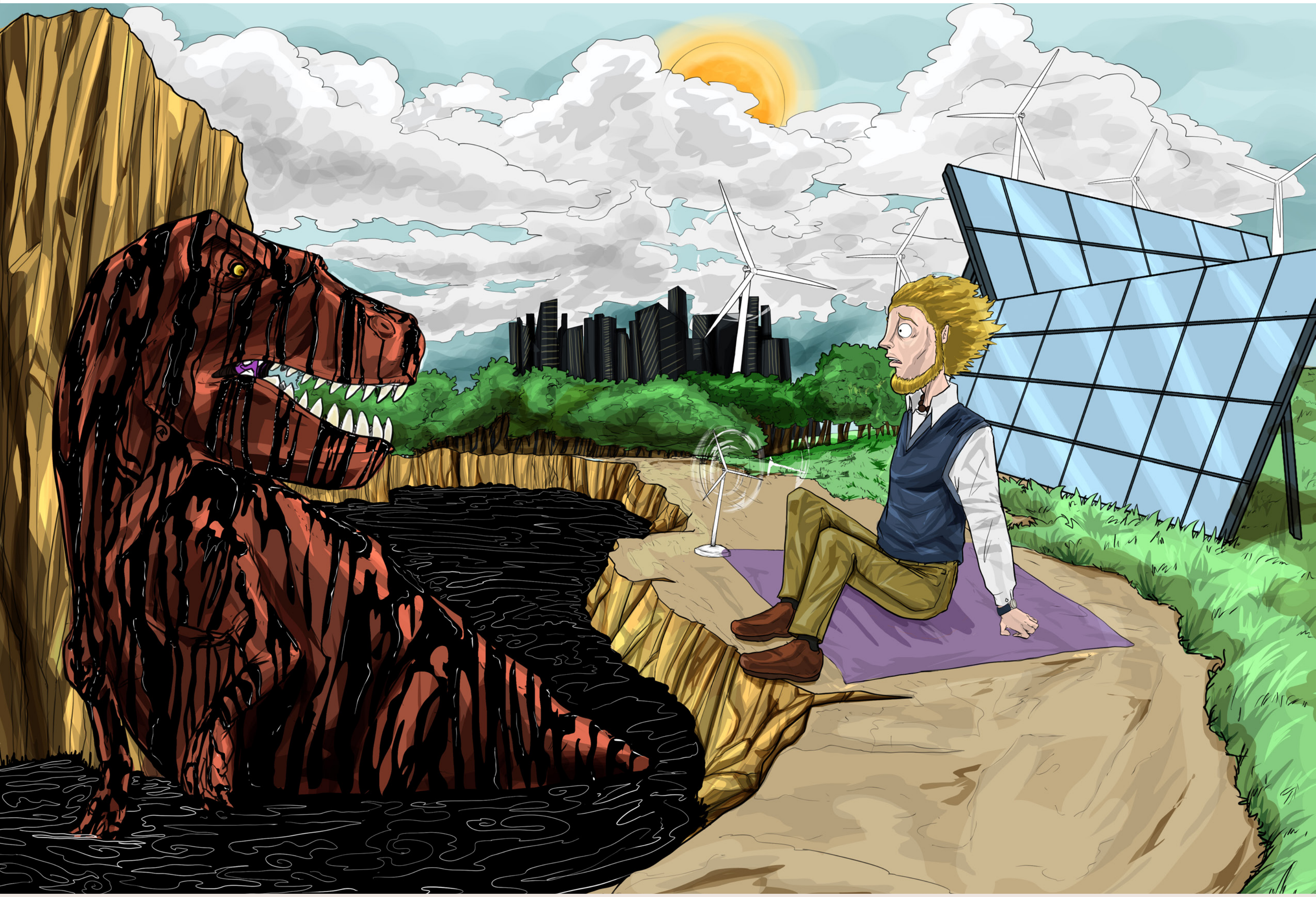
EYE ON THE MARKET

2021 Annual Energy Paper

MICHAEL CEMBALEST | JP MORGAN ASSET AND WEALTH MANAGEMENT



Future shock. Absent decarbonization shock treatment, humans will be wedded to petroleum and other fossil fuels for longer than they would like. Wind and solar power reach new heights every year but still represent just 5% of global primary energy consumption. In this year's energy paper, we review why decarbonization is taking so long: transmission obstacles, industrial energy use, the gargantuan mineral and pipeline demands of sequestration and the slow motion EV revolution. Other topics include our oil & gas views, President Biden's energy agenda, China, the Texas power outage and client questions on electrified shipping, sustainable aviation fuels, low energy nuclear power, hydrogen and carbon accounting.

J.P.Morgan

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Eye on the Market

Chairman of Market and Investment Strategy

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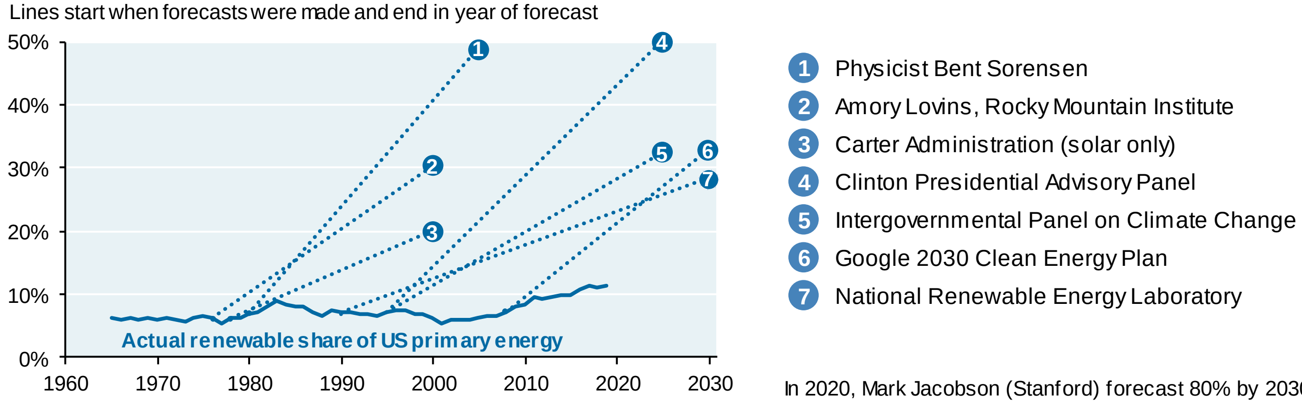
Welcome to our 11th annual energy paper. Each year, we examine what's happening on the ground as the fourth great energy transition unfolds. Our main focus this year: why is the transition taking so long? Deep decarbonization plans assume massive changes in electric vehicles, electricity transmission grids, industrial energy use and carbon sequestration, but each faces headwinds often not accounted for by energy futurists. As shown below, many prior forecasts of the renewable transition were too ambitious since they ignored energy density, intermittency and the complex realities of incumbent energy systems. We follow up with an update to our bullish oil and gas call from last year and examine Biden's energy agenda. We discuss China's rare earth metals diplomacy, US distributed solar power and conclude with last words on the Texas power outage and answers to client questions on electrified shipping, sustainable aviation fuels, hydrogen and carbon accounting.

As always, I would like to acknowledge the insights and oversight provided by our technical advisor **Vaclav Smil**, who has patiently guided my energy journey since this paper's inception 11 years ago. This effort has been one of the most rewarding experiences in my 34 years at JP Morgan.

Overly ambitious forecasts of the 4th great energy transition

Renewable share of US primary energy consumption

Lines start when forecasts were made and end in year of forecast



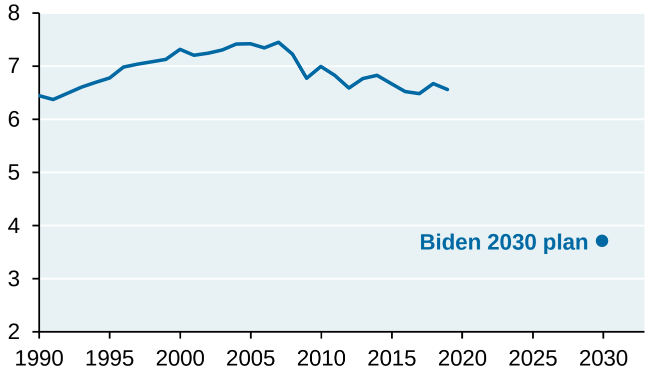
In 2020, Mark Jacobson (Stanford) forecast 80% by 2030

Source: EIA, listed authors, Vaclav Smil, JPMAM. 2019. Renewables include wind, solar, hydropower, geothermal, biomass, wood and waste.

Executive Summary

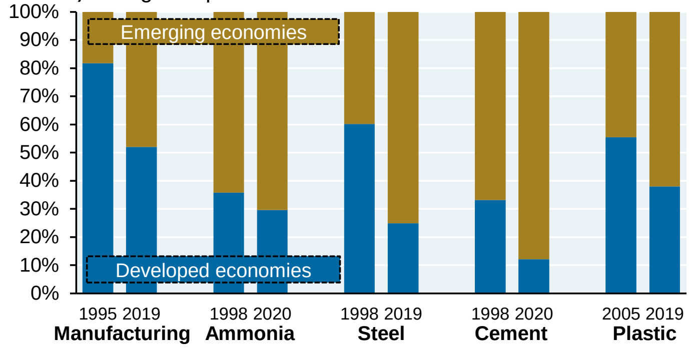
President Biden just announced a new GHG emissions target: a 50% decline by 2030 vs a 2005 baseline. This very ambitious target implies a decarbonization pace in the next 10 years that's four times faster than in the last 15 years. Even with the amount of money the administration plans to dedicate to the task, it's an enormous hurdle. In this paper, we will be discussing some of the reasons why.

The Biden plan: halving emissions from 2005 to 2030
GHG emissions, billion tonnes of CO_2 equivalent



Source: EPA, UN, JPMAM. 2019.

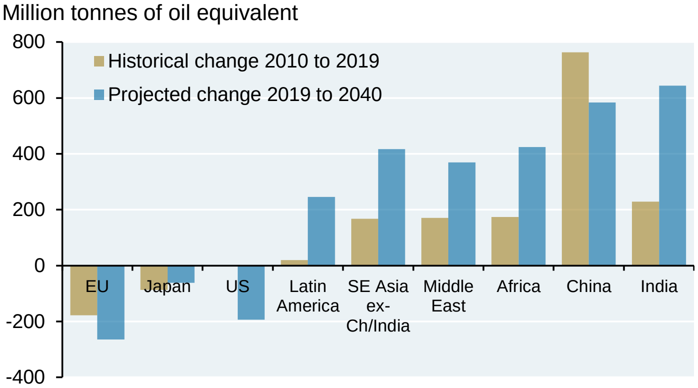
A shift in energy intensive manufacturing to the emerging world, % of global production



Source: UN Dept. of Social and Economic Affairs, Worldsteel, Plastics*Europe*, USGS. 2020.

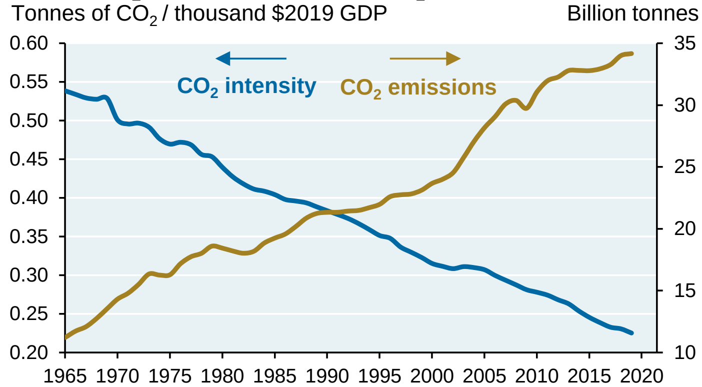
The even more important and larger question: even if the US succeeds, what about everyone else? Over the last 25 years, the developed world shifted much of its carbon-intensive manufacturing of steel, cement, ammonia and plastics to the developing world. As a result, **developing world adoption of wind, solar, storage and nuclear power may end up being the primary determinant of future global emissions outcomes**. That has certainly been the case over the last decade: Europe and Japan reduced primary energy use[1] by 4%-6% but developing world increases were 6x higher than their reductions; China/India energy use is still soaring; and Africa's energy use is rising from per capita levels seen in Europe in the 19th century. The world gets more energy *efficient* every year, but *levels* of emissions keep rising. That's why most deep decarbonization ideas rely on replacement of fossil fuels rather than reducing fossil fuel consumption per capita or per unit of performance.

Change in primary energy use, past and future
Million tonnes of oil equivalent



Source: International Energy Agency Stated Policies Scenario. 2020.

Global CO_2 intensity declining, CO_2 emissions rising
Tonnes of CO_2 / thousand $2019 GDP Billion tonnes



Source: BP Statistical Review of World Energy, Conference Board. 2020.

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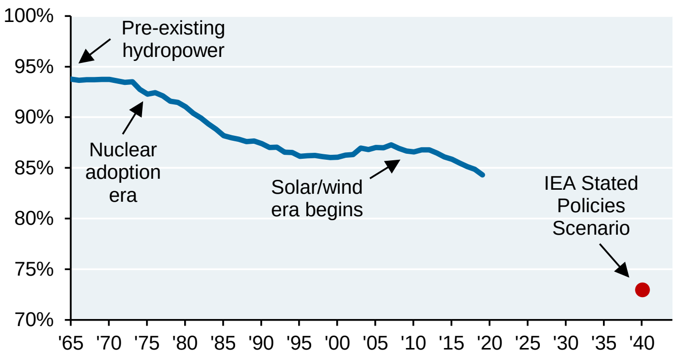
[1] **Primary energy** refers to thermal energy contained in fossil and biomass fuels and also to thermal equivalents of primary electricity generated from nuclear and renewable sources. Converting primary electricity to primary energy can be done by using its thermal equivalent (1 kWh=3.6 MJ or 3,412 BTU) or by using an average annual heat rate of fossil fuel plants (40% efficiency, equal to 9 MJ/kWh or 8,530 BTU). **Final energy consumption** is equal to primary energy less (a) energy lost in the conversion of fossil fuels (crude oil refining, natural gas processing) (b) energy lost in conversion of fossil fuels to electricity, (c) power plant consumption of electricity and (d) transmission losses.

How is the global energy transition going? Taken together, the aggregate impact of nuclear, hydroelectric and solar/wind generation reduced global reliance on fossil fuels **from ~95% of primary energy in 1975 to ~85% in 2020.** In other words, energy transitions take a long time and lots of money. The IEA expects fossil fuel reliance to decline at a more rapid pace now, fueled in part by "Big Oil" companies becoming "Big Energy" companies and by a faster global EV transition. In 2021 renewables are for the first time expected to garner more capital spending than upstream oil & gas. This process is influenced by diverging costs of capital: 3%-5% for solar and wind, 10%-15% for natural gas and up to 20% for oil projects.

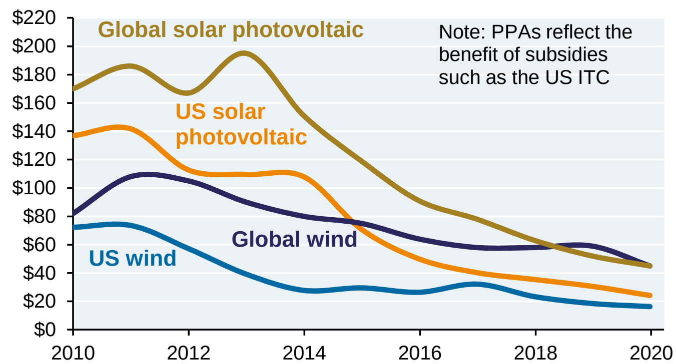
However, the IEA still projects that 70%-75% of global primary energy consumption may be met via fossil fuels in the year 2040. Why don't rapid wind and solar price declines translate into faster decarbonization? As we will discuss, renewable energy is still mostly used to generate electricity, and electricity as a share of final energy consumption on a global basis is still just 18%. **In other words, direct use of fossil fuels is still the primary mover in the modern world, as the demise of fossil fuels continues to be prematurely declared by energy futurists[2].** As shown in the last three charts, wind/solar capacity is growing and gains in renewable electricity generation are impressive, but in primary energy terms they are much smaller.

The world uses fossil fuels for ~85% of its energy
% of global primary energy consumption from coal, oil and nat gas



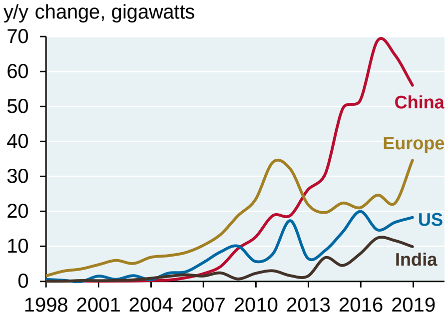
Source: BP Statistical Review of World Energy, IEA. 2020.

Average power purchase agreement prices for wind and solar, Real 2019 $ per megawatt hour



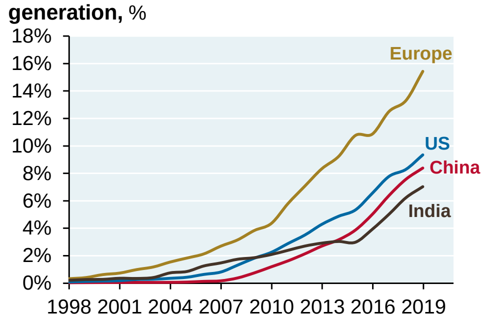
Source: Lawrence Berkeley National Laboratory, IRENA. 2020.

