lot of excitement about hydrogen. As shown below, hydrogen-linked equities quadrupled from 2019 to 2021 before falling 35%-40% from peak levels. Enormous hydrogen research reports are commonplace now, extolling the long-awaited arrival of the hydrogen economy[25]. Hydrogen is also mentioned as a critical option for Europe to reduce reliance on imported Russian energy.

To be clear, the hydrogen economy is in its infancy other than legacy hydrogen uses completely reliant on fossil fuels. As shown in the second chart, 90 million metric tons of hydrogen are used each year to produce ammonia for fertilizer, and in oil refining to reduce the sulfur content of diesel fuel. A very small amount is also used in steel production as an iron ore reducing agent alongside carbon monoxide. **In other words, almost no hydrogen is used in power, transport, home heating, shipping, rail, aviation or other widely discussed use cases**. And: practically all hydrogen is created via steam reformation of fossil fuels (grey hydrogen), with less than 1% created via electrolysis using renewable energy (green hydrogen). Hydrogen is not a native energy *source*, it's an energy *carrier*: ~2% of global primary energy is converted into hydrogen each year, a level roughly unchanged since the year 2000.

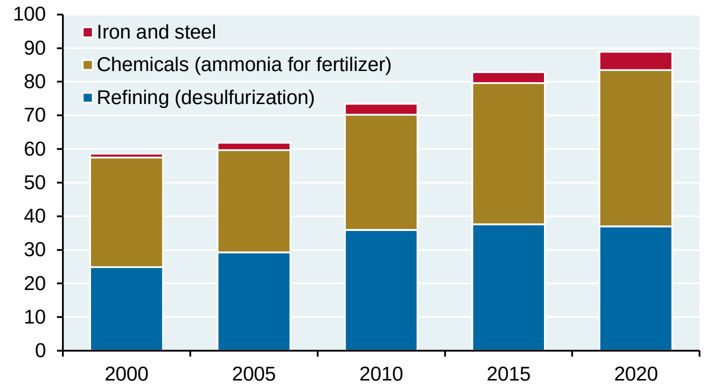
I got into a discussion with some bullish hydrogen energy analysts recently and it led to a longer conversation about hydrogen use cases. This section is a synopsis of that discussion.

The performance of hydrogen linked equities
Index (100 = Jan 2019), 3 day smooth



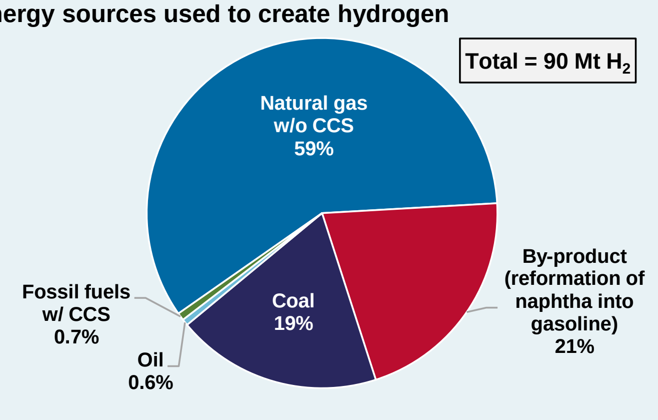
Source: Bloomberg. May 3, 2022.

Hydrogen demand by sector
Million metric tons



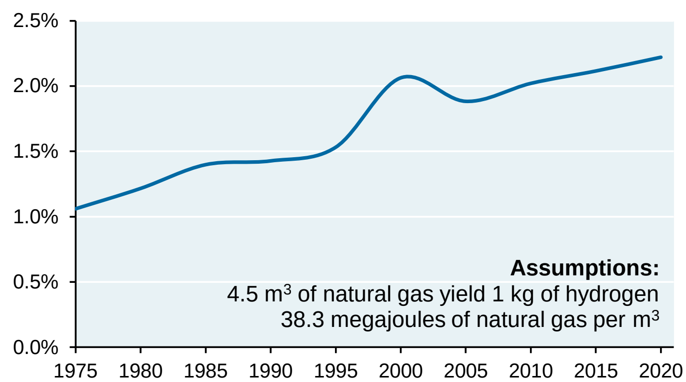
Source: IEA. 2021.

Energy sources used to create hydrogen



Source: IEA. 2020. CCS = Carbon capture and storage.

Share of global primary energy used to create hydrogen
%



Source: IEA, S&P Global, BP, NREL, JPMAM. 2020.

[25] Examples include these behemoths: "*Global Hydrogen Review*", International Energy Agency, 2021, 223 pages; *"Carbonomics: The clean hydrogen revolution"*, Goldman Sachs, February 2022, 144 pages; *"Hydrogen: A climate megatrend"*, Barclays, May 2020, 66 pages; *"EMEA Hydrogen: A revolution in need of realism"*, JP Morgan, February 2021, 157 pages; "*Green Hydrogen Cost Reduction*", IRENA, 2020, 106 pages

The long and winding road: a discussion with hydrogen optimists (HO) on the future

Natural gas field compressors and grey hydrogen energy math

- **HO**: In the US, 25,000 upstream, midstream and downstream natural gas field compressors account for 2%-3% of US natural gas consumption[26]. Midstream energy companies are now considering hydrogen to power them instead. GE has designed hydrogen fueled compression turbines with more than 100 in operation
- **MC**: Yes, but if they use today's "grey" hydrogen produced via steam methane reformation of fossil fuels (SMR) to power these compressors, they would *increase* CO_2 emissions compared to using natural gas directly due to the ~30% losses involved in the conversion of natural gas to hydrogen[27]

Pipeline blending

- **HO**: What about midstream companies considering hydrogen blends in existing natural gas pipelines?
- **MC**: Again, that only makes sense when using "green" hydrogen produced via renewables. In other words, it would make no sense to blend grey hydrogen into natural gas pipelines given the increase in CO_2 emissions that would entail (applying the same logic with respect to pipeline compressors). There's also the question of whether natural gas pipelines can physically *withstand* a lot of hydrogen

- **HO**: What do you mean; there are already hydrogen blending pilot projects underway
- **MC**: Pipeline engineers have to look for "embrittlement" which refers to cracking and other pipeline degradation. Valves, flanges, compressors and tubes need to be retested and at hydrogen blend rates over 10% some equipment might have to be replaced. While pilot programs have been launched in Scotland, Australia, Colorado, California and Long Island, pipeline blending needs more research. A new NREL study found that physical properties of steel, polyethylene and rubber are changed by exposure to hydrogen; and that hydrogen permeates metal and can permeate polyethylene walls 5x faster than methane[28]. Hydrogen leakage is also affected by pressure, contaminants, the angle of the pipeline and other factors
- **MC (continued)**: Even without leakage, hydrogen blending in gas pipelines has plenty of skeptics. The Fraunhofer Institute found that hydrogen blending would reduce emissions by 6%-7% and increase energy costs by 43%; the IEA estimates that hydrogen blending equates to emissions abatement costs of $500 per tonne of CO_2; and Agora Energiewende estimates that adding 20% hydrogen to the gas grid would increase European consumer heating costs by 33% in 2030

Blue hydrogen and commercial demand for CO_2

- **HO**: What if these field compressors and pipeline blends used "blue" hydrogen instead, which refers to grey hydrogen production combined with geologic sequestration of CO_2 via carbon capture and storage (CCS)?
- **MC**: CCS is the most overhyped industrial process in the modern era, with hundreds of academic papers written and still just 0.1% of global CO_2 emissions are sequestered underground. Europe is forging ahead with 76 CCS projects, mostly dedicated to enhanced oil recovery (EOR)[29]. Even so, Europe's sequestration potential from these projects in 2030 is 50 million metric tons per year of CO_2, which is 1% of its annual emissions. US sequestration potential from projects under development also amount to less than 2% of US CO_2 emissions[30]. Similarly, McKinsey estimated that global sequestration may only reach 1% of global emissions in 2030, and that's with supportive policies in place[31]. The CCS infrastructure required for a more substantial impact would be enormous, and rival the size of existing oil pipeline infrastructure[32]. By the way, recent research has thrown cold water on the climate benefits of blue hydrogen production

[26] "*US Natural Gas Compression Infrastructure: Opportunities for Efficiency Improvements*", Ebara Corp, 2018

[27] "*Updates of Hydrogen Production from SMR Process*", Argonne National Labs, 2019

[28] "*Hydrogen blending into natural gas pipeline infrastructure*", Topolski et al, NREL, October 2022

[29] "*CCUS In Europe*", IFRI Center for Energy & Climate, August 25, 2021 and Global CCS Institute

[30] *"Global Status of CCS 2021"*, Global CCS Institute, October 2021

[31] "*Driving CO_2 emissions to zero (and beyond) with carbon capture, use and storage*", McKinsey, June 2020

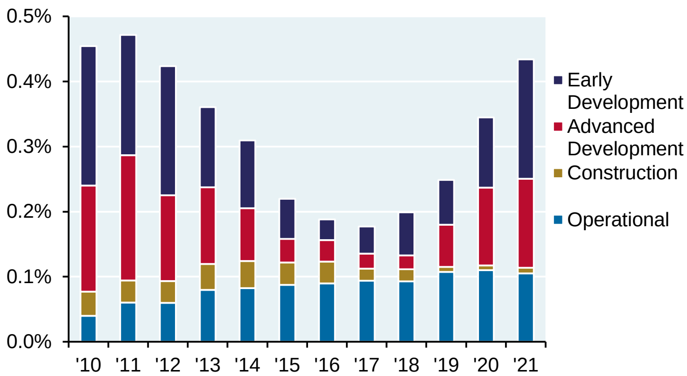
[32] See "*Future shock*", annual energy Eye on the Market, 2021, page 22