Wind and solar capacity additions
y/y change, gigawatts



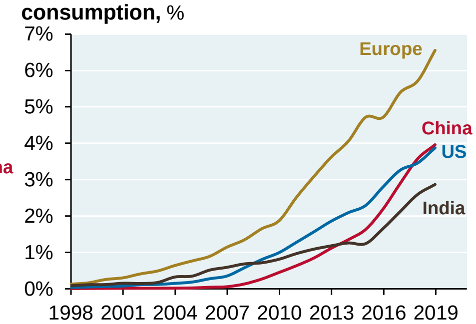
Source: BP Statistical Review of Energy. 2020.

Wind and solar share of total electricity generation, %



Source: BP Statistical Review of Energy. 2020.

Wind and solar share of total primary energy consumption, %



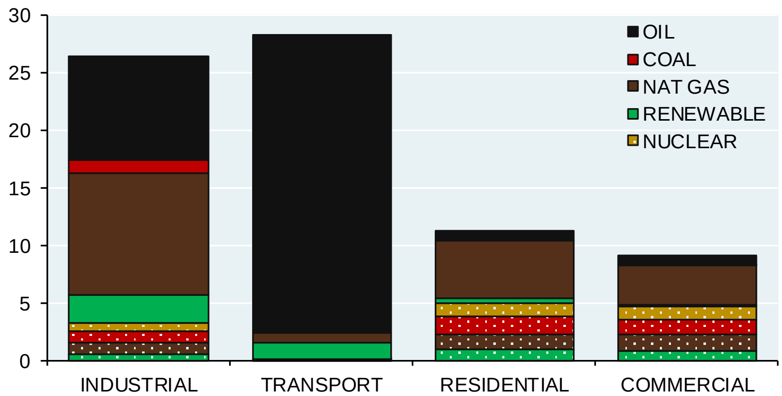
Source: BP Statistical Review of Energy. 2020.

[2] An example: the CEO of the **Rocky Mountain Institute** wrote last year, citing Carbon Tracker, that post-COVID global fossil fuel consumption may never surpass 2019 levels. **Really?** The EIA projects a full recovery in liquid fuels consumption by 2022 and projects the same for natural gas. Global coal consumption is projected to decline by 240 million metric tons from 2019 to 2025, but the IEA's projected increase for global natural gas consumption by 2025 of 390 billion cubic meters is 2.8x the decline in coal in energy (exajoule) terms. **So, even if liquid fuels consumption plateaus at 2019 levels, world fossil fuel demand has almost certainly not peaked yet.** Also: December 2020 global CO_2 emissions were *already* above December 2019 levels (IEA).

Let's take a closer look at energy consumption in the US, Europe and China which collectively represent a little over half of the global total. The charts show final energy consumption by end-user and type of fuel, with the dotted segments indicating electricity consumption, also broken down by fuel.

United States

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	99.9
Quads of final energy consumption	75.1
Electricity % of energy consumed	17%
Electricity % of industrial energy consumed	12%
Electricity % of transport energy consumed	0%
Fossil fuels % of primary energy	80%
Passenger car energy % of transport energy	60%
Passenger car energy % of primary energy	17%
Industrial fossil fuels % of primary energy	27%
Renewable % of electricity generation	18%
Renewable energy % of primary energy	11%
Low carbon % of electricity generation	40%
Low carbon energy % of primary energy	20%
Coal to natural gas ratio in primary energy	0.4
Hydropower share of renewable electricity	40%

Source: Energy Information Administration, JP Morgan Asset Management. 2019. Electricity generation segments are net of thermal conversion, power plant consumption and transmission losses. "Low carbon" refers to renewable generation plus nuclear generation.

The US is still highly reliant on fossil fuels which account for 80% of primary energy. Renewable electricity is the lowest of the 3 regions at 18%, although nuclear adds significant carbon-free electricity. Electrification of industry is the lowest of the three regions at 12%, and electrification of transport is almost non-existent. Around 5% of transport fuel comes from corn ethanol whose GHG benefits vs gasoline are still hotly debated[3]. The US coal-to-natural gas ratio has fallen way below one, a development which reduces air pollution and groundwater risks but whose GHG benefits are still debated as well. As per LBNL, 50% of the decline in power-related CO_2 emissions in the US since 2005 is attributable to coal-to-gas switching, a process which is now ~80% complete.

- *Natural gas is preferable to coal from a GHG perspective*. In its 2019 assessment of lifecycle emissions from natural gas and coal, the IEA concluded that over 98% of gas consumed today has a lower lifecycle emissions intensity than coal when used for power or heat. In its 2020 assessment, the IEA concluded that switching to gas results in average declines of 33% per unit of heat used in industry and buildings, and 50% when generating electricity. Moreover, the IEA found that about three-quarters of today's methane emissions from the oil and gas industry can be controlled by deploying known technical fixes

- *Natural gas GHG benefits vs coal are still unclear.* Some climate scientists are re-evaluating the share of methane emissions that come from pre-Industrial geologic sources vs those from coal and natural gas combustion. Estimates of the latter are rising[4], leading to downward revisions in the methane leakage break-even rate that renders natural gas better than coal from a GHG perspective. Estimates of natural gas methane leakage rates range from 2% to 6%, and the break-even rate vs coal may be as low as 1%[5]

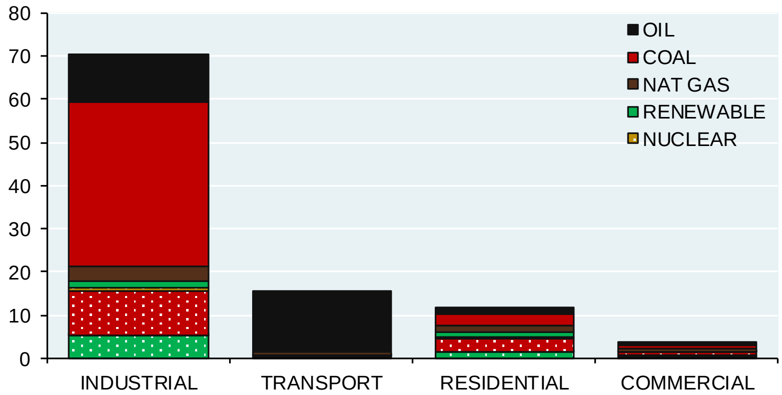
[3] EESI, Argonne Labs and the USDA cite 70%-95% reductions in carcinogenic particulates from **E10/E85 ethanol blends** and 20%-50% reductions in GHG emissions. However, most "EROI" analyses for corn ethanol range from 0.9 to 1.6 ("energy out" is not much different from "energy in"), implying that ethanol GHG savings are at the low end of that range. Unlike Brazilian ethanol whose bagasse is used in production, US ethanol production relies on natural gas. Corn ethanol has one of the lowest EROI measures of all forms of fuel/power; as inexact as EROI measures are, they suggest that corn ethanol is a political decision and not just an environmental one. Also: fertilization and irrigation of corn leads to enhanced nitrogen losses and aquifer depletion.

[4] "*Preindustrial CH_4 indicates greater anthropogenic fossil CH_4 emissions*", Nature, Hmiel et al, February 2020.

[5] "*Natural gas is a dirtier energy source than we thought*", NatGeo, Feb 2020 citing Robert Howarth (Cornell).

China

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	151.0
Quads of final energy consumption	101.5
Electricity % of energy consumed	23%
Electricity % of industrial energy consumed	23%
Electricity % of transport energy consumed	4%
Fossil fuels % of primary energy	81%
Passenger car energy % of transport energy	25%
Passenger car energy % of primary energy	3%
Industrial fossil fuels % of primary energy	57%
Renewable % of electricity generation	31%
Renewable energy % of primary energy	17%
Low carbon % of electricity generation	35%
Low carbon energy % of primary energy	19%
Coal to natural gas ratio in primary energy	10.6
Hydropower share of renewable electricity	58%

Source: Energy Information Administration, JP Morgan Asset Management. 2019. Electricity generation segments are net of thermal conversion, power plant consumption and transmission losses. "Low carbon" refers to renewable generation plus nuclear generation.

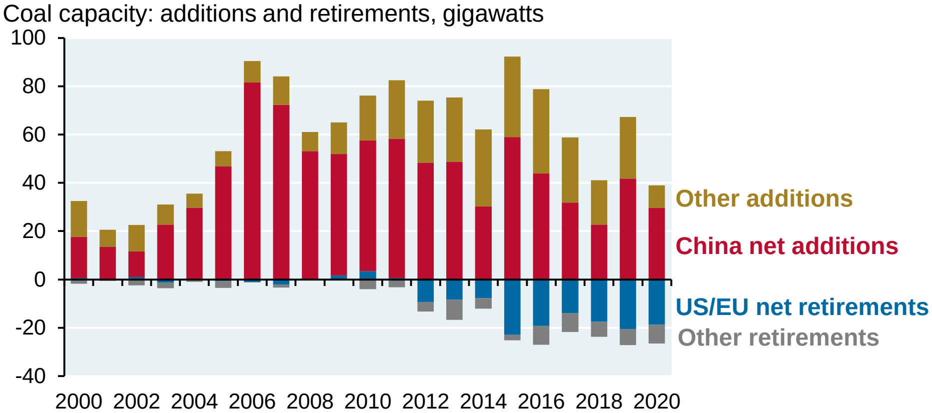
It would be great news if China succeeds with its plan for 25% EVs as a share of vehicle sales by 2025. Even though China's passenger cars represent only 25% of its transport energy consumption vs 60% in the US, that would still be a lot of Chinese electric cars.

But…put EVs aside for a moment and focus on the **elephant in the room**: the number one issue for China and the world is **decarbonization of China's massive industrial sector**, which consumes 4x more primary energy than its transport sector and more primary energy than US and European industrial sectors combined. China has electrified larger parts of its industrial sector than the US (23% vs 12%), but since China's grid is so reliant on coal, electrification provides fewer climate benefits.

In contrast to the US, China uses 10x more coal than natural gas. In 2020, China built over 3x as much new coal capacity as all other countries combined, equal to one large coal plant per week. China commissioned 38.4 GW of new coal plants in 2020, over 3x the amount commissioned in the rest of the world. Its coal fleet grew by net 29.8 GW in 2020 while non-China net capacity declined by 17.2 GW. China initiated 73.5 GW of new coal plant proposals in 2020, 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** as the developed world retreats from it. China currently has 50 GW of nuclear and plans to increase this figure to 130 GW by 2030. The new nuclear plants will represent ~6% of China's 2030 electricity generation and ~3% of its primary energy. So, nuclear is a material part of China's decarbonization agenda but hardly a game changer on its own.

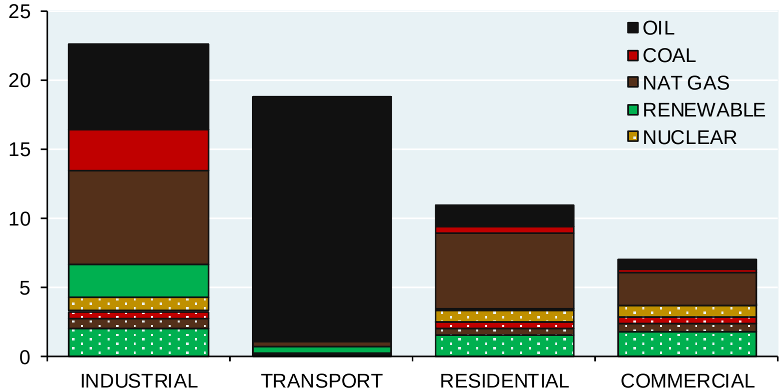
China and coal
Coal capacity: additions and retirements, gigawatts



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

Europe

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



Key stats

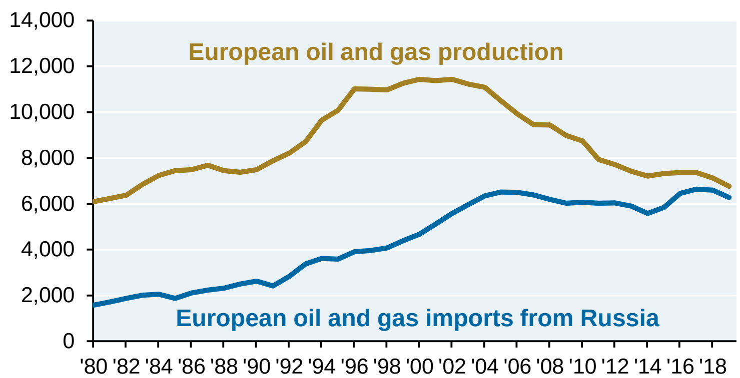
Quads of primary energy consumption	82.5
Quads of final energy consumption	59.4
Electricity % of energy consumed	19%
Electricity % of industrial energy consumed	19%
Electricity % of transport energy consumed	1%
Fossil fuels % of primary energy	66%
Passenger car energy % of transport energy	50%
Passenger car energy % of primary energy	11%
Industrial fossil fuels % of primary energy	24%
Renewable % of electricity generation	47%
Renewable energy % of primary energy	23%
Low carbon % of electricity generation	71%
Low carbon energy % of primary energy	34%
Coal to natural gas ratio in primary energy	0.4
Hydropower share of renewable electricity	46%

Source: Energy Information Administration, JP Morgan Asset Management. 2019. Electricity generation segments are net of thermal conversion, power plant consumption and transmission losses. "Low carbon" refers to renewable generation plus nuclear generation.

Europe is further along than the US and China on renewable/nuclear penetration on the grid and on reducing fossil fuels as a share of primary energy. Even so, electrification of Europe's transport sector was still just 1% at the end of 2019, and its industrial sector is still heavily reliant on fossil fuels.

Europe also faces a unique challenge: while its coal to natural gas ratio is the same (0.4) as in the US, this is the byproduct of large amounts of natural gas imported from Russia every year. As shown below, European oil and gas imports from Russia have now converged with total European oil and gas production. There are a host of geopolitical and energy security issues here that are not in Europe's favor. Europe could import LNG from the US, Qatar and Australia but at a higher cost than pipeline imports from Russia.

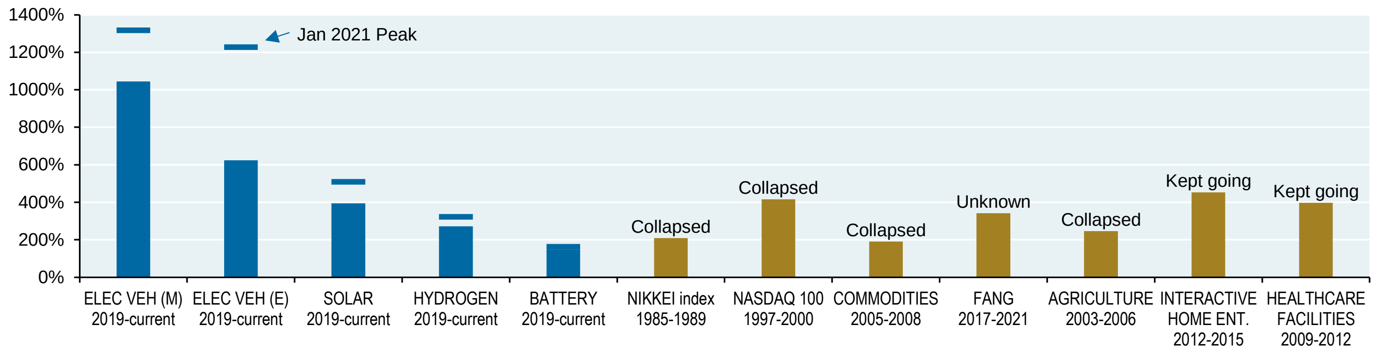
European production vs European imports from Russia
Thousand barrels per day of oil equivalent



Source: BP Statistical Review of World Energy, Gazprom, Eurostat, Perovic et al, JPMAM calculations. 2019. Europe includes EU, Norway and Turkey.

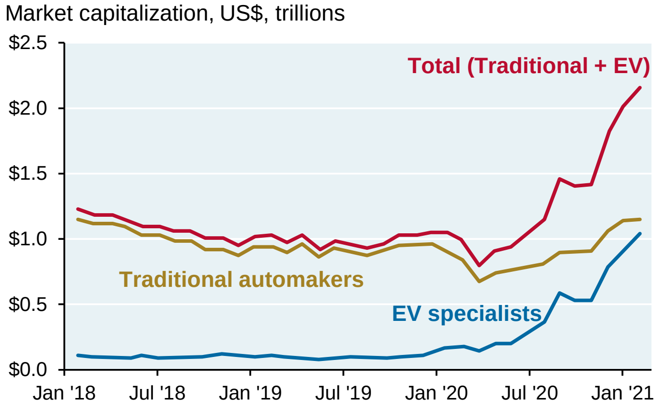
The world is gearing up to spend trillions of dollars to accelerate the fourth great energy transition[6], this time to renewables. Market valuations of renewable companies skyrocketed in early 2020; I'm not sure all of them make sense. One example: why did the *total* valuation of the world's competitive, high-volume auto industry gain 70% in market capitalization in the three years ending January 2021? A subsequent selloff eroded some of the gains but the increases since 2019 are still among the largest on record. Below we compare these renewable gains to prior episodes, some of which were sustainable while others were not. Generous subsidies, tax incentives and grid preferences will sustain many of them even if they are unprofitable. For investors, the challenge will be sorting out the long-term winners that will survive even when/if the subsidies go away.

Renewable stock price surge (2019-2021) vs prior sector/country stock price gains of 200%+ in 3 years or less
Labels indicate what happened 3 years after the stock price surge



Source: Bloomberg, JPMAM. April 26, 2021. EV companies presented both market-cap (M) and equal (E) weighted given Tesla's outsized impact on the former.

Market value of global auto industry
Market capitalization, US$, trillions



Source: "*Big Market Delusion: Electric Vehicles*". March 2021.

This year we start with the four big obstacles to faster deep decarbonization: slow penetration of EVs, required upgrades to transmission infrastructure, geologic carbon sequestration and electrification of industrial energy use. **The overarching message of this paper is not climate nihilism**; it's that the behavioral, political and structural changes required for deep decarbonization are still grossly underestimated. If so, the companies we all rely on for dispatchable, thermal power and energy will need to survive and prosper until we get there.

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[6] The first three: [i] mastery of fire; [ii] a shift from foraging to agriculture and domesticated animals and [iii] a shift from biomass and human/animal labor to combustion of fossil fuels and to mechanical prime movers.

Table of Contents

Acknowledgements and a quick note on our process

Our energy paper is overseen by Vaclav Smil, Distinguished Professor Emeritus in the Faculty of Environment at the University of Manitoba and a Fellow of the Royal Society of Canada. His inter-disciplinary research includes studies of energy systems (resources, conversions and impact), environmental change (particularly global biogeochemical cycles), and the history of technical advances and interactions among energy, environment, food, economy, and population. He is the author of more than 40 books (the latest two, *Grand Transitions: How the Modern World Was Made* and *Numbers Don't Lie* were published last year) and more than 400 papers on energy subjects and has lectured in North America, Europe, and Asia. In 2015, he received the OPEC award for research, in 2019 American Energy Society named him Energy Writer of the Year, and he is described by Bill Gates as his favorite author.

Vaclav and I agreed upfront that we would cover energy sources which reach, at the minimum, early stages of commercialization. Many ideas work on paper or in small-scale lab settings but are not widely commercialized and thus have no real world impact, either for cost or operational reasons. Examples include advanced biofuels like cellulosic ethanol, low energy nuclear reactions, quantum glass batteries, underground thermal energy storage, geoengineering (solar radiation management), ocean thermal energy conversion, liquid fuels from genetically modified algae and electricity generated from the coldness of the universe.

Links to topics from prior papers, which you can access here

- The environmental impact of renewable energy (2020)
- Cost declines required to make the hydrogen economy a reality (2020)
- Measuring climate benefits of reforestation (2020)
- How much energy is stored, and how? (2020)
- The water intensity of hydraulic fracking (2020)
- Geothermal update: present and future (2020)
- Germany and Energiewende: A dispassionate assessment (2019)
- Wildfires: anthropogenic climate change and risks for utilities in fire-prone areas (2019)
- High voltage direct current lines: China leads, US lags (2018)
- The Dream Team rebuttal of the Jacobson "100% renewable electricity by 2050" plan (2018)
- Better safe than sorry: sea level rise, coastal exposure and flood mitigation (2018)
- Hydraulic fracturing: the latest from the EPA and some conflicting views from its Advisory Board (2017)
- Forest biomass: not as green as you might think (2017)
- The myth of carbon-free college campuses (2017)
- US hydropower: how much potential for expansion? (2016)
- Nuclear power: skyrocketing costs in the developed world (2014 and 2015)

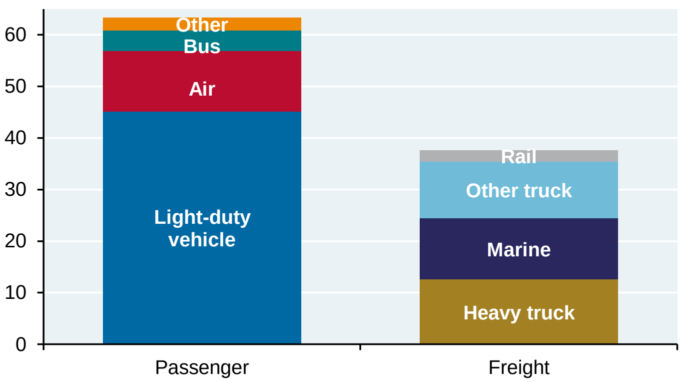
Acronyms

BEV battery electric vehicle; **BTU** British thermal unit; **CCGT** combined cycle gas turbine; **CCS** carbon capture and storage; **CH_4** methane; **DACC** direct air carbon capture; **E&P** exploration and production; **EIA** Energy Information Agency; **EPA** Environmental Protection Agency; **ERCOT** Electric Reliability Council Of Texas; **EROI** Energy return on investment; **EV** electric vehicle; **FERC** Federal Energy Regulatory Commission; **GHG** greenhouse gas; **GW** gigawatt; **HVDC** high voltage direct current; **ICE** internal combustion engine; **IEA** International Energy Agency; **IRENA** International Renewable Energy Agency; **kg** kilogram; **km** kilometer; **kV** kilovolt; **kWh** kilowatt hour; **LBNL** Lawrence Berkeley National Laboratory; **LENR** low energy nuclear reactions; **LMP** locational marginal pricing; **LNG** liquid natural gas; **m^3** cubic meter; **MJ** megajoule; **MMT** million metric tonnes; **mpg** miles per gallon; **Mtoe** million tons of oil equivalent; **MWh** megawatt hour; **NaOH** sodium hydroxide; **NGL** natural gas liquid; **NIMBY** not in my backyard; **NOAA** National Oceanic and Atmospheric Administration; **NO_x** nitrogen oxides; **NREL** National Renewable Energy Lab; **OECD** Organisation for Economic Co-operation and Development; **OPEC** Organization of the Petroleum Exporting Countries; **PHEV** plug-in electric vehicle; **REE** rare earth element; **RNG** renewable natural gas; **SUV** sport utility vehicle; **TWh** terawatt hour; **USGS** US Geological Survey; **Wh** watt hour.

[1] Electric vehicles, Will Ferrell, Norway and the rest of the world

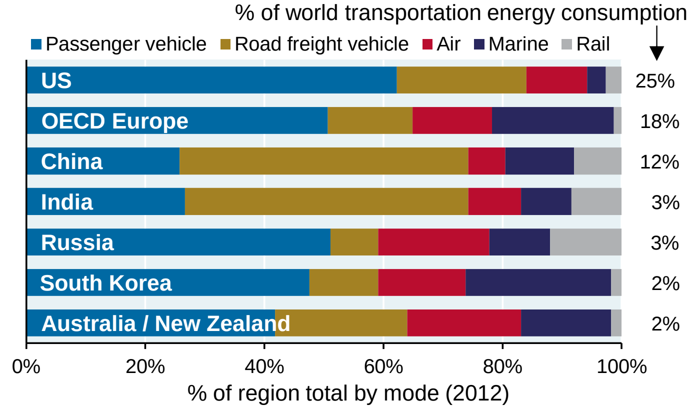
Passenger cars and light vehicles account for 40%-50% of global transport energy use. Other categories could be electrified (buses, heavy trucks) while some are more difficult (shipping, see p.39). A faster EV revolution in the US could have a large climate benefit since the US accounts for 25% of global transport energy consumption and since light vehicles represent 60% of this amount, both figures being the highest in the world.

World transportation energy consumption by mode
Quadrillion BTUs



Source: Energy Information Administration. 2016.

Transportation energy consumption by region and mode
% of world transportation energy consumption



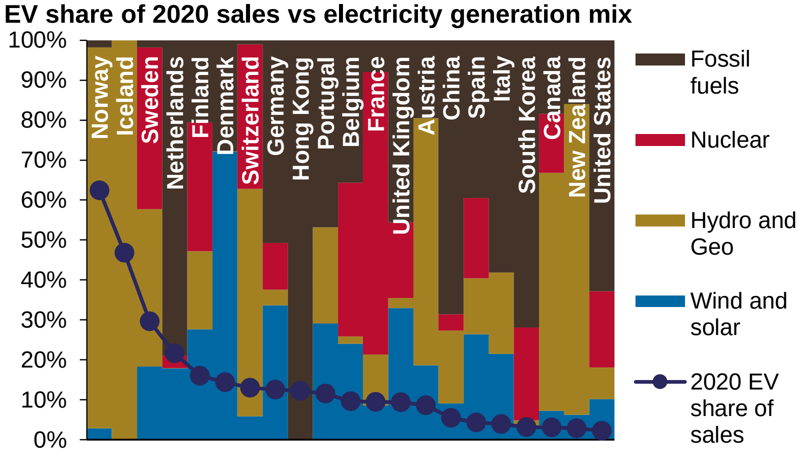
Source: Energy Information Administration. 2016.

I enjoyed the Will Ferrell commercial for GM during the Super Bowl which stated that **Norway** is "eating our lunch" on EVs. As shown below, they sure are: Norway EV sales were 60% of all vehicle sales last year compared to 2% in the US. But there are a few things about Norway that are important to understand:

- Norway has 5 million people and a population density that is 5%-15% of most other European nations
- 97% of Norway's electricity comes from hydropower; its electricity prices are 40%-70% of European levels
- In Norway, EVs are exempt from VAT taxes and receive a 50% discount on toll roads and parking fees while ICE cars are subject to a 25% VAT, a CO_2 tax, an NO_x tax and a weight tax. As a result, Norwegian ICE cars are more expensive to buy and 75% more expensive to operate
- A full conversion to EVs would put its EV subsidies at the second largest gov't expenditure behind pensions

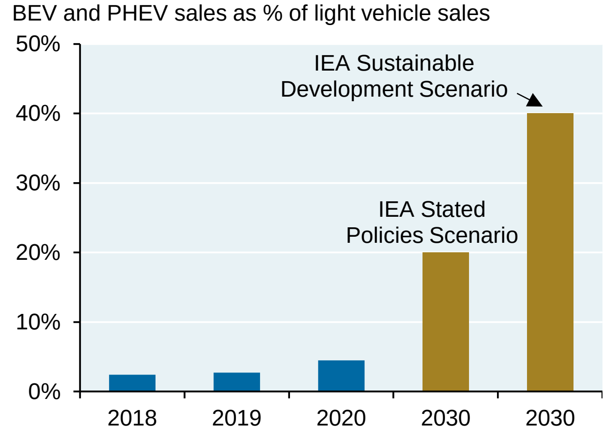
So, let's dispense with Norway as a paradigm for the world's high density, car-loving countries and see how the EV revolution is going elsewhere. Other than in a few small Northern European countries, EV sales as a share of vehicle sales are still mostly less than 10%[7]. Globally, the EV share in 2020 was 4.5%, up from ~2.5% in 2018 and 2019. Note how this compares to IEA scenarios of 20%-40% EV shares in the year 2030.

EV share of 2020 sales vs electricity generation mix



Source: IRENA, EIA, EV Volumes, JPMAM. 2020.

Global EV share of light vehicle sales
BEV and PHEV sales as % of light vehicle sales

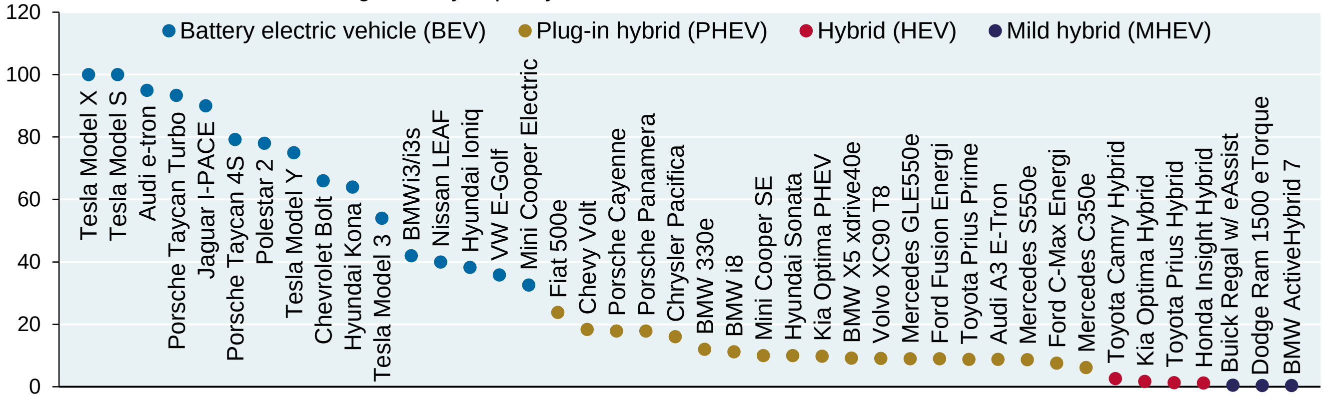


Source: EV Volumes, IEA, JPMAM. 2020.

[7] Light vehicle sales > 500k units and EV shares < 2%: JPN, INDIA, BRA, RUS, MEX, AUSTRA, TUR, THA and MAL.

EV analyses are defined by the scope of what an EV is assumed to be. Our definition includes battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) since the prime mover in both cases is the electric motor, even though some PHEVs have large backup fuel tanks as well. We do not include hybrid electric vehicles (HEV) since its primary mover is usually an internal combustion engine (this depends on the length of average trips and other driving behaviors). We include light trucks and not just passenger cars since the former is 75% (!!!) of all vehicle sales in the US. The next chart illustrates battery capacity by EV type and is another indication of why we only include BEVs and PHEVs in our EV analysis, and not hybrids.

Electric vehicle battery capacity by type
Kilowatt hour, sorted in descending order by capacity

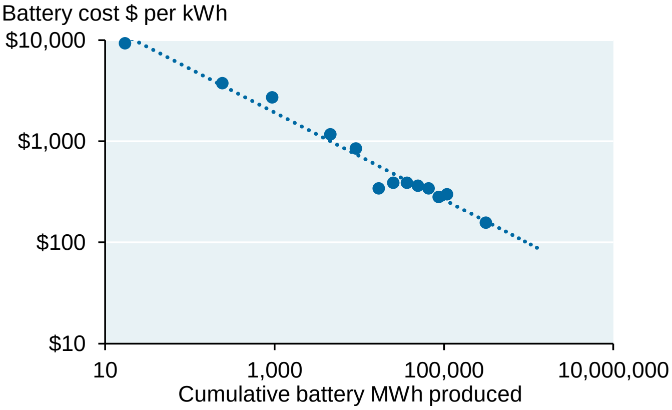


Source: Car and Driver, Automotive World, vehicle manufacturers. February 2021.

To be clear, hybrid vehicles can make substantial contributions to fuel economy; the 2021 Toyota Prius is EPA rated at up to 58 mpg in city driving. But the world envisioned in deep decarbonization plans involves large fleets of electric vehicles powered by green electricity[8], in which case our EV definition is a better measure of how the transition is going. **Answer: in most places with a lot of people, gradually so far.**

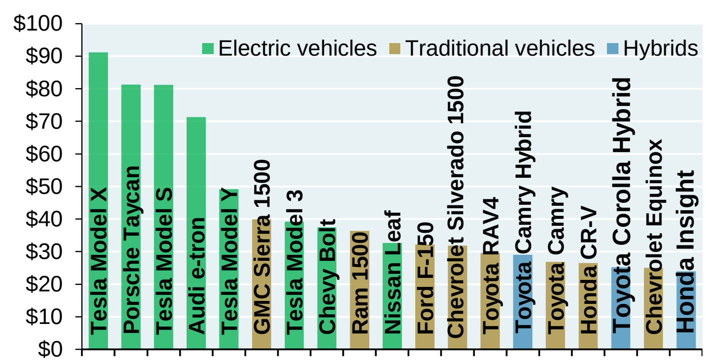
There has been an enormous decline in battery costs over the last decade, which in principle should boost the pace of EV sales. Some analysts project EV cost parity by 2023.

Lithium ion battery learning curve
Battery cost $ per kWh



Source: ARK Investment Management. 2021.

Top-selling EV, traditional vehicle & hybrid vehicle prices
$, thousands, manufacturer suggested retail price



Source: Edmunds, Car and Driver, CleanTechnica. 2021. Excludes subsidies.

[8] **Grid expansion required:** 40% EV penetration would increase electricity consumption by 440 TWh compared to current generation of 4,400 TWh (a 10% increase), and by more in the future depending on the growth rate of the total vehicle stock. Load management investments would be needed to prevent surges in demand that could overwhelm transmission networks. Households generally consume 1-2 kWh per hour while a Level 2 EV charger can consume 8-9 kWh per hour.

Now that battery costs have fallen, many countries and car companies have made commitments to rapidly ramp up EV penetration and production in the years ahead. We'll see; I think it makes more sense to track how quickly EVs are actually selling and actual CO_2 emissions from the transportation sector rather than tracking non-binding future milestones[9]. There are four key things to understand about the EV revolution:

[i] the good news: in most parts of the world, EVs entail GHG benefits per mile vs internal combustion engine (ICE) cars irrespective of the fuel composition of the electricity grid; **but**…

[ii] the lifecycle of today's light vehicles is getting longer which delays vehicle replacement

[iii] EVs still cost more than comparable ICE vehicles when looking at the highest selling cars/trucks in the US

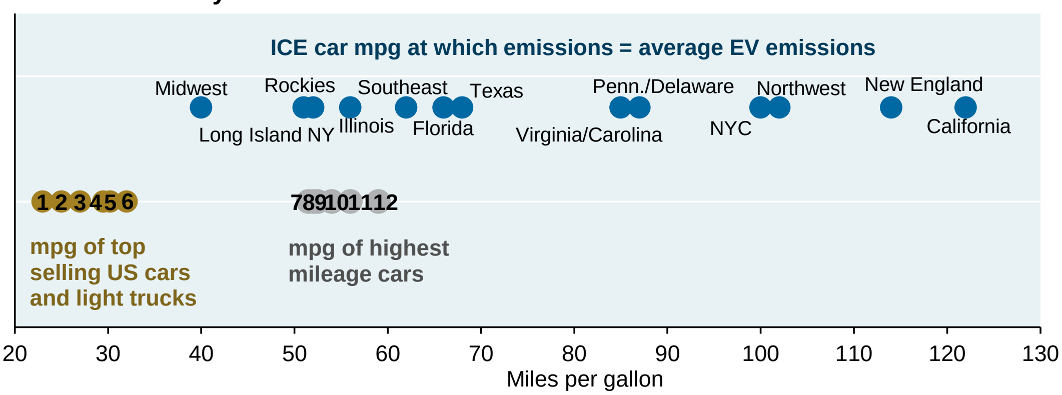
[iv] some research indicates behavioral issues which may reduce assumed GHG benefits from the EV transition

Let's take a closer look.