- **HO**: What cold water is that?
- **MC**: Robert Howarth at Cornell estimates that the GHG impact of blue hydrogen is more than 20% higher than the GHG impact of just burning natural gas or coal directly[33], due to additional energy demands of CCS, a typical capture rate that's well below 100% and the energy intensity of grey hydrogen production

- **HO**: Even so…what if there were growth in commercial demand for the CO_2 that grey hydrogen produces? CO_2 could be used for enhanced oil recovery (EOR) and other commercial applications
- **MC**: I don't get the sense that there's that much commercial demand for CO_2. It's only used in 2.5% of US crude oil production, and global EOR consumption of CO_2 in 2019 was just 72 million metric tons, which is 0.2% of global emissions. McKinsey cites potential CO_2 demand of 10,700 million metric tons in 2030 from producers of synthetic and algae based fuels[34], but that's another one of those "anything could happen" renewable energy forecasts which have little basis in currently commercialized fuel systems

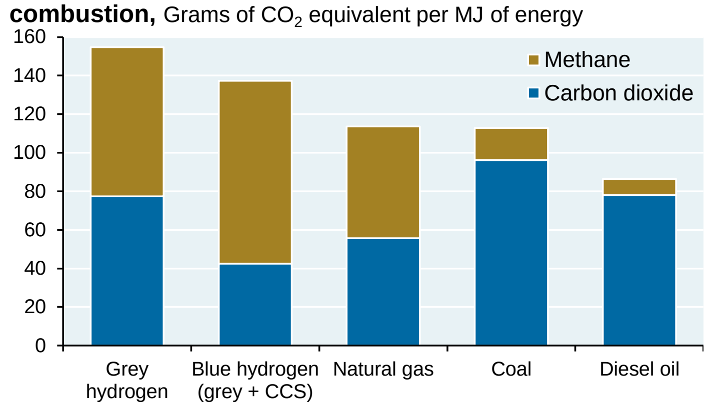
- **HO**: Existing CCS distribution networks are small, but what if large portions of the US natural gas pipeline network were repurposed for carbon instead once enough wind and solar exist?
- **MC**: I cannot envision such a thing taking place in my lifetime, and I am 60

Global carbon capture and storage capacity as a percentage of global CO_2 emissions, %



Source: Global CCS Institute. 2021.

Blue hydrogen GHG higher than direct natural gas combustion, Grams of CO_2 equivalent per MJ of energy



Source: *"How green is blue hydrogen?"* Howarth (Cornell). July 2021.

[33] "*How green is blue hydrogen?*", Robert Howarth et al, Energy Science Engineering, 2021

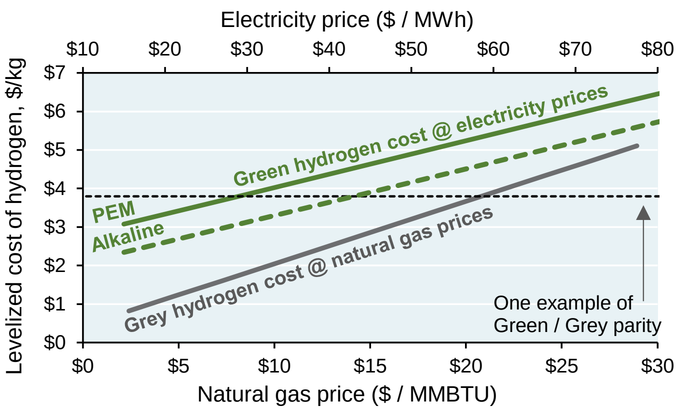
[34] "*Driving CO_2 emissions to zero (and beyond) with carbon capture, use and storage*", McKinsey, June 2020

Green hydrogen costs

- **HO**: OK, so let's talk about green hydrogen costs. Goldman Sachs projects steep declines in electrolysis costs that are similar to those achieved during prior learning curves on wind, solar and batteries (see page 39)
- **MC:** Yes, they expect green hydrogen costs to decline to $2 per kg by the end of the decade assuming high electrolyzer utilization rates, low renewable electricity costs and further declines in electrolyzer costs. That compares to current prices of $1 - $2 per kg for grey hydrogen, assuming natural gas prices of $2.5 - $ 10 per MMbtu (i.e., US levels). We'll see; actual adoption rates will tell us more than projections

- **HO:** In Europe, don't much higher gas prices put them a lot closer to green/grey hydrogen parity?
- **MC: Only if you believe that industrial companies base 20-year investment decisions on wildly gyrating spot market prices (which they generally don't)**. Start with the hydrogen cost curves below. They include amortized capital costs, operating costs and fuel costs (natural gas for grey hydrogen and electricity for green hydrogen). One example of parity: unhedged grey hydrogen producers paying $20+ per MMbtu for natural gas vs green hydrogen producers using PEM[35] electrolyzers paying $30 per MWh for wind and solar power (European PPAs are $5-$10 higher than that right now[36] and may rise further given inflation across wind and solar supply chains). **But this approach is only relevant if industrial companies consider today's price levels representative of the next 10-20 years.** Obviously, in Europe a lot depends on what happens to natural gas prices as Russian pipeline gas is gradually replaced by more imported LNG. For what it's worth, the forward curve for natural gas in Europe on May 3rd priced in a 33% decline by April 2024
- **MC (continued)**: I saw a chart in a hydrogen report entitled "Green H_2 Now Competitive Across Several End Uses". It showed $5.0-$6.5 per kg breakeven prices for green hydrogen for trucking, steel and ammonia. In my view, it was **very misleading**: the chart was based on wartime March 2022 spot prices of $35 per MMBTU in Europe for natural gas (the spot market in Europe is already down to $16); assumed no increase in electricity costs despite rising PPA levels; did not incorporate capital costs for steel production; and didn't make clear that the chart was only relevant for European producers. Furthermore, none of this information accompanied the chart. All of this is unfortunately standard practice in a lot of hydrogen research
- **MC (continued)**: My sense is that some green hydrogen projects underway are taking place *despite* their higher costs and not because they have reached cost parity. Timeline for adoption: very long

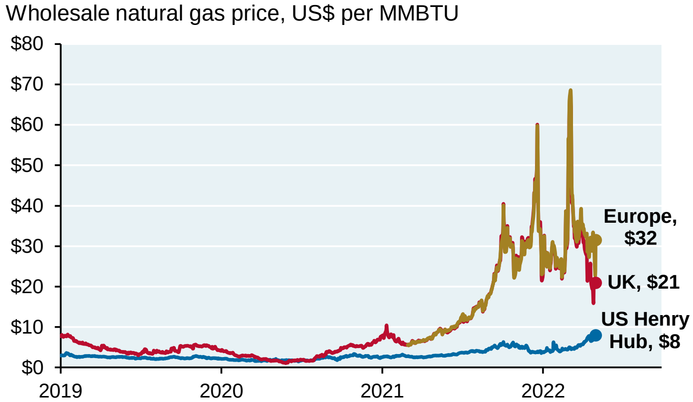
Green vs Grey hydrogen costs as a function of fuel costs



Source: Goldman Sachs Carbonomics data, JPMAM. 2022.

The US-Europe natural gas gap

Wholesale natural gas price, US$ per MMBTU



Source: Bloomberg. May 3, 2022.

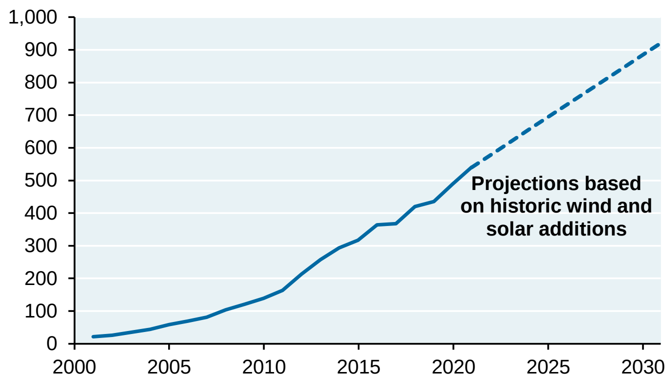
[35] PEM electrolyzers are considered better suited for hydrogen production relying on intermittent renewable energy, while lower-density alkaline electrolyers are targeted to bulk centralised industrial applications

[36] Source: Level Ten Energy Q4 2021 PPA P25 Index. **Breakeven dynamics will be more challenging for hydrogen producers paying industrial rather than wholesale prices for electricity**. For example, US wholesale electricity prices averaged 5.6 cents per kWh in 2021 while industrial prices averaged 7.3 cents per kWh.

- **HO:** Even so, Europe looks like it will be a global leader in green hydrogen production
- **MC:** Europe plans on producing and importing green hydrogen. Let's look at European production: there's 1.5 GW of electrolyzer capacity under construction. If we add in all projects that have reached the Final Investment Decision stage as well, Europe would have 40 GW of electrolyzer capacity. If all 6 million metric tons of green hydrogen from this 40 GW[37] were used for oil refining, that would offset ~2.5% of EU emissions. But if the green hydrogen were used for transport instead, the emissions offset would be lower due to fuel cell energy conversion losses in vehicles. Either way, these green hydrogen projects get the process started but are not transformational. The other question: where will all the green electricity come from to *run* these electrolyzers??
- **MC:** Rystad Energy estimates that globally, announced hydrogen projects may reach 40 million metric tons per year by 2030. However, if used to replace brown hydrogen in oil refining, it would offset just 2% of global emissions, and that's assuming a zero carbon footprint for blue hydrogen projects which comprise around half of the projects Rystad analyzed. As discussed earlier, the true carbon footprint of blue hydrogen is very much still an open question.