[i] EV GHG benefits per mile generally exist irrespective of the fuel composition of the grid

Throughout most of the US and Europe (but not necessarily China), EVs entail positive GHG benefits per mile vs most ICE cars. How can we tell? The Union for Concerned Scientists estimates "break-even" mileage by US region, which is the **mileage your ICE car must achieve to produce the same emissions as the average EV**[10]. See the blue and gold dots in the chart: from California at the top of the range to the Midwest at the bottom, the mileage of all top selling US cars and light trucks are way below these break-even levels. The only overlap is the grey dots: Toyota and Hyundai hybrids in coal- and gas-dependent regions. As more renewables are added to the grid and if EV fuel efficiency improves, these break-even figures may rise. However, ICE mileage could improve as well, such as Mazda's SkyActiv-X engine which may improve fuel economy by 20%-30%.

How efficient does your ICE car need to be for its emissions to be the same as an EV?



Top selling cars and light trucks in the US sorted by miles per gallon:
1. Ram 1500
2. Ford F-150
3. Chevrolet Silverado
4. Toyota RAV4
5. Honda CR-V
6. Chevrolet Equinox

Highest mileage cars:

7. Honda Insight
8. Toyota Camry Hybrid
9. Toyota Corolla Hybrid
10. Hyundai Elantra Hybrid
11. Toyota Prius Eco
12. Hyundai Ioniq Blue

Source: Union of Concerned Scientists, US Department of Energy. 2021. ICE = internal combustion engine
Note: Miles per gallon = combined city/highway mileage

[9] Example: **Japan** had a very low share of EVs in 2020 at just 0.7% of vehicle sales. The Japanese government plans to phase out ICE cars in the mid 2030's at which point all cars must be hybrid or fully electric. That's an aggressive timetable compared to current production.

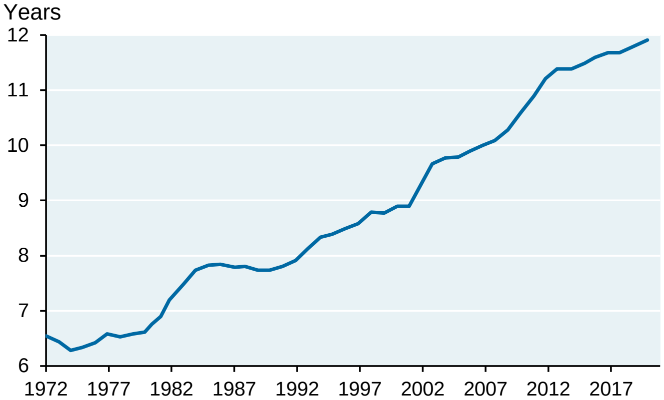
[10] UCS analyzed emissions from fueling and driving both types of vehicles. For ICE cars: emissions from extracting crude oil, moving oil to refineries, gasoline refining, gasoline distribution and tailpipe emissions. For EVs: power plant emissions and emissions from production of coal, natural gas and other fuels.

[ii] Longer vehicle lives delay the EV revolution

My college roommate bought a new Ford Mustang in 1983. It was a not a very good car; it was in the shop a lot, and one day I recall someone almost punching a hole through the door. Since then the quality of domestic and imported cars has improved, leading to longer useful lives. The average age of light vehicles in operation has doubled since 1972. That's great for productivity and household wealth but has the unintended consequence of delaying penetration of new technologies like EVs. **Misunderstanding of this dynamic** may partially explain why so many projections of the US EV share of sales in 2020 made ten years ago were wrong (Deutsche Bank 11%, PwC 10%, BNEF 9%, Roland Berger 7%, BCG 5% vs actual 2020 US levels of 2%).

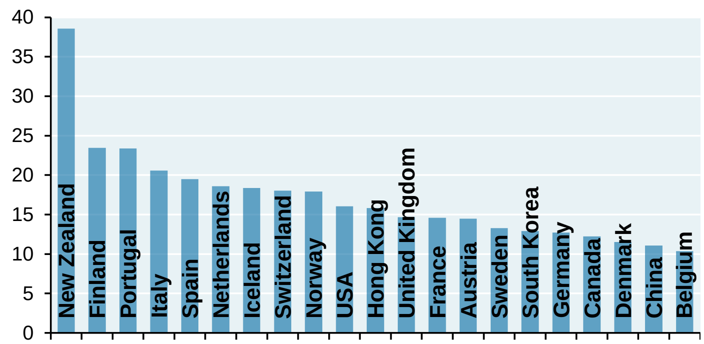
The chart on the right shows a proxy for the vehicle replacement cycle in years (i.e., divide the stock of cars by annual sales, and that's the number of years it could take for the entire stock to be electrified if EVs were 100% of new vehicle sales). EV *penetration* as a % of the stock depends on projections of the annual EV share of total sales, the growth rate in overall vehicle sales and vehicle scrappage rates. Bloomberg New Energy Finance (BNEF) now projects 30% US EV penetration by 2037, and I think they will be too high again.

Average age of US light vehicles in operation
Years



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

Vehicle replacement cycle in years
Total light vehicle registrations divided by light vehicle sales



Source: European Automobile Manufacturers Association, country departments of transportation, EV Volumes. 2019.

[iii] When considering the kind of cars and light trucks US buyers prefer, the EV price gap is still large

In some research we've seen, analysts compare the price of a Toyota Camry to an EV like the Chevy Bolt or Nissan Leaf to illustrate the declining price gap between EVs and ICE cars. However, as mentioned earlier, SUVs and other light trucks account for 75% of US light vehicle sales. As a result, the Bolt and Leaf are not really product substitutes for people buying light trucks and SUVs. The table shows what we see as more relevant comparisons. The price gaps (measured in dollars and % terms) are larger than Camry-Bolt comparisons, and the range differentials in miles are often larger as well. Learning curves may drive all EV costs down further, but we consider the most relevant ICE-EV price gaps to be larger than the ones often reported.

Electric vehicle: *ICE vehicle:*	Chevy Bolt Toyota Camry	Ford F150 EV Ford F150	Chevy Silverado EV Chevy Silverado	Dodge Ram EV Dodge Ram	SUV EV Composite Toyota RAV4	SUV EV Composite Honda CRV
EV price ($, thousands)	$32.0	$70.0	$50.0	$70.0	$44.8	$44.8
ICE price ($, thousands)	$26.0	$30.6	$29.0	$30.5	$27.4	$26.5
Price gap ($, thousands)	**$6.0**	**$39.4**	**$21.0**	**$39.5**	**$17.4**	**$18.3**
Price gap (%)	**23%**	**129%**	**72%**	**130%**	**64%**	**69%**
ICE range - EV range (miles)	193	320	208	268	155	134
ICE units sold (2020)	294,000	787,000	593,000	564,000	430,000	324,000

Sources: Car and Driver, JPMAM. 2021. EV and ICE model costs based on entry level vehicles. ICE mileage from Department of Energy.
SUV EV composite based on average of Volkswagen ID4, Hyundai Kona EV and Volvo XC40 Recharge.

Note: the IEA concluded that by 2040, the **global ascent of SUVs** has the potential to offset carbon savings from more than 100 million EVs *[iv] Research points to behavioral issues which may reduce GHG benefits from the EV transition*

Tracking actual CO_2 emissions from the transport sector will be the best way of measuring the contribution of EVs to climate mitigation.

- Will EVs replace ICE cars or supplement them? In Norway, subsidies promoted new EV purchases but two-thirds of families **supplemented** their ICE cars instead of replacing them, with 60% of driving miles by two-car families via their ICE cars vs 40% from their EVs[11]. Other analyses on Norway found that EV subsidies resulted in a sharp reduction in public transit and bicycle use compared to people owning ICE cars
- What kind of cars would most EV buyers have bought instead? A study from UC Davis found that many EV buyers **would have bought higher mileage cars instead**, which could mean that the emissions savings from EV transitions could be overstated by as much as 50%[12]
- Why do EV owners tend to drive their cars for much fewer miles per year than ICE cars? Whether the answer is **range anxiety or their status as a second car** rather than a replacement, the implications are not positive for EV adoption trends and GHG benefits. University of Chicago researchers extrapolated miles driven by monitoring their electricity bills before and after purchase. Adopting an EV increased household electricity consumption by 2.9 kWh per day. After correcting for out-of-home charging, this translated to approximately 5,300 miles traveled per year by EV owners, which is under half of the US fleet average[13]

Pulling it all together

Biden's policies (see Section 7) may substantially increase US EV penetration. But as things stand now, the US 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 distance driven per capita, the lowest public transit usage, the lowest gasoline prices AND **almost the lowest EV penetration as well**. No wonder Will Ferrell is so mad.

	EV share of light vehicle sales	Avg gasoline price	% income spent on gasoline	Cars per 1,000 people	Vehicle km per capita	Biking frequency	Public transit usage	Road fuel consum. per capita
Australia	1%	3.78	1.53	741	10,800	0.02	27	580
Canada	3%	4.06	2.92	667	8,500	0.03	23	886
Denmark	14%	7.02	0.95	508	6,300	0.25	–	244
France	9%	6.56	0.59	590	6,250	0.04	28	106
Germany	13%	6.16	1.09	610	7,000	0.13	33	222
Italy	4%	6.81	0.99	707	6,250	0.12	–	158
Japan	1%	5.02	1.38	718	4,000	0.16	31	329
Netherlands	22%	7.19	1.17	543	6,150	0.25	–	242
Norway	62%	7.35	0.53	754	6,500	0.16	–	213
Sweden	30%	6.47	1.23	542	7,000	0.16	32	302
UK	9%	5.99	1.08	544	6,250	0.04	37	220
United States	**2%**	**3.05**	**2.16**	**875**	**14,000**	**0.02**	**12**	**1,106**

Source: California State University, EV Volumes. 2020.

[11] *Statistics Norway*, August 15 2019

[12] *"Correcting Estimates of Electric Vehicle Emissions Abatement: Implications for Climate Policy",* Muehlegger and Rapson (UC Davis, NBER), January 2021

[13] *"Low Energy: Estimating Electric Vehicle Electricity Use",* Burlig et al. (University of Chicago), February 2021

[2] Transmission Dreams

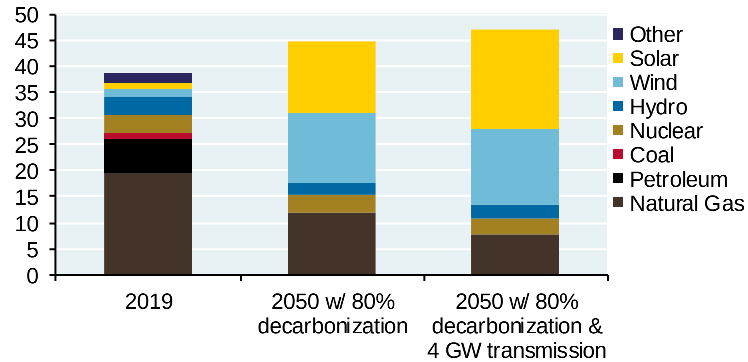
Most deep decarbonization plans acknowledge the need for massive transmission grid updates. In this section, we look at two recent ones: an MIT study on electricity optimization between Canada and New England, and a Princeton analysis aiming for full decarbonization by 2050.

MIT: Electricity optimization in New England[14]

The goal: decarbonize New England electricity and examine benefits of new transmission to allow greater trade of Canada hydropower and New England wind/solar power. The first chart shows the capacity mix required for 80% decarbonization of New England electricity by 2050.

Now let's look at generation. The chart below (left) shows modeled New England electricity generation for a 2-week period in October 2050 resulting from the new capacity mix. There's some bilateral trade of hydro, wind and solar using 2.2 GW of existing cross-border transmission capacity (red & green segments), but it's pretty small. New England CO_2 emissions would fall from 27.5 million metric tons (MMT) per year today to 6.7 MMT per year in 2050.

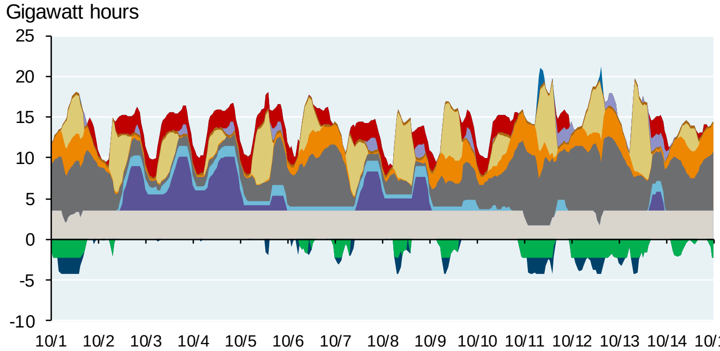
New England capacity mix by energy source
Gigawatts



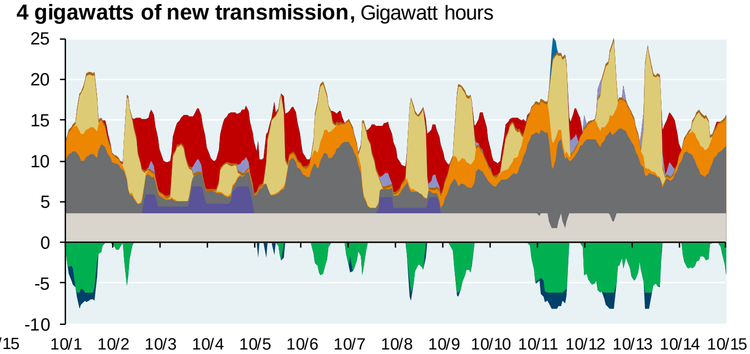
Source: EIA, Emil Dimanchev, MIT Center for Energy and Environmental Policy Research. February 2020.

Now let's add some more transmission. The chart on the right assumes 4 GW in new transmission lines which would allow New England to double its electricity imports/exports. MIT estimates that the financial cost of building new transmission would be offset by lower cost Canadian hydropower, and that New England CO_2 emissions would fall from 6.7 MMT per year to just 2.0 MMT per year. So: it looks like there's a positive cost/benefit from a lot more transmission in this decarbonized system. **Sounds great on paper**, until the New Hampshire siting committee gets involved…which we discuss in the next secetion.

Modeled hourly New England generation using 2050 capacity mix
Gigawatt hours



Modeled hourly New England generation using 2050 capacity mix + 4 gigawatts of new transmission, Gigawatt hours



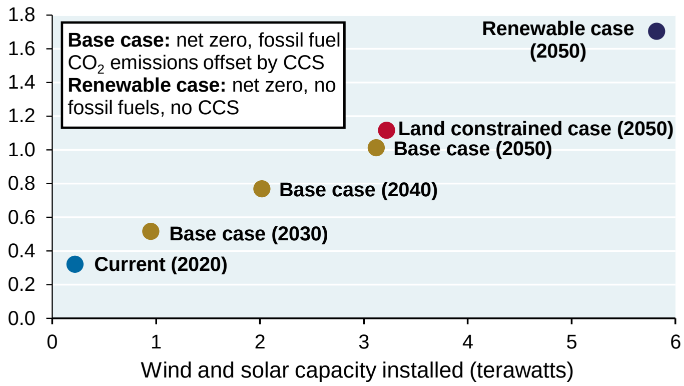
Source: *"Two-Way Trade in Green Electrons: Deep Decarbonization of the Northeastern US and the Role of Canadian Hydropower."* Emil Dimanchev et al., MIT. February 2020.

[14] "*Two-Way Trade in Green Electrons: Deep Decarbonization of the Northeastern US and the Role of Canadian Hydropower*", Dimanchev et al, MIT Center for Energy and Environmental Policy Research, February 2020.

The Princeton paper proposes Net Zero primary energy by 2050[15] (i.e., not just decarbonization of *electricity*, but decarbonization of *everything*). As illustrated in the first chart below, this transformative proposal includes a 14x buildout of wind and solar capacity and a 3x-5x buildout of transmission capacity[16].

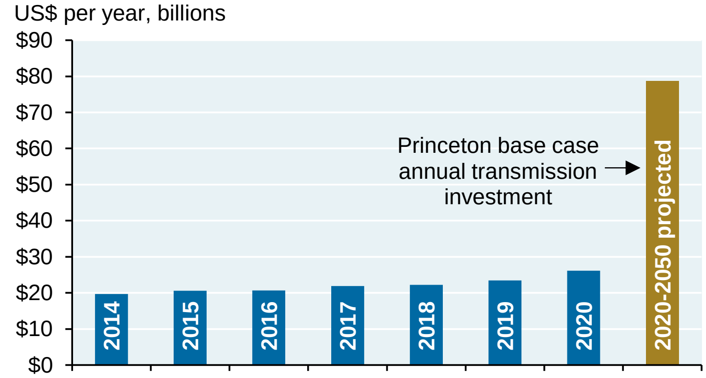
Consider the pace of Princeton's transmission expansion relative to history. The base case $76 billion per year cost of this proposal is three times higher than prevailing spending on transmission infrastructure (second chart). Furthermore, some current investment is *replacing* old transmission infrastructure rather than adding new capacity. **The third chart is quite the hockey stick**: from 2004 to 2020, US transmission grid miles only grew by 1.2% per year and would have to accelerate to 3.9%-5.7% (these are very big differences when compounded over decades). Finally, look in the fourth chart at ***where* this new capacity would need to be built**: Texas, but also California and the Northeast, regions with NIMBY and other obstacles to development. As a result, any analysis of Transmission Dreams also has to confront Transmission Realities…which we address next.

Princeton Net Zero plan
Transmission lines > 345 kilovolts, million gigawatt-kilometers



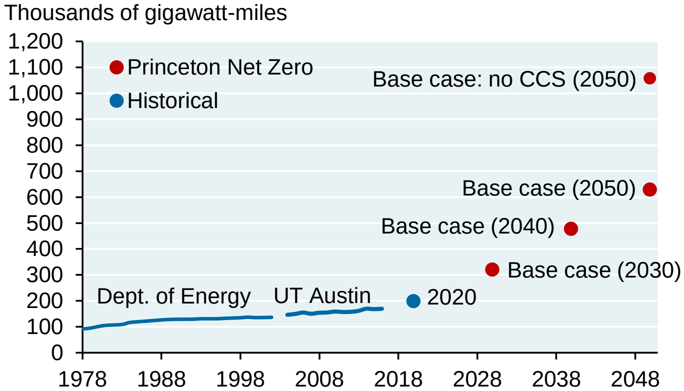
Source: "*Net Zero America*", Larson et al., Princeton. 2020.

Historical and projected transmission investment
US$ per year, billions



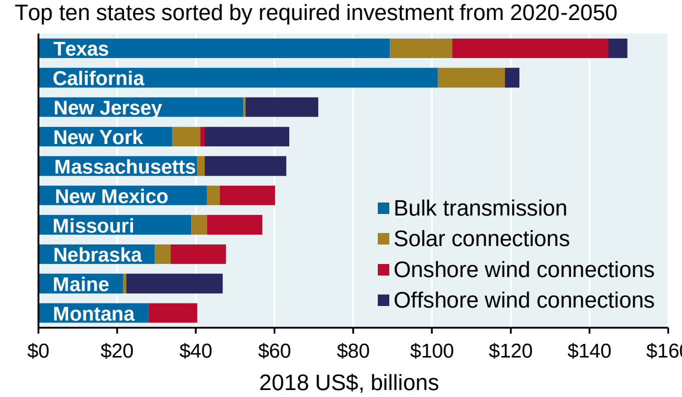
Source: Edison Electric Institute, *"Net Zero America"*, Larson et al., Princeton. 2020.

US transmission infrastructure
Thousands of gigawatt-miles



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

Princeton plan transmission required by state
Top ten states sorted by required investment from 2020-2050



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

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15 Larson, Greig, Jenkins, Mayfield, Pascale, Zhang, Drossman, Williams, Pacala, Socolow, Baik, Birdsey, Duke, Jones, Haley, Leslie, Paustian and Swan, "*Net-Zero America: Potential Pathways, Infrastructure, and Impacts*", interim report, Princeton University, December 15, 2020.

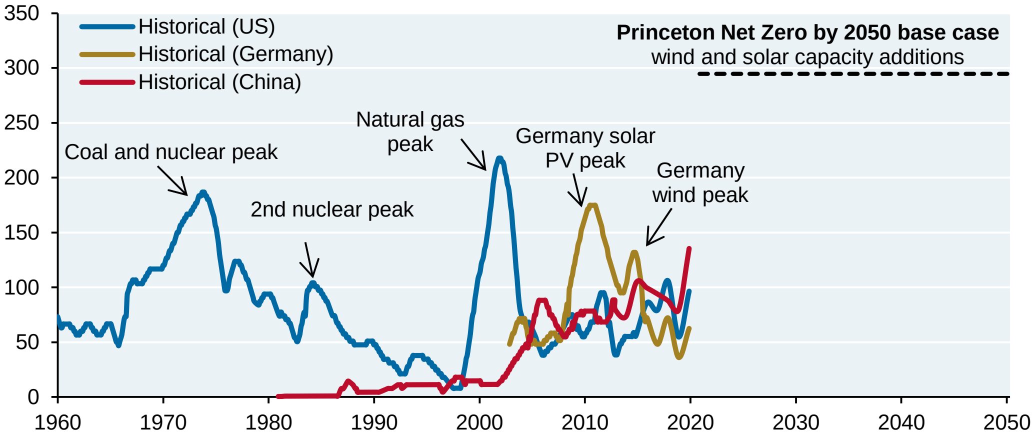
16 Other Net Zero proposals have lower transmission targets for 2050 than Princeton but they are still enormous relative to today's grid. Examples include the Zero Carbon Consortium Deep Decarbonization Pathways Project and the Carbon Neutral Pathways Project from James Williams at the University of San Francisco. Both entail transmission buildouts that are 65%-80% of Princeton levels.

A brief comment on the pace of wind and solar expansion assumed in the Princeton paper

The primary purpose of Sections 2 and 3 is to examine new transmission required in deeply decarbonized systems. That said, it's also worth examining the **generation** expansion in the Princeton report. The chart below shows generation capacity additions measured as watts per capita per year, highlighting peaks by fuel type. The challenge with the Princeton plan is not just its *level* but its *consistency*: while peak capacity additions in the US were 2/3 of the 300 watt figure in the Princeton plan, they were only sustained for a couple of years. The Princeton plan requires 300 watts ***every year for 30 years***. It remains to be seen if the climate threat (see bottom chart on warming oceans) translates into support for this magnitude of capacity expansion.

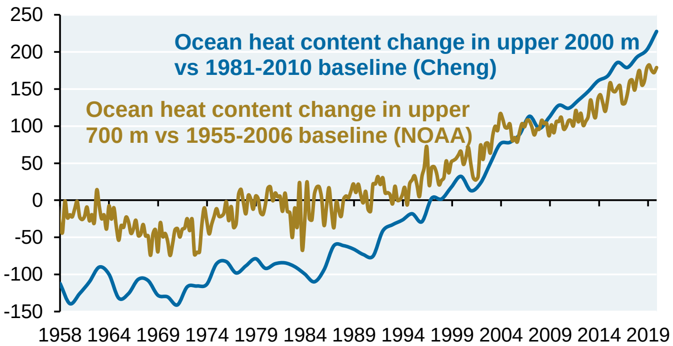
For anyone thinking that energy efficiencies will reduce electricity demand, remember the parable of the airline industry: despite a 75% decline in jet aircraft fuel consumption per kilometer since 1960, aircraft fuel consumption and related CO_2 emissions quadrupled as declining ticket prices led to a surge in aviation. In other words, increased use can more than offset any efficiency gains.

Historical rates of installed electric-generating capacity per capita
Capacity additions, watts per year per capita



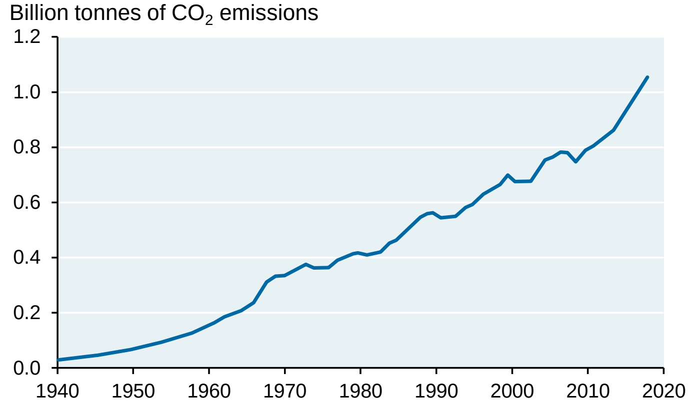
Source: *"Net Zero America"* (Princeton study), American Public Power Association, EIA, China Electricity Council, Fraunhofer ISE, Clack et al. (pre-2014 data). 2020.

Warming oceans
Zettajoules



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

Global carbon dioxide emissions from aviation
Billion tonnes of CO_2 emissions



Source: Our World in Data. 2018.

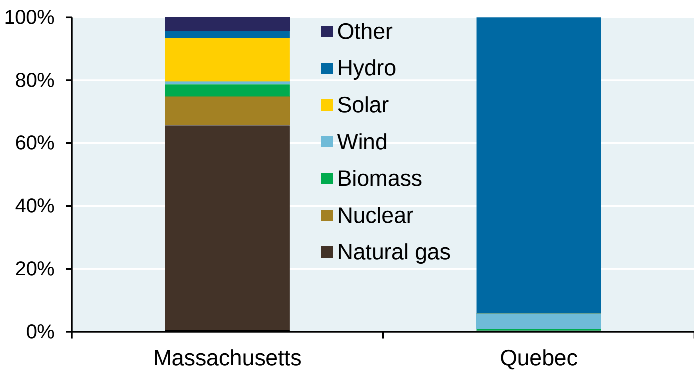
[3] …and Transmission Realities

While MIT and Princeton assume rapid growth in transmission infrastructure, *actual* development can be a hornet's nest of siting challenges and legal costs even when projects are eventually built after years of planning. Let's start with HydroQuebec's plan to sell hydropower to the US. New York shares a border with Canada and is planning a 1.3 GW transmission line from the Quebec-NY border to NYC, buried under Lake Champlain and the Hudson River. Same for Minnesota, which increased its imports of hydropower from Manitoba via a new 500 kV transmission line completed in 2020. However, **a state like Massachusetts has no such luck**.

Take Northern Pass, a 1.1 GW transmission project to bring hydropower from Quebec to the Northeast through New Hampshire (80% via existing right-of-ways or underground lines). Hydropower that displaces natural gas has clear climate benefits given lifetime hydropower CO_2 emissions that are 5% of natural gas levels [IPCC]. Assuming 5% transmission losses and 83% utilization[17], Northern Pass could deliver 7.5 TWh of hydropower to New England and reduce emissions by 3.0 million metric tons of CO_2 every year. The chart below on neighboring generation mixes makes it clear why cross-border electricity trading could result in more optimal outcomes.

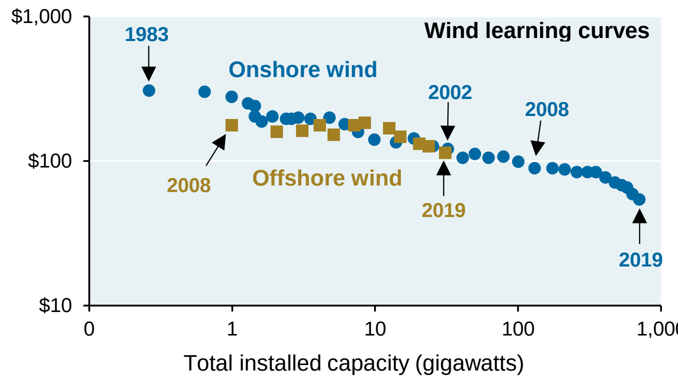
However, a New Hampshire siting committee blocked Northern Pass[18], giving new meaning to New Hampshire's state motto "*Live Free or Die*". Now Massachusetts is trying to import Canadian hydropower through Maine ("New England Clean Energy Connect") but **has already run into an injunction** due to opposition from environmental groups. As described on p.15, MIT believes that the best answer for New England is 4 GW of new two-way transmission lines between New England and Quebec. **So, 4 new Northern Pass projects? Good luck with that**. Offshore wind planned for completion by 2035 in New England could *eventually* replace Canadian hydropower multiple times over, but there's a long way to go from today's demonstration projects[19]. Note the path of the offshore wind learning curve vs onshore wind at the lower right.

Electricity generation by source
% of total



Source: EIA, Canada Energy Regulator. 2019.

Levelized cost of energy (LCOE) vs installed capacity
LCOE (2019 US$/megawatt hour)



Source: NREL, Beiter et al. February 2021.

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[17] "*Cost benefit and local economic impact of Northern Pass transmission project*", London Economics, 2015

[18] **The Death of Northern Pass**. The project was killed by the "New Hampshire Site Evaluation Committee". Our understanding is that primary objections came from **environmental groups** and also from **New Hampshire power generators** concerned about surplus Canadian hydropower putting downward pressure on electricity prices within the New England ISO.

[19] **Offshore wind**. While there are only two small offshore wind pilot projects operating in the US right now, Eastern US states have committed to build 25-30 GW by 2035. Projects require approval from the Bureau of Ocean and Energy Management; the Biden administration will reportedly accelerate approvals more quickly now. Around 5.2 GW are planned for MA and CT; assuming a 50% capacity factor, offshore wind could generate 23 TWh per year compared to 7.5 TWh from Northern Pass. Currently, LBNL estimates offshore wind costs at 8 to 12 cents per kWh compared to the most productive onshore wind projects at 3-4 cents per kWh, and compared to Canadian Hydropower at 6 cents per kWh.

What about outside the Northeast?

We've written before about the fate of **Clean Line's** Plains & Eastern project which aimed to connect Oklahoma wind and Tennessee. While Federal courts eventually overrode Arkansas landowner objections, mounting court costs crippled the project's finances. The Tennessee Valley Authority declined to support it (reportedly at the urging of Ten. Senator Lamar Alexander), and the TVA stuck with its mix of nuclear, gas and coal. Clean Line sold the project to NextEra Energy, but they were unable to get anywhere either: Arkansas Senators Cotton and Boozman argued to Trump Energy Secretary Perry that the Obama administration violated Arkansas property rights in approving the project in the first place. The project was finally euthanized in 2018, and Clean Line eventually sold or liquidated its other projects after years of endless court fights at state and county levels[20].

Another legacy Clean Line project is on the ropes as well: the **Grain Belt Express**, designed to bring wind power from Kansas to the East Coast by joining SPP, MISO and PJM grids. In February 2021, the Missouri State House passed a bill banning the use of eminent domain for above-ground utility projects; its State Senate will review next. Meanwhile, five hundred Missouri landowners along the route continue their fight against the project. Easement payments of $150,000 have been offered (110% of assessed land value) and landowners can continue to farm or build on the easements, but so far only a third of landowners have accepted.

Some developers take advantage of corridors used for existing infrastructure. Siemens is working on a 350-mile 2.1 GW underground HVDC connection between Iowa's wind farms and Chicago. The majority of the line will run alongside a railroad corridor right of way, which *should* make it easier to obtain permits, a strategy used to expand high-speed internet networks. Other good news: the Southern Cross project will join ERCOT with the SPP region (OK, KS, NE and the Dakotas) and begins construction in 2022.

However, even when projects are approved, they're built at a snail's pace compared to deep decarbonization requirements. The TransWest Express project, designed to bring wind power from Wyoming to California, has been in development since 2007 despite being fast-tracked by the Obama administration, despite being only 15% reliant on private lands, and despite having been granted eminent domain status by the 4 states it traverses. TransWest is projected to begin delivering power in 2023.

Transmission challenges in Germany were addressed through underground cabling and legislation. In some places, burying transmission cables reduced resistance although at a large increase in cost. Germany passed an "acceleration law" in 2019 to streamline and simplify transmission approval procedures. As of Q3 2020, Germany had completed 20% of planned transmission build-out with another 11% approved for construction. Even so, bottlenecks hamper transmission of its wind generation: Germany is reportedly exporting wind power to Denmark and **paying Danish wind farms *not* to generate power**. Reports cite Danish wind curtailment as high as 6% as a result[21]. Germany intends to shut down its last remaining nuclear plants in 2022 which will amplify the importance of completing North-South transmission lines for wind.

China relocated 1.3 million people during the construction of the Three Gorges Dam and related transmission networks. China does not face the same constraints as Western countries with respect to building transmission lines over objections from local municipalities. Let's just leave it at that.

[20] "*Ambitious Clean Line energy: Wrapping Up*", Wind Power Monthly, February 2019.

[21] "*Germany's Maxed-Out Grid Is Causing Trouble Across Europe*", Greentech Media, March 31, 2020.

The transmission road not taken: Federal override of state objections

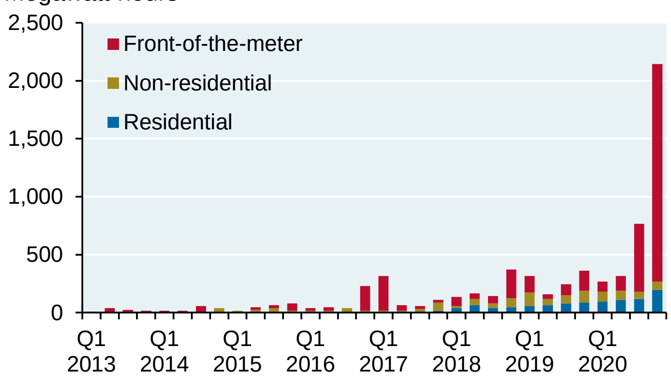
- Unlike natural gas pipelines in the 1930's and the interstate highway system in the 1950's, **there is no broad legislation supporting Federal eminent domain for electricity transmission projects**
- Since 2005, transmission projects can qualify as "national interest electric transmission corridors" according to the US DoE, in which case FERC statutes allow such projects to proceed even if states do not grant approval (Section 1221 of the Energy Policy Act)
- However, 2010/2011 Court of Appeals judgments limited Section 1221 FERC backstop siting authority and provoked a state backlash. National interest electricity corridors haven't been used since
- A former NYU law professor now at the DoE believes that Section 1222 can be used instead. While its geographic scope excludes the Northeast and Florida, this statute involves the Federal gov't participating in the project itself, in which case it has pre-emptive siting authority that overrides any state objections. A Federal District court in Arkansas upheld this statute in 2017. We're watching to see if it's used more actively by the Biden administration

What about distributed storage?

Distributed storage can make sense (it certainly would have helped Texas last February), and can be a partial alternative to transmission upgrades in some locations. Storage ideally moves power from off-peak periods to peak periods, in which case transmission capacity does not always have to equal ***peak*** demand. But in a deeply decarbonized system, you still need a lot of transmission to handle 10x-15x increases in wind and solar capacity.