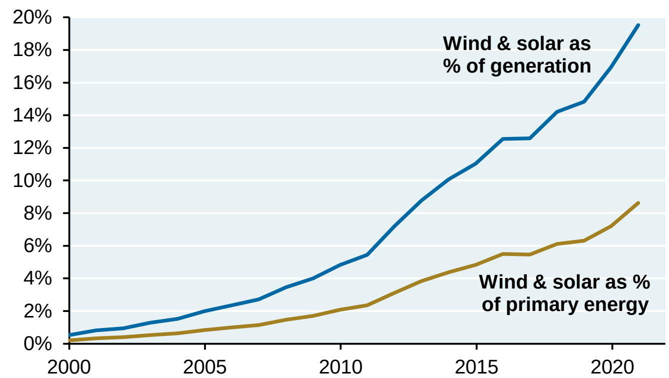
- **HO:** What do you mean; Europe is building a lot of wind and solar power
- **MC: Yes, but how many energy uses can draw on the same green GW?** Europe generates ~40% of its electricity from renewables, almost half of which is from hydropower. One of Europe's primary stated goals is to further decarbonize its electricity grid. European solar and wind generation has grown at ~38 TWh per year since 2010. At the current pace, Europe will add another 380 TWh of renewable power by 2030[38] which would increase its renewable share of electricity generation by another 10%-15%. So if Europe's wind and solar additions are mostly used to displace coal, gas and decommissioned nuclear power on the grid, I don't see where all the new hydrogen-dedicated wind and solar capacity is going to come from. If new renewable generation is used primarily for hydrogen, then what happens to grid decarbonization?

European Union wind and solar electricity generation
Terawatt hours



Source: Ember, Agora Energiewende. 2021.

European Union wind and solar energy
Percent



Source: BP Statistical Review of World Energy, JPMAM. 2021.

- **HO:** Don't forget about the green hydrogen that Europe plans to import as well
- **MC:** Germany just entered into a partnership with companies in the UAE to provide green hydrogen, possibly shipped in liquid form via Liquid Organic Hydrogen Carriers (see p. 34) since there are no hydrogen pipelines in place. But there are a lot of details to work out. First, this all starts with a UAE demonstration project which will generate blue hydrogen rather than green hydrogen. Other projects are underway for the importation of blue and green ammonia into Germany, but again, this is all very early stage

[37] Some industry sources estimate that each GW of electrolyzer capacity could produce 0.15 to 0.18 million metric tons of hydrogen per year. This implies a high efficiency rate of 80%; in practice, the efficiency rate of a 1 GW electrolyzer could be closer to 50%.

[38] "*EU Power Section in 2020*", Ember Climate research

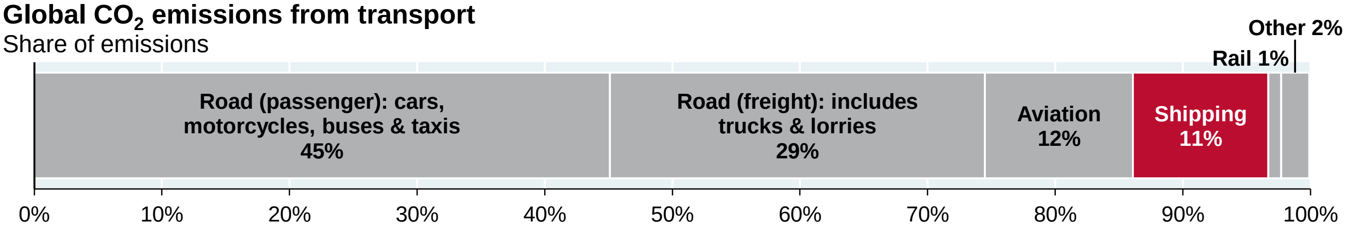
Long haul shipping using hydrogen or ammonia as fuel

- **HO**: Shifting gears for a minute, there's definitely potential for hydrogen as a fuel for long haul shipping
- **MC:** One thing's for sure: lithium ion batteries are nonsensical for shipping given cost and energy density constraints. Using state of the art electric batteries with 300 Wh/kg of energy density, an electric version of Maersk's Triple-E class containership might require 40% of its cargo capacity for batteries[39]. There's a start-up called Fleetzero looking to electrify long-haul shipping, but they don't have a working model yet. In principle, battery cargo space could fall to 15%-20% for regional trips of 10,000 km, assuming an energy density of 470 Wh/kg, and there are plenty of studies now hailing the arrival of electrified long haul shipping that's competitive with today's ICE fleet. But some commercialization is needed for proof of concept

- **HO**: Exactly, and that's why we think green hydrogen is a better fuel for ships than batteries
- **MC**: While hydrogen has high energy density by *weight*, it has a very low energy density by *volume.* The size of hydrogen storage tanks on ships might need to be very large, and if ships used liquefied hydrogen instead the refrigeration costs could be prohibitively high (liquid hydrogen has to be stored at cryogenic conditions of -253°C). A consortium of shipping companies recently highlighted critical development issues that still to be resolved: safety considerations for cryogenic liquid hydrogen, leakage/detonation risks and the need for new bunkering infrastructure[40]. A 2021 analysis in *Energy Environmental Sciences* highlights the challenge: there is no hydrogen storage solution that combines high energy density, low energy input, easily available and is easy to handle and store[41]

- **HO:** The challenges with using hydrogen as a shipping fuel have led some companies to focus on using ammonia as a shipping fuel instead, produced from green hydrogen via the traditional Haber-Bosch process. Wartsila and MAN have announced green ammonia engines for 2024, and large containerships designed to run on ammonia are now in the concept stage in China, Korea, Japan and the US
- **MC:** Green ammonia may be a promising hydrogen carrier given its hydrogen content (17.6%), its existing distribution network[42], its ability to be liquefied at higher temperatures (-33°C) than hydrogen, its higher volumetric energy density vs other alternatives and relatively low energy losses when transported over long distances. The hydrogen in ammonia could then be released through catalytic decomposition, or the ammonia could be consumed directly in a fuel cell designed for it. However, all these conversions carry energy penalties: when used in transport, the round-trip efficiency of liquid ammonia produced from green hydrogen may be just 11%-19%[43], even lower than ICE engines at ~25%. Timeline for adoption: long

Global CO_2 emissions from transport
Share of emissions



Source: Our World in Data. 2020.

[39] "*Electric container ships are a hard sail*", Vaclav Smil, IEEE Spectrum March 2019:22

[40] "*Five lessons to learn on hydrogen as ship fuel*", DNV Maritime, September 2021

[41] *Challenges in the use of hydrogen for maritime applications*", Van Hoecke (Antwerp) et al, Energy Environmental Sciences, 2021. Hydrogen shipping fuel storage methods analyzed in this paper include compressed hydrogen, liquid hydrogen, ammonia, Fischer–Tropsch diesels, synthetic natural gas, methanol, formic acid, aromatic liquid organic hydrogen carriers and several solid-state hydrogen carriers

[42] Synthetic ammonia has been used for over 100 years as fertilizer to feed 50% of the world population. Current annual production is 180 million metric tons (market value ~$70 bn) and is distributed by barge, rail cars and pipelines as part of a worldwide market with 120 ammonia-equipped ports

[43] *"H_2 and NH_3 – the Perfect Marriage in a Carbon-free Society",* El Kadi et al (Univ. of Cambridge), May 2020

- **HO:** Well, despite these low efficiency rates, there are some large green ammonia projects underway which are targeting the shipping fuels market and land-based markets too
- **MC:** Yes, I see that. A new carbon-free city is being built in Saudi Arabia, powered by 1.2 million metric tons per year of ammonia created from solar and wind (projected completion 2025)[44]. Also, Yara is planning a large ammonia project based on Netherlands offshore wind, one in Norway drawing on hydropower and another in Western Australia based on solar power. We'll see if this catches on, and at what cost after factoring in green ammonia production costs and other technical hurdles. Some estimates for green ammonia costs are 3x higher than conventional ammonia, such that green ammonia only becomes competitive at renewable power input costs of 2 cents per kWh and a carbon credit of $100 per ton[45]

- **HO:** What technical hurdles are you talking about?
- **MC:** Aligning ammonia production with renewable energy may require redesign of the energy intensive Haber-Bosch process to handle intermittent renewable energy, unless large battery storage is also deployed to store surplus renewable or thermal energy. Another issue: using a hydrogen fuel cell to harness energy stored in ammonia is complicated, since unreacted trace amounts of ammonia need to be removed to avoid poisoning fuel cell catalysts[46]. Bottom line: cost, energy loss and safety issues still to be sorted out

- **HO:** What about "liquid organic hydrogen carriers" such as dibenzyl toluene? It looks like a good hydrogen storage and transportation solution since it can react with hydrogen, remain as a stable liquid within a wide range of ambient temperatures and experiences no hydrogen losses in transport
- **MC:** Primary challenges: the energy required for hydrogenation and dehydrogenation (i.e., storing and releasing the hydrogen); its hydrogen density is low at 6.2% hydrogen by weight (the mass and volume of hydrogen transport would be inefficient); and there's also a need to return the "carrier" molecules back to the point of production to transport hydrogen again. Let's see what the ultimate cost and efficiency will be