There's also the issue of cost. MIT published a study on the value of storage in deeply decarbonized systems[22]. The authors found that storage can displace transmission investment at low levels of storage penetration, but that its value is quickly exhausted: once storage capacity reached 4% of peak demand, further storage investment didn't reduce transmission requirements further when assuming lithium ion battery costs of $320 per kWh for 4 hours of storage. Assuming future costs of $150 per kWh for 4 hours of storage, cost-effective storage penetration ranged between 4% and 16% of peak demand. **In other words, you still need a lot of new transmission in deeply decarbonized grids.**

US energy storage deployments
Megawatt hours



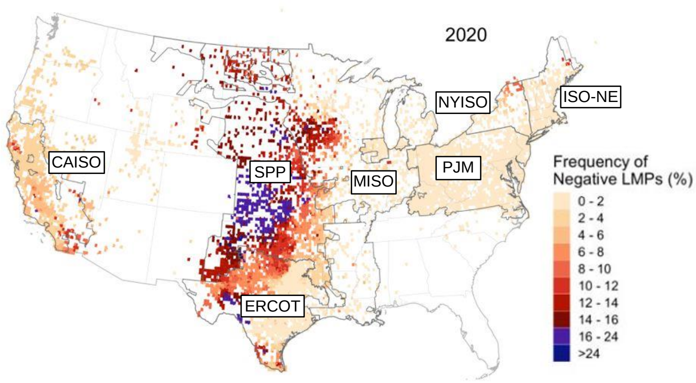
Source: Wood Mackenzie, US Energy Storage Association. Q4 2020.

Energy storage comparisons
It costs $15-$18 per barrel to purchase an oil storage tank. To store an amount of electricity equal to the energy in one barrel of oil (1,700 kWh), it would cost $510,000 based on the $300 per kWh cost of the Tesla Megapack, software costs included.

[22] "*Long-run system value of battery energy storage in future grids with increasing wind and solar generation*", Mallapragada et al, Applied Energy, July 2020.

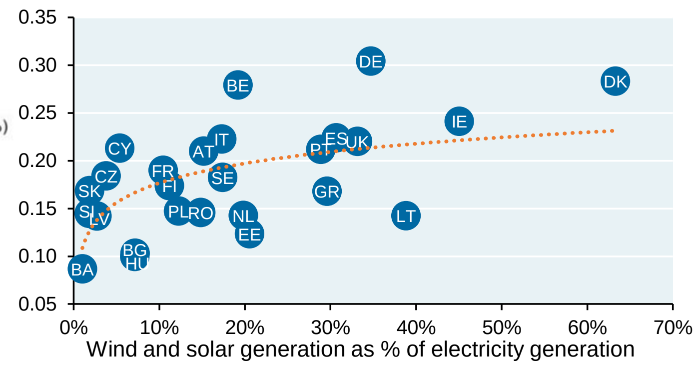
What can happen when there isn't enough transmission in areas with a lot of renewable energy? Negative wholesale electricity pricing…and the jury is out on consequences for consumers

The map shows US regions according to frequency of "negative marginal pricing". In other words, the percentage of time power producers are paid below zero for their generation. You might think, "why would a power producer ever accept negative prices??" One example[23]: wind operators flooding Midwestern grids at the same time since there's not enough interstate transmission to export surplus electricity to other places, and not enough distributed storage to save it for periods of higher demand. As a result, wind operators might accept negative pricing of -$5 per MWh since without it, they would not collect tax credits worth $24 per MWh that are **only payable if they generate electricity**.



Source: Ryan Wiser, Lawrence Berkeley National Laboratory. March 2021.

European household electricity prices vs wind and solar penetration, Euros per kilowatt hour



Source: Eurostat, EMBER. 2020. Electricity prices include all taxes and levies.

Negative wholesale electricity prices sound like a good thing, but are they? Not necessarily; negative prices mean that at certain times of day, there's so much wind/solar oversupply in that location that prices decline until some producers (wind, gas, solar or nuclear) agree for economic reasons to cut back until generation equals demand. Later that day, there could be a sharp *decline* in wind/solar generation, in which case other forms of dispatchable power are still needed (that's what happens in California for those familiar with the "duck curve"). That power could come from natural gas; or from utility-scale pumped storage, lithium ion batteries or fuel cells; or imported from other regions. **Either way, it has to come from someplace**. And if there are too many hours of low or negative prices for thermal producers, they may stop adding new capacity to the grid, leaving it exposed to brownouts and instability.

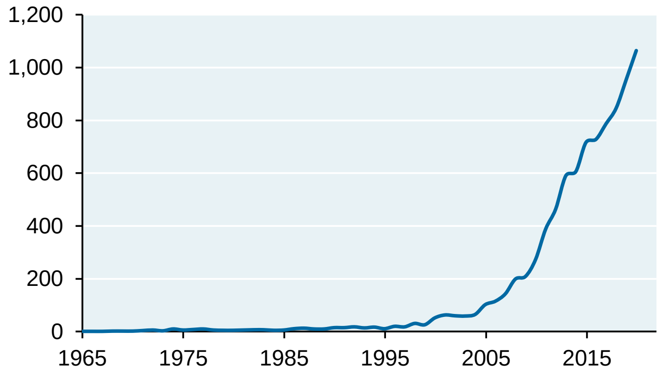
Ultimately, the price of electricity incorporates the cost of the ecosystem needed to meet demand, *including* periods of unanticipated spikes, and *including* whatever backup thermal capacity, storage capacity and new transmission are needed to accompany growing renewables. That's the reason that I do not pay much attention to "levelized costs of energy" as estimated by the EIA and Lazard, since they do not incorporate the entire cost implications of highly renewable grids. Europe is further along in its renewable transition, and higher shares of wind and solar are in many cases associated with higher electricity prices (see chart above right).

[23] Another reason: **nuclear** facilities cannot be easily ramped up and down during the day. To be present on the grid when intraday prices are high, nuclear operators also participate during periods of negative prices.

[4] The Song Remains the Same: geologic sequestration of carbon may face the steepest climb of all

After 20 years of planning and conjecture, by the end of 2020 carbon capture and storage (CCS) facilities stored just 0.1% of global CO_2 emissions. Challenges include cost overruns, failure of bellwether projects (Kemper Mississippi), the US Dep't of Energy withdrawing support for demonstration projects (FutureGen), cancellations in Europe, legal uncertainties about liability and a 20%-40% energy drag required to perform CCS in the first place. Norwegian Authorities just approved the Northern Lights sequestration project involving Total, Equinor and Shell whose 2024 capacity will be just 0.0045% of global emissions. **The highest ratio in the history of science: the number of academic papers written on CCS divided by real-life implementation of it**.

Academic papers on carbon capture
Number of papers published per year



Source: PubMed. 2020.

<u>**Princeton CCS proposal for the US**</u>
Buildout = 850 million tonnes of CO_2 stored per year via 65,000 miles of pipeline infrastructure
Supercritical CO_2 storage = 800 kg/m^3
Supercritical CO_2 stored per year = 1.1 billion m^3

<u>**US annual oil production**</u>
2019 = 746 million tonnes distributed and refined across 190,000 miles of pipelines
Density of oil = 1.15 m^3 per tonne
US annual oil production = 858 million m^3

As a result, I'm not sure what to make of the Princeton study's sequestration assumptions. The authors assume that 65,000 miles of CO_2 pipeline infrastructure will divert 929 million tonnes of CO_2 each year from cement, gas-powered generation, natural gas reforming and biofuel production facilities to centralized locations where they will be mostly sequestered underground (a small amount is assumed to be converted into synthetic fuels). This compares to current US CCS infrastructure of 5,280 miles and 80 million tonnes per year, mostly used for enhanced oil recovery[24]. **The Princeton CCS buildout, just to sequester an amount equal to 15% of current US GHG emissions, would require infrastructure whose throughput volume would be higher than the volume of oil flowing through US distribution and refining pipelines**, a system which has taken over 100 years to build (see box). Princeton's CCS projections are not that different from the ones found in pieces from Morgan Stanley, Goldman and other research houses.

We had a conversation with Peter Haugan, Director of the Geophysical Institute at the University of Bergen (Norway). **We talked about the Sleipner Field in the North Sea, one of the few existing CCS locations on the planet**. As it turns out, CCS is a very complex process: some nearby CO_2 injection sites were abandoned since they turned out to be much less permeable than originally anticipated, in which case higher levels of pressure could have caused cracks; and in other locations, polluted water injection sites *did* cause cracks since injected water was found at the surface of the ocean. In other words, the success of Sleipner so far is not a clear signal regarding the ease of CCS injection, even in well-known formations like the ones in the North Sea.

[24] A 2021 paper by David Victor (Brookings/ Deep Decarbonization Initiative) and a group of colleagues examined attempted CCS projects and found that capital cost, technological readiness and credibility of project revenues were the most important factors in getting projects completed (compared to population proximity, employment impact or local opposition).

What about carbon mineralization? Carbon mineralization is a form of storage in which carbon dioxide, rather than being stored as a compressed gas underground, reacts with certain rocks (magnesite, basalt, etc) and is permanently mineralized. It's not as easy as it sounds…

- In **ex-situ** versions of this idea, billions of tons of calcite or magnesite would need to be mined each year even if just a small amount of annual CO_2 emissions were removed from the atmosphere. To mineralize 15% of global CO_2 emissions, much more magnesite would need to be mined every year than annual global mining of iron ore, for example. The materials handling costs would be enormous, and efforts to accelerate the chemical reaction vs its natural rate have been very challenging
- The **in-situ** version of the idea involves injection of CO_2 (mixed in water) into basalt rocks, and in which the carbon mineralization reaction can occur in just a year or two. However, while you don't have to mine and move rocks in this version, you **do** need to move the CO_2 to where the basalt rocks are… which brings us back to the need for a massive build-out of CCS infrastructure (pipelines, compression, storage etc) to make even a small difference

What about direct air carbon capture as an option for gathering CO_2 emissions from distributed sources (i.e., vehicles)? Some net-zero studies allow for small amounts of fossil fuel combustion that are offset by direct air carbon capture (DACC). However, the material and energy demands of DACC are beyond daunting:

- The most promising direct air capture method is based on aqueous hydroxide solutions
- Let's assume that 10 gigatons of CO_2 are captured each year, around 25% of global emissions
- Somewhere between 1.7 and 3.0 gigatons of NaOH (caustic soda) would be needed; NaOH reacts with CO_2 to create water and sodium carbonate Na_2CO_3, which can be heated to produce a gaseous CO_2 stream…
- This amount of NaOH is 20-40 times its recent annual production, and also equivalent to 40%-67% of recent global crude oil extraction by weight
- Electrolysis required to produce the NaOH would consume **25%-40% of world electricity,** and hydroxide regeneration (used to reduce NaOH requirements by regenerating and reusing most of the reactant) would claim another **11%-17% of global primary energy**. Putting both pieces together, NaOH electrolysis plus regeneration would require 15%-24% of global primary energy to capture 25% of CO_2 emissions
- **A last nail in the coffin: 2,400 – 3,800 kWh per tonne of captured CO_2 via DACC would be needed before whatever energy is required to actually store the CO_2 underground;** DACC energy needs appear to be 6x-10x higher than traditional CCS energy estimates, a process which itself is stuck in neutral

As per authors of the paper cited below, "**DACC is unfortunately an energetically and financially costly distraction in effective mitigation of climate changes at a meaningful scale**" [25].

Sequestration summary

- To sequester 15%-20% of US CO_2 emissions, CCS volumes would need to exceed oil production, refining and distribution volumes
- Mineralizing 15% of global CO_2 emissions would require more tons of mined magnesite and basalt than current global mined tons of iron ore
- Sequestering 25% of global CO_2 through direct air capture would require 25%-40% of the world's electricity generation plus 11%-17% of its primary energy

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

[5] Decarbonization of the industrial sector: costs, challenges and limitations

The industrial sector is the largest fossil fuel end-user on a global basis. Could some industrial processes be **electrified** to eventually use more renewable energy as the grid is decarbonized?

In 2018, Lawrence Berkeley Laboratory outlined the possibilities: some primary metals, secondary steel, machinery, wood products, plastics and rubber. What do they have in common? **Most use fossil fuels primarily for "process heat" which could be replaced by electric heat**. We also assume high electrification potential for certain mining activities related to transport, excavation, pit crushing and belt conveying systems.

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

Industrial sectors with high electrification potential

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

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

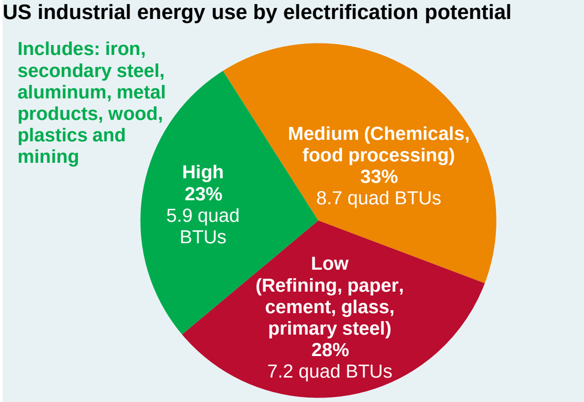
Industrial sectors with medium/low electrification potential

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

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

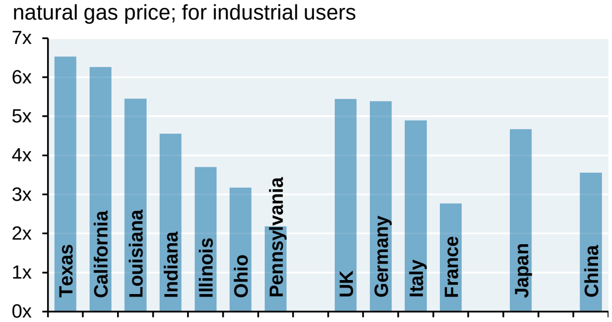
The challenge: low/medium electrification potential sectors use 2.5x the energy as high potential sectors. Even if we assume that all sectors are eventually electrified using new technologies[26], there's still a large increase in cost. In addition to upfront switching costs, industrial companies would face costs per unit of energy that are **3x-6x higher for electricity than for direct natural gas**. Electric heating efficiency gains vs combustion could offset part of this cost, but not all of it.

US industrial energy use by electrification potential



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

Electricity is 3x-6x more expensive than natural gas
Cost per megajoule of energy, electricity price divided by natural gas price; for industrial users

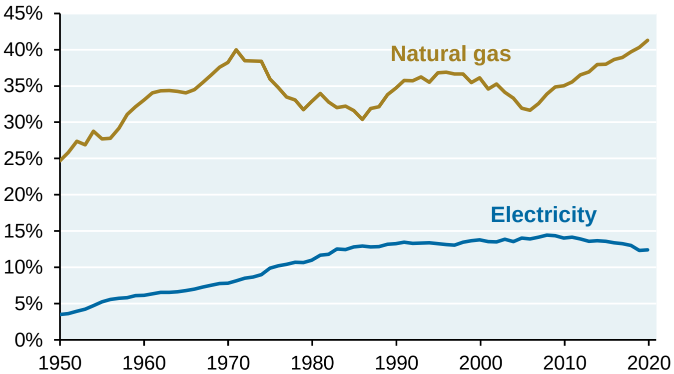


Source: EIA, Eurostat, IAEE, CEIC, IFPEN, JPMAM, World Bank. 2019. States shown are largest industrial users of US primary energy.

[26] For **cement** (8% of global CO_2 emissions), there are **pilot projects** underway to (a) use less limestone, less heat and more clay; (b) cure cement with captured CO_2 instead of water; (c) add bacteria to concrete that absorbs CO_2 from the air; and (d) create cement bricks from bacteria and aggregate. Some approaches could only be used for light-duty load-bearing materials such as pavers, facades and temporary structures.

Bottom line: chemistry and cost explain the low rate of industrial electrification around the world, and why the electricity share of US industrial energy use has been roughly unchanged at 12%-15% since the early 1980's.

Industrial energy use by type
Share of industrial energy use



Source: EIA. 2020.

A comment on primary steel production

Secondary (recycled) steel is produced in electric arc furnaces, which allows for green electricity to be used when available. However, **primary steel production** accounts for ~70% of global steel production and is much harder to decarbonize. Most primary steel production relies on coke ovens and blast furnaces that use carbon as a reducing agent to strip oxygen from iron oxide, a process which produces CO_2. Around 5% is produced using direct reduced iron (DRI) whose CO_2 footprint per ton is roughly half of the blast furnace method. DRI uses natural gas to generate carbon monoxide and hydrogen, which is used to reduce iron ore in a furnace, which is then combined with scrap steel in an electric arc furnace. The lower carbon content of natural gas vs coal is part of the reason for DRI's lower carbon footprint.

Some pilot projects aim to decrease the carbon footprint of primary steel by using green hydrogen as the reducing agent to strip oxygen from iron oxide. A consortium of Swedish companies (Vattenfall, LKAB and SSAB) aims to do just that, planning for some commercial production in 2026. **However, the Nordic steel industry produces just 6 million metric tons per year, which is 0.35% of global production**. So, even if the entire Nordic steel industry adopts this new approach by 2045 (the stated roadmap), it won't have much of an impact unless other countries adopt the same approach, and do so much faster.

As a reminder, China and other emerging country production methods will be the primary drivers of future global emission changes given Western deindustrialization over the last 25 years. At last count, **China made 50% of the world's steel, 33% of the world's ammonia, 61% of the world's cement and 31% of the world's plastics**. Its transition to cleaner energy and more modern production methods may be the single largest determinant of the planet's future over the next two decades.

Steel production volumes by type, MMT per year		
Primary	Blast furnace: basic oxygen furnace (BF-BOF)	1,186
Primary	Direct reduction of iron: electric arc furnace (DRI-EAF)	89
Primary	Other	8
Secondary	Electric arc furnace	388
Secondary	Basic oxygen furnace	60
Total		1,731

Source: World Steel Association. 2019.

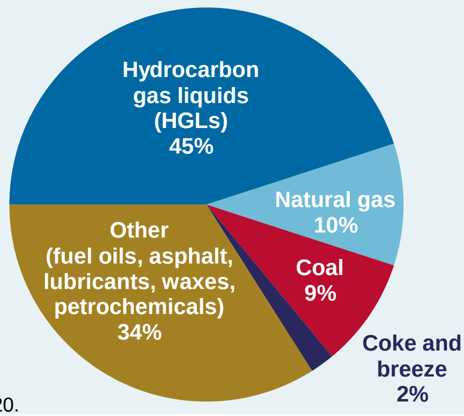
Current primary steelmaking emissions Kilograms of CO_2 per ton of steel	Blast furnace: basic oxygen furnace	Direct reduction of iron: electric arc furnace
Electricity	87	312
Coal	1,592	44
Natural gas	50	508
Total	1,729	864

Source: Resources for the Future, "*Potential of hydrogen for decarbonization*", 2021.

What about fossil fuels used as raw material feedstocks?

In addition to using fossil fuels for process heat, industrial producers also use them as raw materials. It's tempting to believe that since they're embedded into physical products (i.e., plastic in soda bottles or the rubber in your car tires), they would not contribute to increased GHG emissions. But none of these products lasts forever, and usually end up in waste incineration plants, in decomposing landfills or in the ocean[27]. As a result, there's research underway to replace fossil fuels with (for example) CO_2 captured from industrial emitters, which is then converted into polyethylene using a "methanol to olefins" approach. Another approach involves gasification of crop residue to produce olefins, which are used to make plastics. However, the cost of such feedstock alternatives may be prohibitive and few have been commercialized at any meaningful scale.

Energy sources used as raw materials by US industrial producers



Source: EIA. 2020.

Industrial use of fossil fuels as raw materials

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

Lubricants derived from crude oil minimize friction in everything from airline turbofan engines to miniature bearings, and differ from other fractions of crude oil by their very high boiling point. They can be for intermittent use (motor and aviation oils) or continuous service (turbine oils). Globally, the auto industry is the largest consumer, followed by textiles, energy, chemicals and food processing. Annual use of lubricants surpasses 120 megatons; for comparison, global output of all edible oils such as olive oil and soybean oil is 200 megatons a year. Synthetic lubricants made from simpler compounds are more expensive, so demand for lubricants from crude oil may keep rising.

Another product derived from crude oil: **asphalt**. Global output is now around 100 megatons, with 85 percent used for paving and most of the rest for roofing.

Source: Smil, V. 2022 (forthcoming). "*How the World Really Works*"

[27] The DoE and EIA made detailed permanent carbon storage assumptions by product in a 260-page document in 2008 which is still in use today. Carbon in asphalt is considered 100% stored while for lubricants storage is assumed to be 50%. The IPCC assumes 80% carbon storage in plastics, but as described above, actual storage rates may be lower due to incineration or decomposition in landfills.

[6] Oil and gas update: our bullish call on the sector, one year later

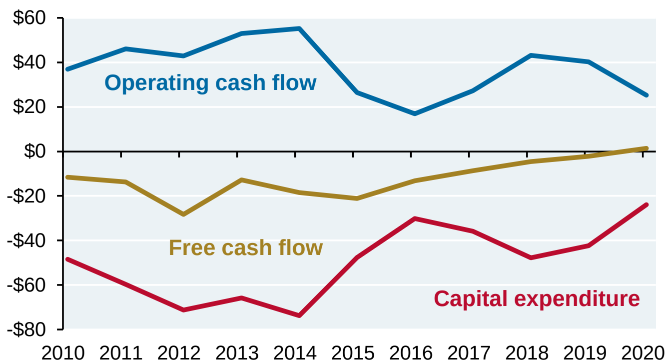
In last year's paper we made a bullish call on the oil & gas sector. Since then, energy rebounded and outperformed the overall market. We recommend that investors stick with the oil & gas sector for now.

During the prior decade, investing in the US shale revolution was often a train wreck. Take a 23-stock universe of companies associated with the US shale boom from 2010-2019[28]:

- As a group, their aggregate free cash flow was negative in every year
- Seven of these companies never experienced a single year of positive cash flow
- Another eleven companies only experienced positive free cash flow in 3 or fewer years out of 10

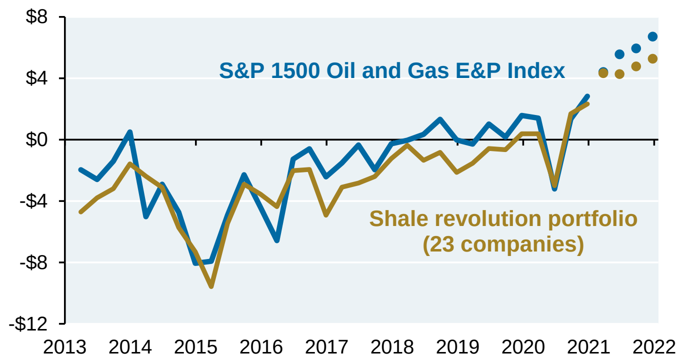
We felt that this poor performance was based on (a) the collapse in capital discipline by management and by investors and (b) the supply shock from hydraulic fracturing rather than (c) a sign that demand for fossil fuels was at a permanent, downward inflection point. In other words, **investors and management could solve this problem after a period of bankruptcies, consolidation and a renewed focus on free cash flow**. Since last summer, signals are mostly positive. The industry is now more focused on generating cash flow for investors, and both rig counts and capital spending have bottomed out.

Shale revolution: a revolution in supply, not profit
Select cash flow measures for 23 shale companies, US$, billions



Source: Bloomberg. 2020.

Energy sector free cash flow
US$, billions

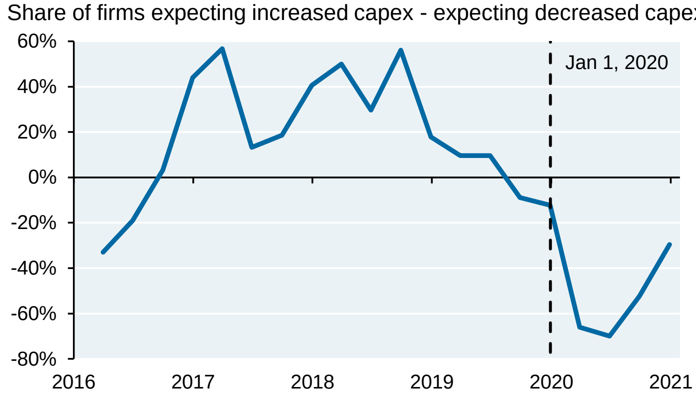


Source: Bloomberg. Q4 2020. Dots represent estimates.

Number of US oil and gas rigs

Source: Baker Hughes, Bloomberg. April 23, 2021.

E&P year ahead capital spending expectations
Share of firms expecting increased capex - expecting decreased capex

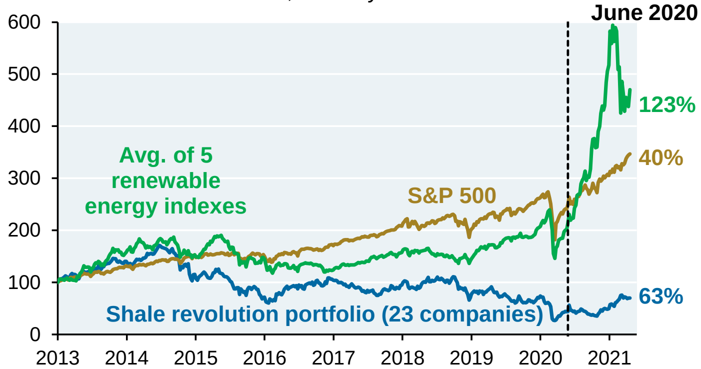


Source: Federal Reserve Bank of Dallas. Q4 2020.

[28] The 23 companies in our shale universe: Antero, Apache, Cabot, Callon, Chesapeake, Cimarex, Continental, Denbury, Diamondback, EOG, EQT, Hess, Laredo, Marathon, Matador, Murphy, Oasis, PDC, Pioneer, Range, SM, Southwestern, and Whiting. The following 6 companies were included in the shale analysis in our 2020 energy paper, but have since been acquired: Anadarko, Carrizo, Concho, Noble, WPX and QEP.

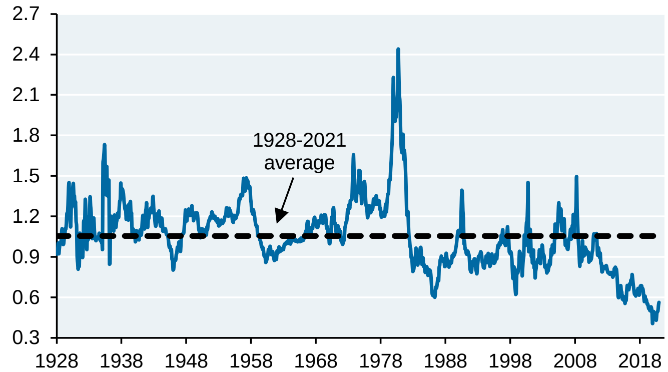
Market results. Shale stocks rebounded from 2020 lows and outperformed the broad market since our energy paper last year. However, these gains are eclipsed by the rise in renewable energy stocks. Despite the rebound, the oil & gas sector still trades close to the largest discount vs the market in its 90-year history.

Energy rebound vs the market since June 2020
Cumulative total return index, January 2013=100



Source: Bloomberg. April 26, 2021.

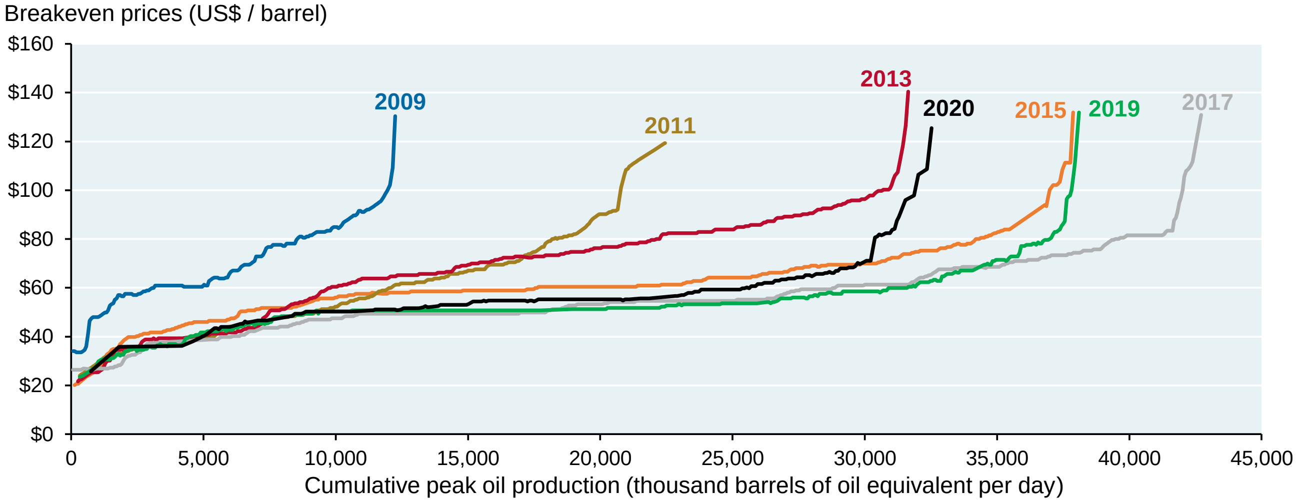
Energy sector valuations at all-time lows vs the market
Energy stocks price to book divided by market price to book



Source: Empirical Research Partners. March 2021. Equal weighted portfolio.

We recommend that investors stick with oil & gas for now. World demand for liquid fuels should continue to rebound as COVID vaccinations increase and economies reopen. As demand grows, we expect supply to recover more slowly. "Big Oil" return on capital fell to single digits by 2016 due to excess competition; we expect these returns to rise back to 1990's levels of 10%-15%. And while publicly traded oil companies only represent 2/3 of global production, their trends are notable: 60% decline in reserve lives since 2014, steepening oil cost curves since 2017 and declining capital commitments[29].

Cost curve for new oil projects (pre-sanction, under development and producing) 2009-2020
Breakeven prices (US$ / barrel)



Source: Goldman Sachs. 2021. Identified projects (pre-sanction, under development and producing) are evaluated each year and assigned a breakeven price and peak oil production. The oil cost curve depicts the cumulative peak oil production of identified projects.

[29] "*Top Projects 2021: Shrinking Reserves and Rising Profits*", Goldman Sachs, March 24, 2021. See Exhibits 1-4.

Lastly, the world is not on track to strand a lot of oil and gas in the future and is much closer to the IEA Stated Policies scenario than its Sustainable Development scenario[30]. **Only in the latter are oil, gas and coal assets projected to be left stranded in the ground, which you can see in the table**. As a result, peak oil *demand* forecasts may end up being just as wrong as peak oil *supply* forecasts were a generation ago[31].

World liquid fuels consumption
Million barrels per day

Source: EIA Short-term Energy Outlook. March 2021.

Comparing stranded asset risks in IEA scenarios

Stated Policies Scenario: only coal assets stranded

	Proven reserves, 2018	Cumul. extraction, 2019-2070	Stranded in 2070	Percent stranded
Oil	235,931	265,353	0	0%
Nat gas	169,334	228,266	0	0%
Coal	596,540	197,890	398,650	67%

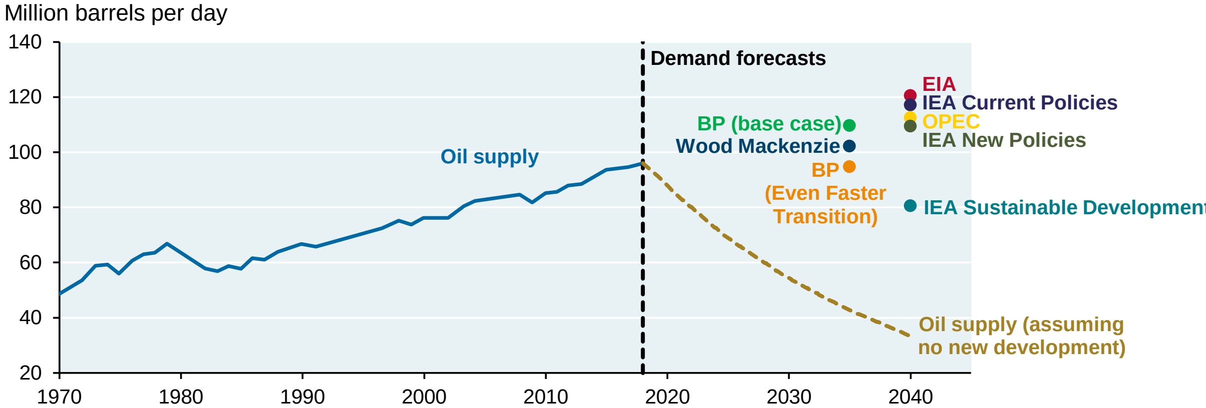
Sustainable Development Scenario: large amounts of stranded oil, gas & coal

	Proven reserves, 2018	Cumul. extraction, 2019-2070	Stranded in 2070	Percent stranded
Oil	235,931	137,478	98,454	42%
Nat gas	169,334	125,259	44,075	26%
Coal	596,540	77,560	518,980	87%

Source: BP, IEA, JPM. Units shown are million tons of oil equivalent. 2019.

This is the "oil wedge" chart: it shows different projections of future oil demand and the amount of oil supply from existing fields assuming no new development. Even in the IEA's highly ambitious Sustainable Development scenario, world oil demand in 2040 is still twice the level of supply from existing fields. **Is everyone sure that we should starve this industry of capital starting now?**

Oil "future production wedge": demand vs existing field supply
Million barrels per day



Source: BP. 2019.

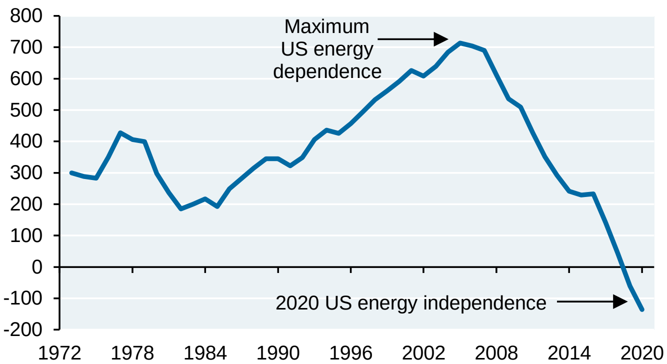
[30] **The IEA Stated Policies scenario is *not* the status quo**; it reflects some far-reaching and ambitious targets that have been legislated or announced by govt's around the world. The **IEA Sustainable Development scenario** is even *more* ambitious, and assumes the following by 2030: global primary energy use declines 7% from 2019 to 2030 (compared to a 20% increase over the prior 11 years); solar generation grows by a factor of 5.6x, wind generation grows by a factor of 2.4x; nuclear generation increases by 23% (no decommissioning); coal use for power/heat declines by 51%; and electric vehicles sales reach 40% from today's 4.5% levels.