Steel production

- **HO**: What about using hydrogen as a reducing agent in primary steel production instead of carbon? Swedish steel makers and Arcelor Mittal have both announced demonstration plants to do this
- **MC**: There are pilot projects in Sweden, the UAE and elsewhere. Using green hydrogen as a reducing agent, iron ore can be transformed into sponge iron and then converted to steel in an electric arc furnace using a lot of electricity and only a small amount of carbon, possibly pulverized coal (a process referred to as H_2 DRI-EAF, Direct Reduced Iron/Electric Arc Furnace)[47]. Some estimates show decarbonization potential of 70%[48]
- **MC (continued)**: But look at the timeline: McKinsey estimates "cash competitiveness" of Nordic hydrogen-based steel production sometime between 2030 and 2040, and that's assuming existing plants are simply written off before their useful lives are exhausted[49]. The Nordics also represent just 0.5% of global production; the **elephant in the room is China which produces more than 50% of the world's steel, and whose steel plants are younger than European counterparts (i.e., much further from their "mothball" dates)**. Arcelor Mittal announced that it has now made steel in Canada via partial use of the H_2 DRI-EAF process. But only 7% of the natural gas normally used in the DRI process was replaced, and it's still a demonstration project[50]. Timeline for adoption: long term, negligible global impact without China

[44] "*Is ammonia the fuel of the future?*", Petrochemicals Magazine, March 8, 2021

[45] "*Large investments, high renewable power costs challenge green ammonia*", IHS Markit, August 13, 2021

[46] *"H_2 and NH_3 – the Perfect Marriage in a Carbon-free Society",* El Kadi et al (Univ. of Cambridge), May 2020

[47] "*Hydrogen in steel production: what is happening in Europe*", Bellona Climate Foundation (Oslo), May 2021

[48] "*The Potential of Hydrogen for Decarbonization: Reducing Emissions in Iron and Steel Production*", Resources for the Future, Jay Bartlett and Alan Krupnick, February 2021. Hydrogen as a reducing agent might also be used for **aluminum and magnesium** but their carbon footprints are just 20% and 1% of steel, respectively.

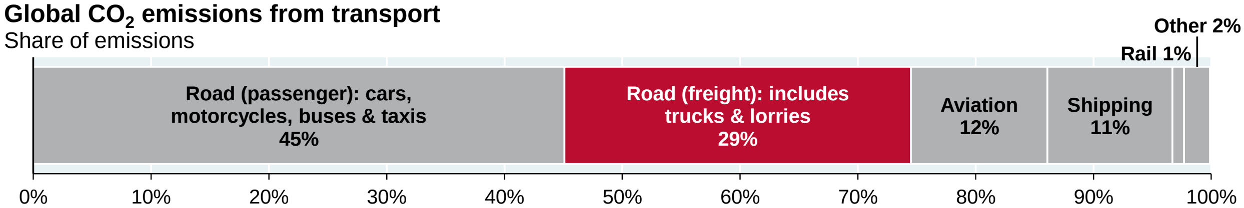
[49] "*Decarbonization challenge for steel*", McKinsey, June 3, 2020

[50] *"ArcelorMittal successfully tests use of green hydrogen at Canadian plant"*, Financial Times, May 2, 2021

Ground transportation (trucking)

- **HO**: Trucking looks like a great hydrogen use case given faster refueling
- **MC**: Think about the two major alternatives to internal combustion engines for vehicles:
  Electric: electric motor powered by a battery fueled via electricity sourced from renewable energy
  Hydrogen: electric motor powered by a fuel cell whose energy is sourced from hydrogen produced via electricity sourced from renewable energy[51]
  So: this debate is about cost, supply chain and operational differences between EV batteries (which are rapidly improving) and hydrogen fuel cells. I don't think fuel cells are compelling for passenger vehicles given fuel tank space constraints which make their range similar to EVs[52], but with higher energy conversion losses than EVs (see below) and less power[53]. However, sustained EV production bottlenecks due to lithium supply chain problems are a risk to monitor. For fuel cells, platinum supply chains are more important
- **MC (continued):** Using hydrogen for long haul trucking makes a bit more sense since compressed hydrogen allows for longer range and faster refueling, and there's fewer space constraints. For example: Freightliner's pending eCascadia class 8 EV truck weighs 82,000 pounds, has a range of 250 miles and mileage of 0.5 miles per kWh. In comparison, Hyzon's pending class 8 hydrogen fuel cell truck has the same weight, but with a longer range of 375-500 miles on 50-70 kg of hydrogen (it also *might* cost less as well)
- **MC (continued)**: But the word "**PENDING**" is important here since hydrogen truck companies are in their infancy and have limited track records for cost, performance, maintenance, durable lives, warranties, etc. Remember when the fuel cell truck company Nikola had its own "Theranos" moment[54]? Let's wait for actual vehicle sales before making projections. Long haul trucking could be a viable use case *if* green hydrogen costs decline, and *if* fuel cell trucks are delivered as advertised. One forecast: Cummins Engine expects just 2.5% hydrogen shares in long haul heavy duty trucking by 2030[55]. Timeline for adoption: medium term

Global CO_2 emissions from transport
Share of emissions



Source: Our World in Data. 2020.

Round trip efficiency of hydrogen in vehicles: starting with 1 kWh of renewable electricity (AC)...

	AC/DC conversion	Electrolysis	Hydrogen compression	Hydrogen transport/ transfer	Fuel cell	Electric motor
Efficiency	95%	75%	90%	80%	50%	90%
Remaining energy	95%	71%	64%	51%	26%	23%

Source: Center for Sustainable Road Freight (UK). As a comparison, EV battery round trip efficiency = 69% assuming 10% loss from AC transmission, 15% loss for AC-DC conversion/ battery charging, 10% loss from motor

[51] Many fuel cell trucks also contain an electric battery to store electricity generated by the fuel cell that is not immediately used, and to recapture vehicle braking energy

[52] A hydrogen car fuel tank cylinder that's 3 feet long and 1 foot in diameter, pressurized to 350-700 bar, would hold at most 2.8 kg of hydrogen. After fuel cell conversion losses at 50%, its effective capacity would be less than 60 kWh, compared to 100 kWh for the longest range Tesla

[53] Example: Toyota Mirai horsepower of 182 vs 670-1020 horsepower for Tesla Model S

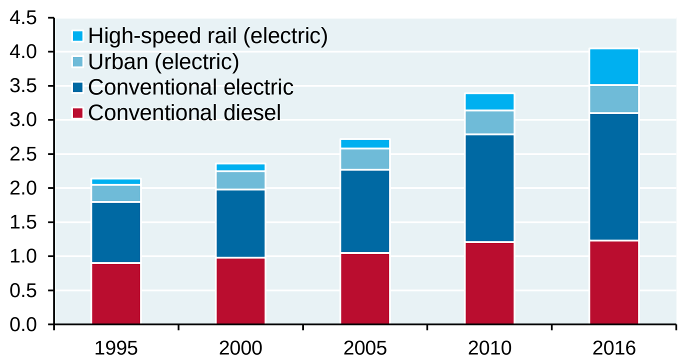
[54] **SPAC-launched Nikola Motors** was fined by the SEC for staging its hydrogen truck rollout. As per Federal prosecutors, the truck's gear box was empty during the demo since Nikola didn't have a working model. The company used extension cords, winches and masking tape to create the illusion of a truck propelled by hydrogen. See "*The rise of Trevor Milton and the collapse of Nikola trucks*", MEL magazine, February 2022

[55] "*Making sense of heavy duty hydrogen fuel cell tractors*", North American Council for Freight Efficiency, 2020

Non-electrified passenger and freight rail that still runs on diesel

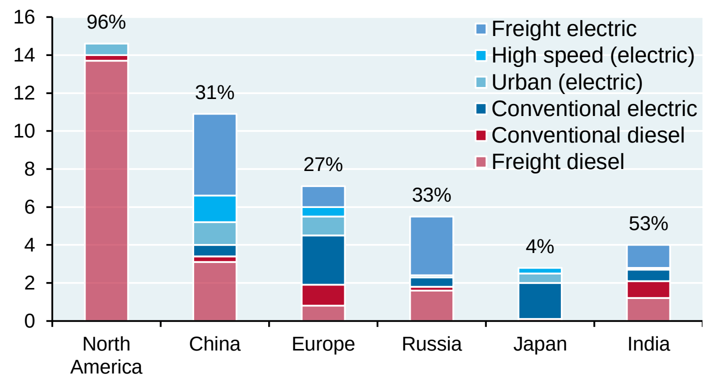
- **HO:** It makes no sense to use hydrogen to power trains that are already electrified, but what about all the passenger and rail freight that still run on diesel fuel?
- **MC**: Agreed on diesel trains, since the cost of extending overhead electricity infrastructure on long corridors can be very high[56]. There are hydrogen trains in operation, so proof of concept exists (China 2019, Germany Coradia iLint 2017, UK HydroFlex 2019). Alstom has an order book to provide additional fleets to operators in the UK and Germany. But let's look at the potential size of a hydrogen rail market. First, as shown below, rail only accounts for 1% of global transport emissions. And on passenger rail, 70% of global kilometers traveled were already electrified by 2016. The larger opportunity for hydrogen would be replacing diesel-powered freight, but in China, Russia and India, large portions of freight rail are already electrified as well
- **MC (continued)**: The largest hydrogen opportunity would be in the US which has a very large freight rail system that is almost entirely diesel powered, and which often carries 10x the payloads of European freight trains[57]. However, we see little movement on hydrogen for freight in the US, and there also might be competition from batteries. Since freight trains are already diesel-electric, a battery-electric pathway offers a cost-effective, long-term solution and could even function as a source of clean backup power[58]. One of the handful of hydrogen rail projects in the US: a small San Bernardino passenger rail project scheduled for completion in 2024. Timeline for adoption: very long term

Global passenger rail transport activity by fuel type
Trillion passenger-km



Source: IEA. 2019.

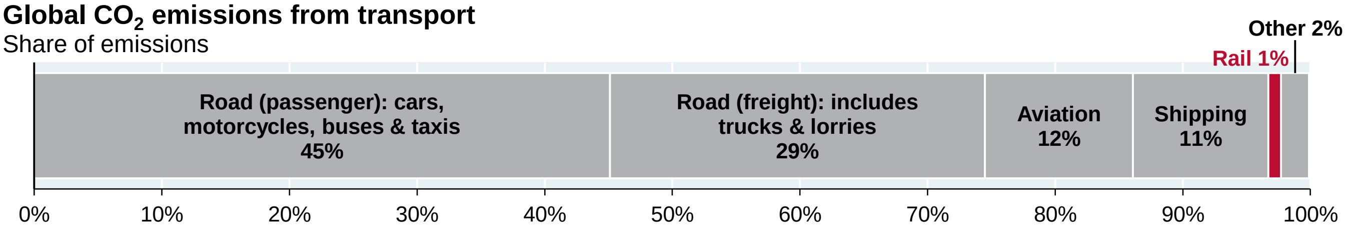
US freight is the largest non-electrified rail opportunity
Rail energy consumption, Mtoe, with share of diesel



Source: IEA. January 2019.

Note: in the charts, **conventional** rail is defined as medium- to-long distance non-urban passenger train journeys with a maximum speed under 250 kilometers per hour

Global CO_2 emissions from transport
Share of emissions



Source: Our World in Data. 2020.

[56] Extension of the electricity grid to power trains via overhead lines is referred to as "catenary infrastructure". A 2017 analysis from SINTEF research cited catenary expansion costs at 55 million Euros per year, 2.5x more than the cost of both hydrogen fuel cell and electric battery powered trains. Germany is testing **electric road systems** (overhead power lines that trucks access via overhead "pantographs") but if SINTEF is correct, this could be a very expensive option for freight transportation

[57] *"Technology Assessment: Freight locomotives",* CA EPA Air Resources Board, November 2016

[58] "*Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric*", Popovich (LBNL) et al, Nature Energy, November 2021

Backup power

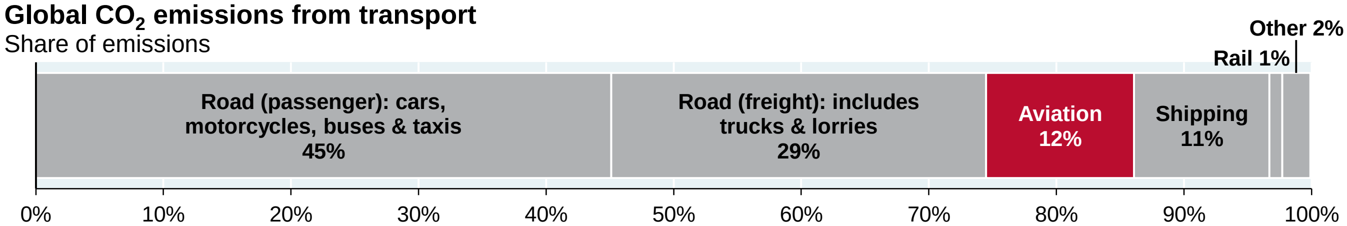
- **HO**: Well, there's always commercial back-up power demand which hydrogen can be used for
- **MC**: There are commercial back-up storage applications where hydrogen might make sense. One example is the need for wireless companies to provide more redundancy and power to remote cell tower networks as the 4G->5G transition occurs. They currently rely on diesel generators since most towers are not close to natural gas pipelines. Hydrogen storage tanks could be protected for safety purposes in these remote locations, but even here the cost per kWh could be ~2x the cost of power from existing diesel generators. Timeline for adoption: medium term but very small

- **HO**: What about residential backup power?
- **MC**: Most backup power companies offer diesel/gas generators and lithium ion batteries. There are startups offering residential hydrogen fuel cell systems. One can store 40 kWh of power, which is 3x the kWh of storage in the Tesla Powerwall. However, its power output is the same 5 kW (just enough for many central air conditioning systems), its energy efficiency is 50% compared to 85%-90% for the Powerwall, and it costs 3x more than the Powerwall before other added costs

Aviation

- **HO**: The last frontier on hydrogen is aviation. Did you see that Time Magazine called an aviation company's hydrogen technology one of the best innovations of 2020?
- **MC**: Cool your jets. That 8-minute flight on a tiny hydrogen prop plane relied on lithium batteries as well as its fuel cells, and the manufacturer reportedly had to replace four of the plane's five seats to accommodate the hydrogen storage tanks and other equipment[59]
- **MC (continued)**: Big picture…after accounting for hydrogen's lower fuel density (kilograms per cubic meter) and its higher gravimetric/specific energy density (joules per kilogram), a plane could hold 5.6x more jet fuel than pressurized hydrogen at 700 bars of pressure, and 3.3x more jet fuel than liquid hydrogen

Global CO_2 emissions from transport
Share of emissions



Source: Our World in Data. 2020.

- **HO**: Anything we haven't covered?
- **MC**: There are other ideas floating around such as building dedicated nuclear plants to generate electricity used for hydrogen electrolysis; using high nuclear heat for methane pyrolysis (thermal decomposition of methane) to produce solid carbon and hydrogen; and obtaining hydrogen from water via a thermochemical cycle. We will monitor these emerging ideas to see what their all-on costs of production end up being
- **MC (continued):** One more thing. Applications that entail delivery and transport of compressed hydrogen have to be highly controlled to prevent leakage. Hydrogen is the lightest gas and can cause ozone layer reduction. There's already evidence that non-automotive hydrogen sources are rising[60]. According to Environmental Defense Fund studies, higher levels of hydrogen leakage could substantially reduce the net benefits of a hydrogen economy[61]

[59] "*ZeroAvia's hydrogen fuel cell plane ambitions clouded by technical challenges*", TechCrunch, Sep 24, 2021

[60] "*Researchers find 70% increase in atmospheric hydrogen over the past 150 years*", Phys.org, Sep 10, 2021

[61] "*Climate consequences of hydrogen emissions*", EDF, July 2022

Whydrogen conclusions: a very, very long journey has just begun and some paths will be dead ends

A lot depends on how quickly costs of green hydrogen decline, the time/cost required to build electrolyzer, storage and distribution systems, *and* the time it takes for the world's machines and engines to be redesigned to use hydrogen instead. In other words, the hydrogen economy depends on more than just declining green hydrogen production costs per kg. Energy transitions are not just about learning curves and costs of energy production; the physical plant used for energy distribution and consumption have to change too.

Over the next decade, the "hydrogen economy" may entail pockets of modest demand for hydrogen used in natural gas pipeline blends, shipping/trucking, steel, commercial back-up power and non-electrified rail. If so, there may be opportunities for investors in specific hydrogen companies. But future hydrogen demand may bear little resemblance to the explosive hockey-stick growth forecasts common in today's renewable energy literature… and in the energy literature of the past as well (see below).

Hydrogen has a long history of being right around the corner

"Hydrogen economy: A practical answer to problems of energy supply and pollution" (*Science*, 1972)
"Hydrogen: Its Future Role in the Nation's Energy Economy" (*Science*, 1973)
"Clean hydrogen beckons aviation engineers" (*New York Times*, May, 1988)
"Hydrogen economy in the future" *(International Journal of Hydrogen*, 1999)
"Amory Lovins Sees the Future and It Is Hydrogen" (*Grist*, May 1999)
"The Hydrogen Economy" (Jeremy Rifkin, 2003)

Summary statistics for the Hydrogen Economy

Description	
Global CCS as % of global emissions, 2021	0.1%
Emissions potential of US and European CCS projects under development as % of regional emissions	1%-2%
Nordic share of steel production, 2020	0.5%
Conversion losses from natural gas to hydrogen using Steam Methane Reformation (SMR)	30%
Energy conversion losses from Alkaline and PEM electrolysis (energy value of hydrogen produced as a percentage of the energy in the electricity used)	25%-35%
Fuel cell efficiency (in conversion of hydrogen to electricity)	50%-60%
Round trip efficiency of fuel cells in transportation	25%
Round trip efficiency of hydrogen in transportation when liquefaction, shipping and regasification required	15%-30%
Round trip efficiency of liquid ammonia produced from green hydrogen for shipping	11%-19%
Energy lost in liquefaction of gaseous hydrogen into liquid hydrogen	30%-40%
Global enhanced oil recovery demand for CO_2 as % of global CO_2 emissions	0.2%

Sources: Argonne National Labs, National Renewable Energy Laboratory, Global CCS Institute, Clean Air Task Force, ICCT, ACS Energy Letters, Center for Sustainable Road Freight, University of Cambridge, BP, World Steel Association, Goldman Sachs, JPMAM, 2022.

Hydrogen color spectrum

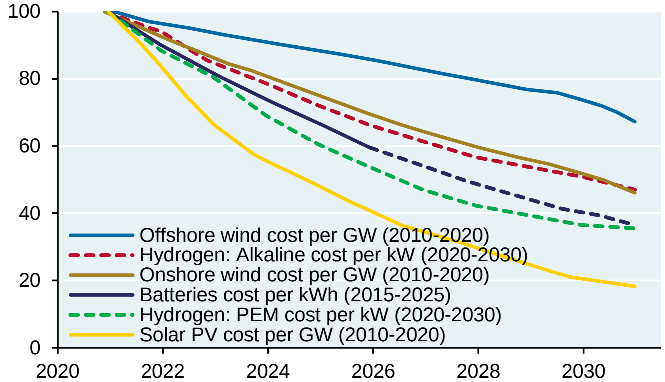
Green: hydrogen produced by electrolysis of water, using electricity from renewable sources like hydropower, wind, and solar. Zero carbon emissions are produced	**Turquoise:** hydrogen produced by the thermal splitting of methane. Instead of CO_2, solid carbon is produced
Pink/purple/red: Hydrogen produced by electrolysis using nuclear power	**Black/gray:** hydrogen extracted from natural gas using steam-methane reforming
Yellow: hydrogen produced by electrolysis using grid electricity	**Blue:** gray or brown hydrogen with its CO_2 sequestered or repurposed
White: hydrogen produced as a byproduct of industrial processes (i.e. fracking)	**Brown:** hydrogen extracted from fossil fuels, usually coal, using gasification

Source: North American Council for Freight Efficiency. 2020.

Whydrogen exhibits

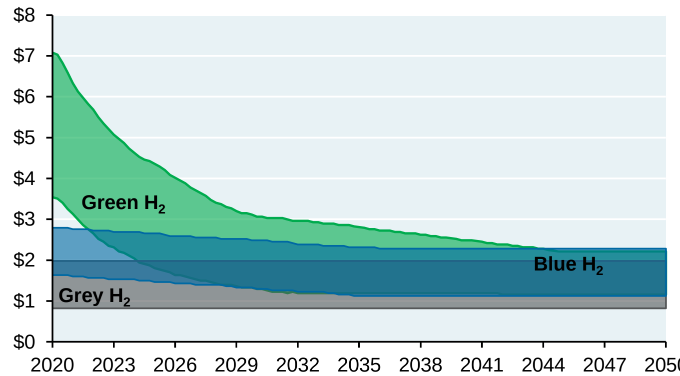
Current green hydrogen production is negligible but some researchers project increases due to falling costs of electrolysis. Goldman's recent report[62] is one example; they assume that prior learning curves apply to hydrogen, in which case its levelized cost could converge with blue hydrogen (which also doesn't really exist today at commercial scale) and with grey hydrogen by the end of the decade.

Learning curves
Indexed cost per unit of capacity



Source: GS. February 4, 2022. Dotted lines indicate estimates.

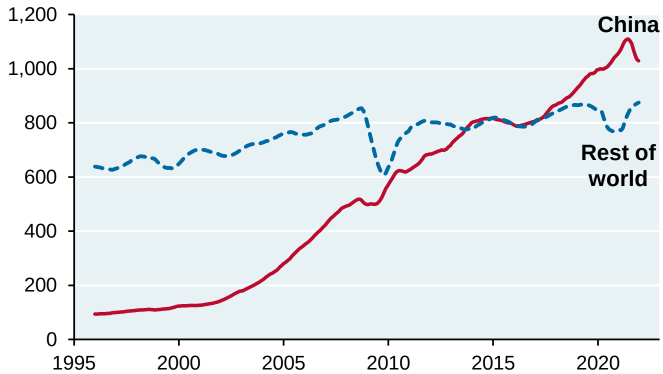
Hydrogen levelized cost projections
US$/kg



Source: GS. February 4, 2022.

China's dominance in global steel production:

Crude steel production: China vs rest of world
MIllion metric tons, rolling 12 month sum



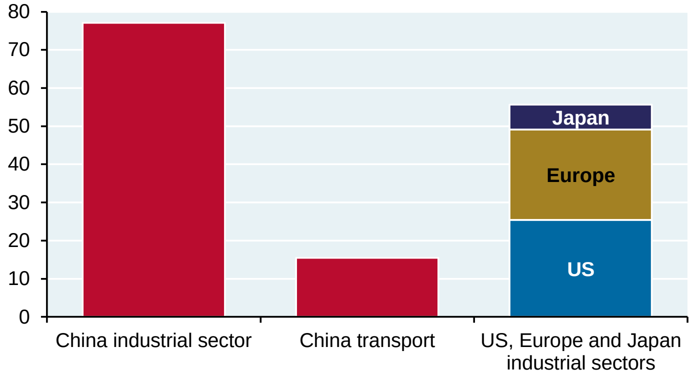
Source: Bloomberg, JPMAM. March 2022.

[62] *"Carbonomics: The clean hydrogen revolution",* Goldman Sachs, February 2022

[5] China deep decarbonization projections are built upon a mountain of very aggressive assumptions

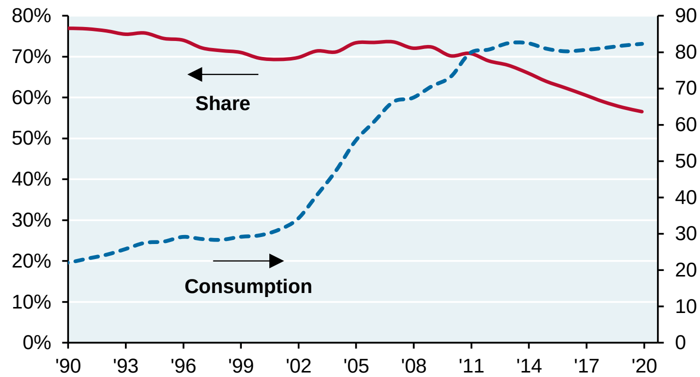
On energy, China is the elephant in the room. China's industrial sector consumes 4x more energy than its transportation sector, and more energy than US, European and Japanese industrial sectors combined. And as we discuss below, China's economy is still highly reliant on coal.

The elephant in the room: China's industrial sector
Quadrillion BTUs of final energy consumed



Source: Energy Information Administration, JPMAM. 2021.

China & coal: declining shares <> declining consumption
Share of primary energy
Exajoules



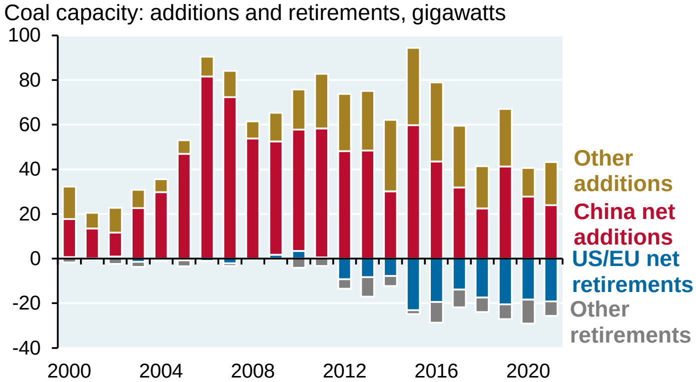
Source: BP Statistical Review of World Energy, JPMAM. 2021.

China and coal. While China's *share* of coal use in its primary energy is declining, its *absolute consumption* of coal has not declined at all. In 2020 and 2021, China built 67 GW of new coal plants while new capacity built in the entire rest of the world was just 35 GW. During these two years, China's coal fleet grew by 52 GW (net of retirements) while the rest of the world's net capacity declined by 23 GW. China also initiated 106 GW of new coal plants in these two years, over 5x the rest of the world combined. You get the point.

There's a lot of discussion on China's plan to forge ahead with nuclear power as the developed world mostly retreats from it. China has 50 GW of nuclear and plans to increase it to 130 GW by 2030[63]. The new nuclear plants will represent ~6% of China's 2030 electricity generation and ~3% of its primary energy. So, while nuclear is a material part of China's decarbonization agenda it is hardly a game changer on its own.

Bottom line: before we get into China's long term decarbonization plans, it should be clear that China today is a very coal-dependent place: coal accounts for ~60% of its primary energy vs 10% in Europe and the US.

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



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

China coal production
Million tonnes

Source: NBS China. December 2021.

[63] *"Nuclear power sector advances"*, China Daily, July 10, 2020.

I suppose we should give China credit for what they have accomplished so far. As shown in the table, China set decarbonization targets as part of its 12th and 13th five year plans and then either met or exceeded all of them. China has built ~40% of the world's PV solar and wind capacity, 50% of the world's electric vehicle stock and 70% of the world's solar thermal capacity[64]. China has also built some of the world's largest hydroelectric projects including the 16 GW Baihetan hydro station which is under construction and which will be the second largest in the world after China's 22 GW Three Gorges Dam[65]. And as illustrated on page 3, China is keeping pace with the OECD regarding renewables as a % of primary energy consumption. As a result, China can claim to be addressing climate issues with equal or greater success than the West.

Recent China Five-Year Plan targets and attainment

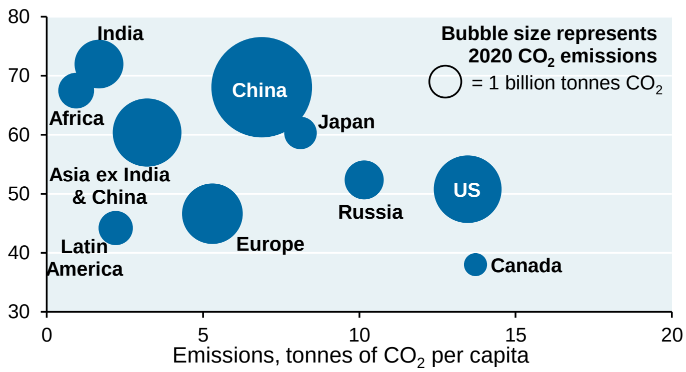
Target indicator	2011-2015		2016-2020		2021-2025
	12th FYP	Attained	13th FYP	Attained	14th FYP
Change in CO_2 intensity per unit of GDP	-17%	-20%	-18%	-19%	-18%
Change in energy intensity per unit of GDP	-16%	-18%	-15%	-14%	-14%
Total primary energy demand (TPED), billion tce	<4	4.3	<5	4.98	tbd
Share of non-fossil fuel in TPED	11%	12%	15%	16%	~20%
Solar PV capacity, GW	21	43	110	253	tbd
Wind capacity, GW	100	131	210	282	tbd

Source: IEA. 2021. tce = tonnes of coal equivalent.

The problem is two-fold. **First, China still has the highest CO_2 emissions and the highest CO_2 intensity of energy production in the world**. Second, these Plan targets were achieved during the easier part of the decarbonization process: the initial addition of intermittent wind and solar onto the grid. The next part of the journey gets harder. In this section, we look at deep decarbonization projections for China and find that they are built on a mountain of very aggressive assumptions.

CO_2 emissions by region in 2020

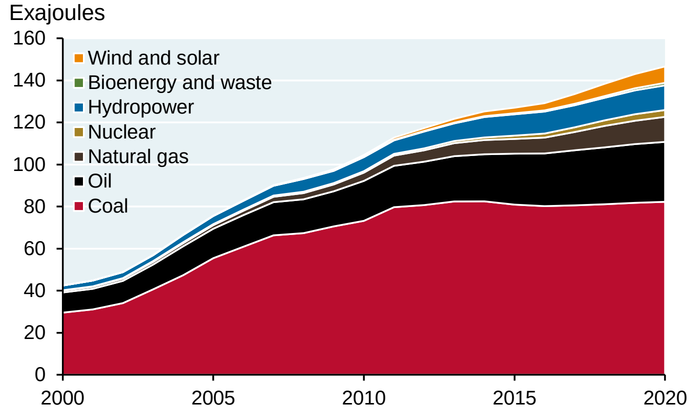
Carbon intensity of primary energy, million tonnes of CO_2 per EJ



Source: BP Statistical Review of World Energy, JPMAM. 2021.

China primary energy consumption by fuel

Exajoules



Source: BP Statistical Review of World Energy. 2021.

[64] *"An Energy Sector Roadmap to Carbon Neutrality in China",* International Energy Agency, September 2021

[65] For context, China has 15 operational hydroelectric dams of at least 3 GW. The US has two, the Grand Coulee Dam (6.8 GW) and the Bath County Virginia Dam (3 GW).

The IEA's deep decarbonization assessment on China

In September 2021, the IEA published a 300-page assessment of China's energy transition entitled "*An Energy Sector Roadmap to Carbon Neutrality in China*". According to the IEA, "China's many strengths make it well-placed to successfully carry out its own transition to carbon neutrality while also demonstrating international leadership in technology and energy policy making". In the report, there are two scenarios the IEA examines:

Stated Policies Scenario (STEPS): Assumes that policy goals adopted by China are implemented, including the following explicit commitments for the year 2030: reduce carbon intensity by over 65% from 2005 levels, increase non-fossil fuel energy to 25% from 16%, increase forest stock by 6 billion cubic meters above 2005 levels and double installed capacity of wind and solar to 1,200 GW

Announced Pledges Scenario (APS): Reflects a pathway to reach peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060, in accordance with targets that Chairman Xi announced in 2020

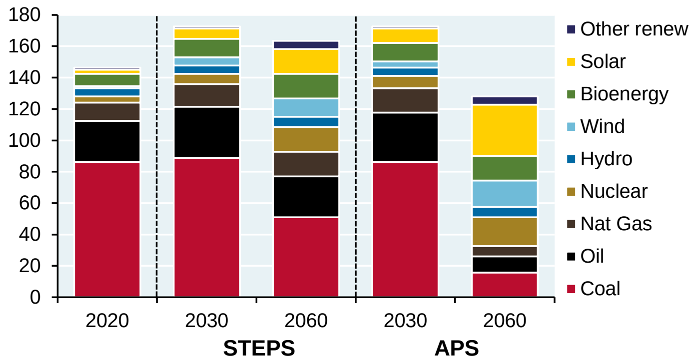
Energy demand and emissions for each scenario are shown below. Not much changes in either by 2030 but in the APS, rapid changes kick in after 2030 such that deep decarbonization is achieved by 2040. The STEPS scenario seems plausible enough but the APS scenario looks remarkably rapid, so we decided to take a closer look at it. Turns out the APS relies on some very aggressive assumptions which we group into three categories:

[A] A large outright assumed decline in Chinese primary energy demand

[B] A lot of assumed reliance on energy technology that is still in demonstration or prototype mode

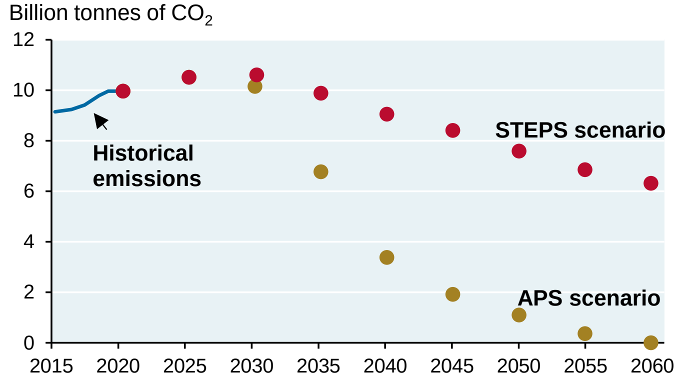
[C] The sudden and simultaneous electrification and decarbonization of everything

China primary energy demand by fuel by scenario
Exajoules



Source: IEA. 2021. STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

China energy-related CO_2 emissions by scenario
Billion tonnes of CO_2

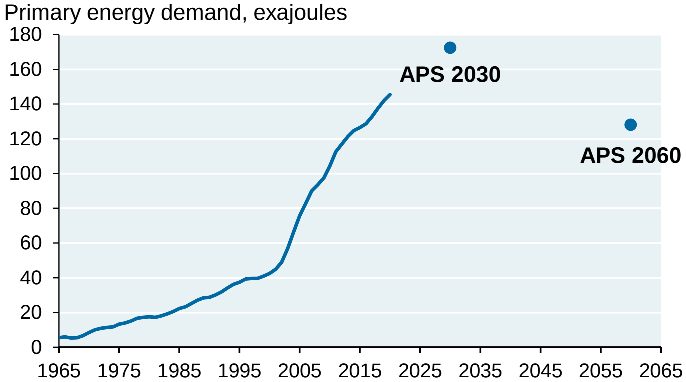


Source: IEA. 2021. STEPS = Stated Policies Scenario, APS = Announced Pledges Scenario.

[A] A large assumed decline in Chinese primary energy demand, particularly for a country very reliant on industrial production

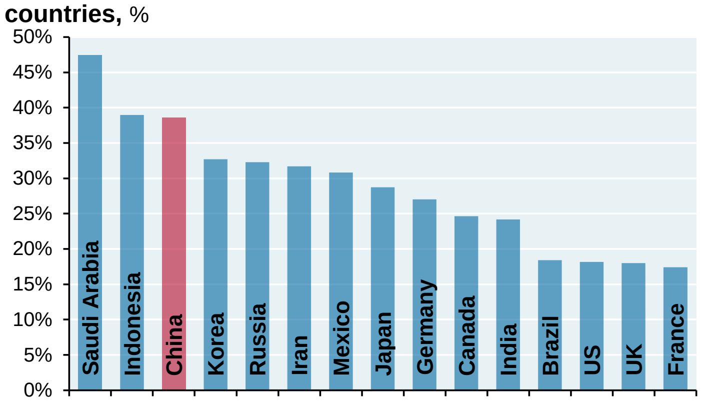
According to the IEA, Chinese primary energy demand will do an abrupt U-turn in 2030 and decline by 25% from its peak level. Such declines are not unprecedented; they occurred in Denmark after peak energy consumption in 1996, and in the UK after its deindustrialization (the UK ranks 30 out of 34 in the OECD with respect to manufacturing share of value added). Similar large energy declines also took place in many ex-Soviet Republics and in Venezuela when their economies imploded. Even so, the projected decline in Chinese energy demand looks very aggressive, particularly for a country heavily reliant on industry.

Will Chinese energy demand really make a U-turn?
Primary energy demand, exajoules



Source: BP Statistical Review of World Energy. 2021. APS = Announced Pledges Scenario.

Industrial share of GDP for top 15 energy consuming countries, %

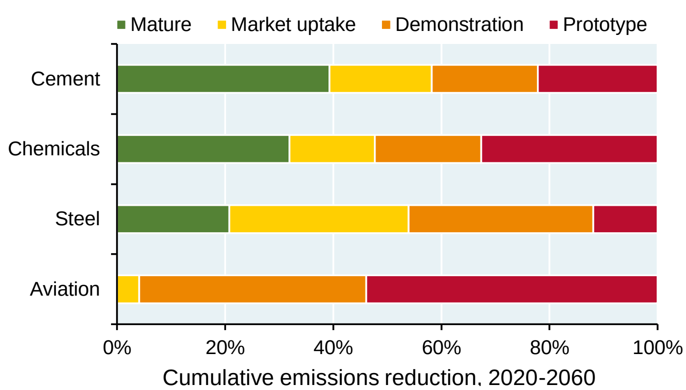


Source: World Bank, BP, JPMAM. 2019.

[B] A lot of assumed reliance on unproven energy and emissions technology

This chart does not need much explanation. A lot of the IEA's assumed emissions reductions in China are driven by technologies that are still in "demonstration" or "prototype" phases of development.

APS China emissions reductions by technology maturity



Source: IEA. 2021. APS = Announced Pledges Scenario

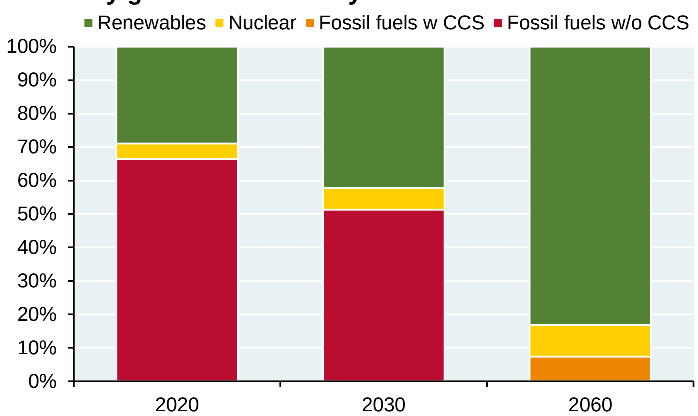
[C] Electrification and decarbonization of everything

According to the IEA, everything in China appears to get electrified and decarbonized at once. I cannot begin to comprehend how such a transition would occur simultaneously across electricity production, transmission and distribution; industrial production; long haul trucking; shipping; and just about everything else.

A few highlights: the growing dominance of renewables in the first chart, the outright decline in industrial energy consumption and rise of hydrogen in the second chart, the elimination of internal combustion engine trucks in the third chart and the wholesale transformation of shipping fuels in the fourth chart. This would be quite a U-turn for a country which as shown on page 40 is still the epicenter of global coal consumption.

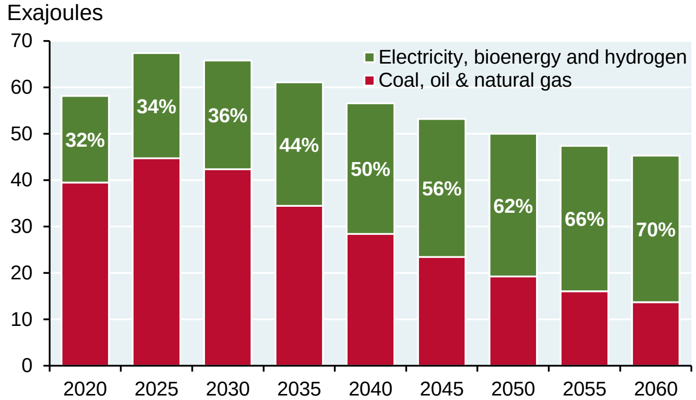
In the beginning of this year's paper, I recommended that you follow actual trends rather than hockey stick projections. That advice certainly applies to China's energy transition as well.

Electricity generation share by fuel in the APS



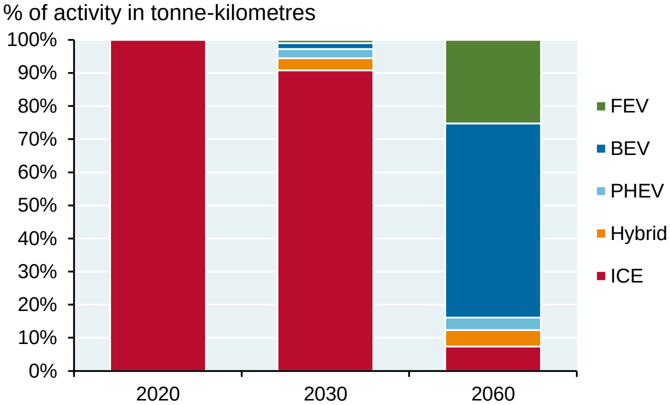
Source: IEA. 2021. APS = Announced Pledges Scenario.

China industrial final energy consumption in the APS
Exajoules



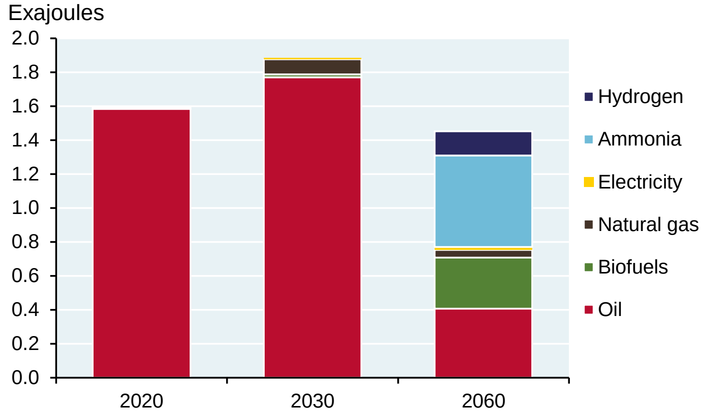
Source: IEA, JPMAM. 2021. APS = Announced Pledges Scenario.

Heavy-duty truck activity in the APS
% of activity in tonne-kilometres



Source: IEA. 2021. APS = Announced Pledges Scenario.

China shipping energy in the APS
Exajoules



Source: IEA. 2021. APS = Announced Pledges Scenario.

Closing comments: "Hello My Name Is…"

You may have concerns about wind power due to its decommissioning costs (~$450k per turbine); its disposal challenges (720,000 tons of wind projected waste over the next 20 years)[66] and negligible recycling as most old turbines are now dumped in landfills; its volatile year to year wind productivity (Europe wind generation was 10%-15% below average in 2021); its supply chain reliance on rare earth metals such as neodymium, praseodymium and dysprosium; and the growing share of power generation coming from non-baseload sources. All these points are at least worth debating (although there are counterarguments to many of them).

Birds killed by wind farms and "white noise syndrome" that drives birds and bats away from traditional habitats are also issues people mention. Some endangered species are highly vulnerable to wind turbines, such as golden eagles, condors, whooping cranes and raptors.

Efforts are underway to do something about it[67]: in Spain, bird watchers were able to alert wind farm operators and reduce bird fatalities by 50% while only losing 0.07% of wind generation. In the US, taller turbines reduced raptor and condor facilities by 50%-75%, and increasing the wind threshold at which turbines turn on from 4.0 meters per second to 5.5 meters per second reduced bat fatalities by 90% while only reducing wind generation by 1%. Another approach: painting one turbine blade black reduced bird fatalities by 72% in a field test in Norway. Artificial intelligence is also being used to train cameras to identify endangered species and then alert wind farm operators. In a field test in Wyoming using this approach, eagle deaths dropped by 70%-80%.

Whether these efforts are successful or not, my point is this. If you're one of those people that delivers diatribes against wind power due to bird deaths, and if you don't mention estimates of birds killed by other energy sources at the same time[68], and/or the 30% decline bird life since 1970 due in large part to rising temperatures[69], I made a name badge that you can use at the next conference you attend. This name badge also works for people who still believe that the 2021 Texas freeze was all about the decline in wind generation rather than the collapse in natural gas generation. Just print, cut it out and peel/stick. See you all next year.

Annual US bird mortality due to energy production

Cause	Avian mortality per year	Avian mortality per GWh
Wind energy 2011 (a)	32,657	0.27
Wind energy 2013 (b)	234,000	1.38
Wind energy 2015 (c)	300,000	1.56
Wind energy 2021 (d)	1,170,000	3.43
Nuclear power 2011 (a)	504,150	0.64
Coal 2011 (a)	**16,224,905**	**9.36**

Sources: (a) *"The avian and wildlife costs of fossil fuels and nuclear power"*, Benjamin Sovacool, University of Vermont, Journal of Integrative Environmental Sciences, 2012; (b) *"Estimates of bird collision mortality at wind facilities in the contiguous United States"*, Migratory Bird Center, Smithsonian Conservation Biology Institute, 2014; (c) US Fish and Wildlife Service; (d) Joel Merriman, American Bird Conservancy, 2021

66 Institute for Energy Research, 2019

67 "*The trouble with turbines*", Nature, June 2012; and "*The Power Environment: making wind turbines work for birds and bats*", Power Technology, February 2021

68 The US Fish and Wildlife Service estimates that tens of millions of birds are killed each year by pesticides, cars and cats. But that's not the point here; in a zero-sum world power has to come from someplace, and to discuss bird deaths from wind without mentioning bird deaths from other power sources is disingenuous at best.

69 "*Decline of the North American avifauna*", Rosenberg et al, Science, September 2019

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