[31] See Vaclav's 2006 "*Peak Oil: A Catastrophic Cult and Complex Realities*". Global oil production **has risen by 20%-60%** since the dates of various peak oil supply forecasts made in prior decades.

[7] Biden's energy agenda: how much oil and gas will the US need in the future?

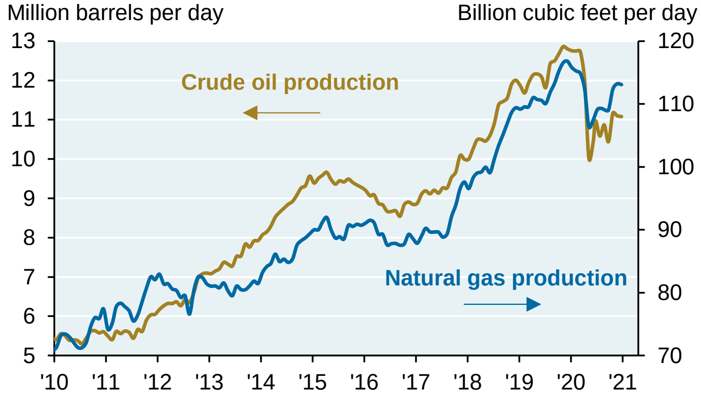
For the first time in my lifetime the US is "energy independent", at least on a net basis. However, 60%-80% of US oil, gas and NGL production is reliant on hydraulic fracturing, and the US is still 75%-80% reliant on fossil fuels for primary energy. Against this backdrop, the Biden administration announced policies to reduce oil & gas supply and demand and to decarbonize the electricity grid by 2035. In this section, we analyze each. To start out, here are some charts on US energy independence and US reliance on hydraulic fracturing.

US net energy deficit, in energy terms
Net imports of oil, natural gas and coal in million tonnes of oil equiv.



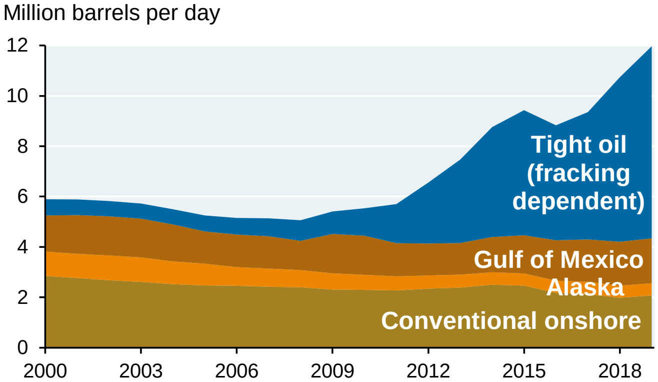
Source: EIA, JPMAM. December 2020.

US crude oil and natural gas production
Million barrels per day
Billion cubic feet per day



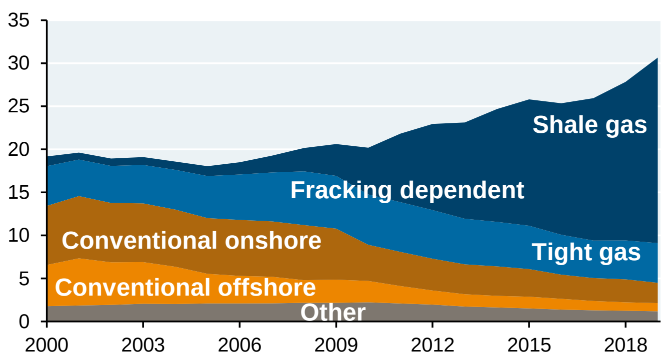
Source: EIA. January 2021.

US oil production by type
Million barrels per day



Source: EIA. 2019.

US dry natural gas production by type
Trillion cubic feet per year



Source: EIA. 2019.

[a] Oil supply and demand

Biden's energy agenda includes the following policies which impact oil/gasoline:

- Ban on new leases for oil & gas production on Federal lands, which currently account for 9% of onshore oil, 9% of onshore gas, 16% of offshore oil and 3% of offshore gas (executive action)
- Termination of 500,000 barrel per day Keystone XL[32] pipeline project (executive action)
- Electrification of the Federal vehicle fleet (executive action)
- $100 billion over ten years for extension of Federal income tax credits for EVs by eliminating the 200,000 unit cap, tax credits for used EV purchases and point-of-sale trade-in rebates for EVs (legislation)
- Improvement in public transit infrastructure, designed to reduce car ownership (legislation)
- A 6% annual emissions reduction in new model years 2026-2030 vs 2020 baseline (executive action)

[32] **Gasoline is only part of the energy supply lost from the Keystone XL cancellation**. Other annual energy supply losses include 2.3 billion gallons of distillate fuels and 800 million gallons of jet fuel, both of which would need to be produced on US private lands or imported from someplace other than Canada.

The table shows the potential impact of each policy on US gasoline demand using our assumptions[33]. The projected reduction in gasoline demand exceeds the reduction in domestic supply by 2.6 billion gallons per year. As a result, these policies **would not under our assumptions worsen US energy independence**.

However, given annual gasoline consumption of 142 billion gallons per year (2019), 12.4 billion in demand reduction would only be a 9% decline. In other words, the US would still need plenty of gasoline in 2030 and beyond even if the Biden agenda is implemented using our assumptions.

Furthermore, a lot is riding on improved mileage standards for new cars and EV incentives. As described earlier, US EV sales last year were just 2%. Our assumptions imply a quick jump to around 12%, which would catapult the US from one of the lowest EV countries to one of the highest. It's unclear if US consumer preferences will change that quickly, and we have already discussed on page 14 how behavioral issues may reduce the assumed GHG benefits in the EV transition. **Bottom line: the reduction in US gasoline supply has a lot more certainty to it than the projected decline in US gasoline demand**.

Policy	Legislative/ Executive	Supply/Demand	Estimated impact in year 5 billion gallons of gasoline per year
[a] Ban on new oil & gas leases	Executive	Supply	(6.4)
[b] Keystone XL Pipeline	Executive	Supply	(3.5)
		Total supply decline	*(9.8)*
[c] Electrification of federal fleet	Executive	Demand	(0.4)
[d] EV incentives	Legislative	Demand	(4.9)
[e] Public transit improvements	Legislative	Demand	(0.5)
[f] Mileage/emissions improvements	Executive	Demand	(6.6)
		Total demand decline	*(12.4)*
		Net demand decline	*(2.6)*

Source: EIA, DOT, BTS, WSJ, EV Volumes, JPMAM. 2020.

[33] Key assumptions for the table above:

- After 5 years, onshore/offshore oil production on Federal lands declines by 50%/20%, with the difference reflecting the much longer lease terms of offshore facilities
- Consistent with research from Europe, public transit investments reduce car ownership by 3%; only 5%-10% of Americans use public transport regularly and 45% currently have no access to public transport
- EV incentives: $100 bn based on Goldman Sachs Economic Research April 16th analysis of Biden energy proposals; subsidy per vehicle based on Senator Schumer's 2019 plan of $6,000 per vehicle
- Real world mpg on new cars increases to 34 mpg by 2030 compared to 22.3 mpg on the existing stock of cars and 25 real world mpg on current new cars sold [EPA data]. Real world mpg differs substantially from rated mileage due to testing, road conditions and driver behavior. EPA estimates of real world mpg for new cars sold are 10 mpg below a unit-weighted average of new car fuel economy sourced from the DoT
- US miles driven for average passenger car/light vehicle: 13,500 per year; unit sales 17 million per year

[b] How much natural gas will the US need in the future (i.e., 2035)?

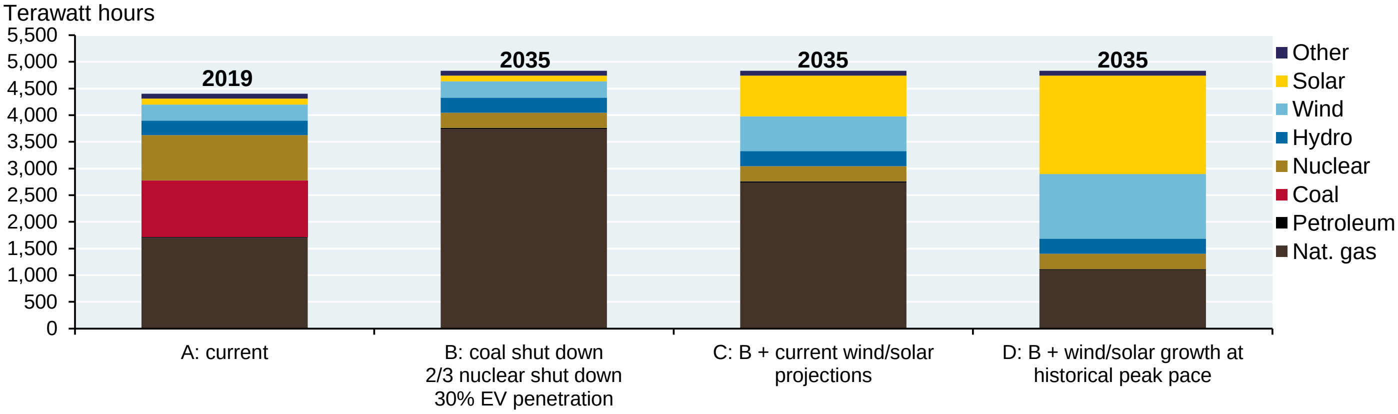
The Biden administration aims to decarbonize the US electricity grid by 2035. In this section we examine implications for the US natural gas industry. By 2035, we assume the following:

- Since most nuclear plants will be 50 years old or more and since many are already unprofitable, 2/3 will be decommissioned; coal plants will be decommissioned as well; hydropower grows by 5% as per prior studies
- US electricity demand grows by 10% to accommodate 30% EV penetration with EVs @3.3 miles per kWh; the overall light vehicle fleet grows by 1% per year; non-EV electricity demand remains constant as efficiency improvements offset a projected rise in population (as has been the case since 2005)
- Median national capacity factors of 25% for utility-scale tracking solar and 35% for onshore wind

If we stop there, the US natural gas industry would need to increase its share of electricity generation from 39% to 77% [Scenario B]. Next, we include wind and solar growth of 25-30 GW per year projected by LBNL before the impact of any Biden infrastructure spending, in which case the natural gas share of generation would be 57% [Scenario C]. Finally, we assume a faster 73 GW pace of wind/solar growth based on the rate of peak US capacity additions during the natural gas boom of the late 1990's. This is **very aggressive** since that capacity boom only lasted two years, and we assume this pace is sustained for 15 years. In this case, the natural gas share of generation would fall to 23% in 2035 [Scenario D].

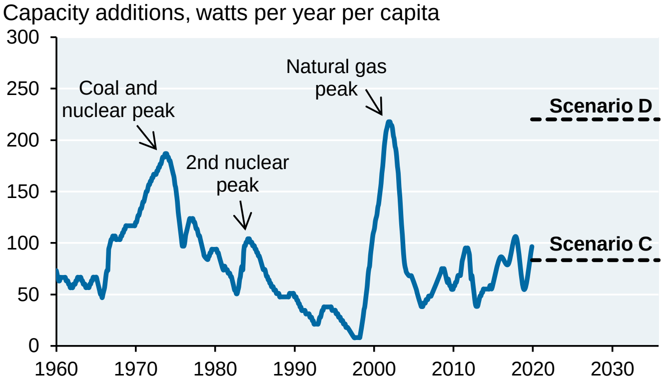
The Scenario D wind/solar capacity expansion would require a lot of new transmission infrastructure as well. The third chart illustrates just how much of a challenge this will be given Federal, state and local transmission bottlenecks discussed in Sections 2 and 3. Without adequate interstate transmission expansion, renewable penetration of this magnitude would be close to impossible, even with growth in distributed storage.

US electricity generation mix
Terawatt hours



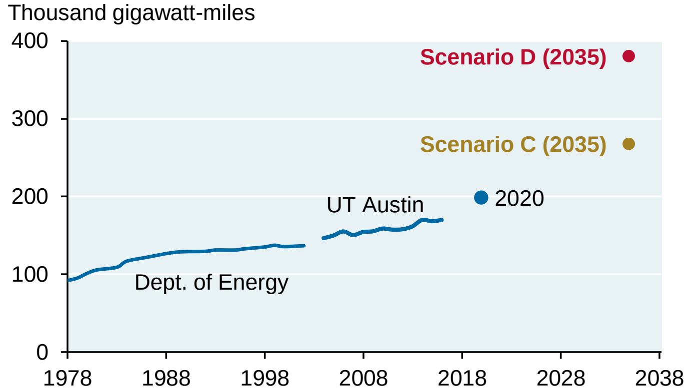
Source: BP, EIA, Lawrence Berkeley National Laboratory, JPMAM. 2019.

Historical rates of installed electric-generating capacity
Capacity additions, watts per year per capita



Source: American Public Power Association, EIA, China Electricity Council, Fraunhofer ISE, BP, LBNL, Clack et al. (pre-2014 data), JPMAM. 2020.

US transmission infrastructure
Thousand gigawatt-miles



Source: DOE, UT Austin, BP, EIA, Princeton Net Zero, LBNL, JPMAM. 2020.

Under Scenario D, natural gas used for electricity generation declines by one-third. **However, as discussed in the Executive Summary, electricity accounts for just 17% of total US final energy consumption. Direct energy use by industry, in transportation and for heating is much larger.** The same is true for natural gas: only 35% is used for electricity while larger amounts are used by US industry plus commercial and residential heating.

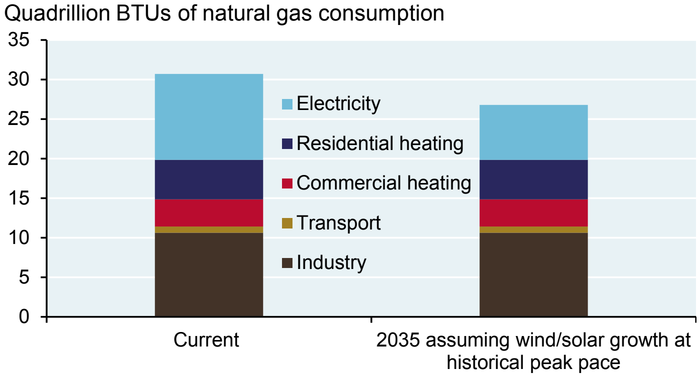
Looking at 2035. Electrification of industrial energy use is a very slow process (see Section 5), and we see no basis for assuming rapid changes in the next decade. Natural gas used for residential and commercial heating has been stable since the 1970's, and we expect any electrification to be minor. In other words, natural gas demand for non-grid reasons is assumed to remain the same. We assume that US primary energy use remains roughly flat, as it has since 2010, with efficiency gains offsetting a growing population. The last chart shows natural gas consumption by sector, today and in 2035 according to Scenario D's rapid solar/wind expansion.

Even when assuming a pace of wind/solar expansion that matches peak 1990's capacity additions, demands on the natural gas industry in 2035 would only decline by 13% vs today's levels. Our base case is in between Scenario C and D, and results in natural gas demand in 2035 that is roughly unchanged vs today. **Important to understand**: if you assume a faster pace of electrified transport, industry or heating, the incremental kWh would have to come from natural gas unless you assume an even faster pace of solar/wind expansion.

As a result, even with plans to achieve greater grid decarbonization, it would be premature to limit the natural gas industry's ability to provide a reliable source of baseload, dispatchable power and direct primary energy to the US economy. Policymakers also need to plan for the unexpected; should wind and solar growth not achieve peak growth, US natural gas demand in 2035 might not be that different than it is today.

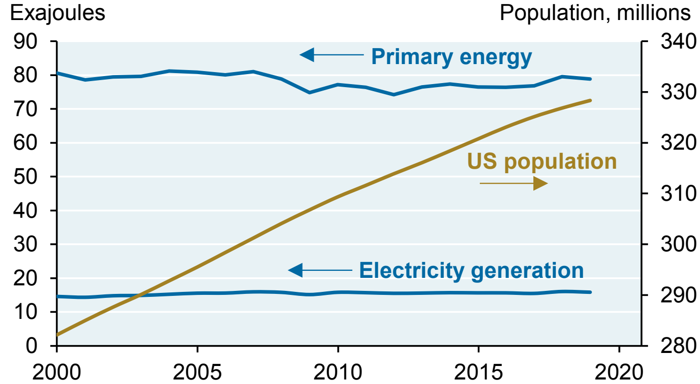
For a 7-page compilation of our views on **the future of US natural gas** (i.e., this 2-page section and other natural gas materials cited elsewhere in this paper), please click [here.]()

Even assuming ambitious solar/wind grid expansion, overall natural gas needs fall by only 13% by 2035
Quadrillion BTUs of natural gas consumption



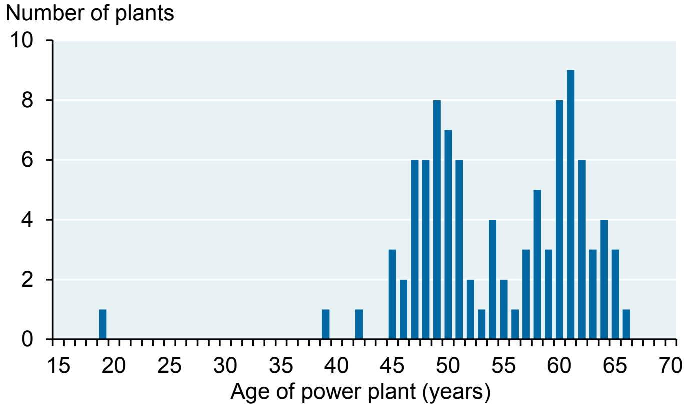
Source: BP, EIA, LBNL, JPMAM. 2019.

US primary energy use, electricity generation & population
Exajoules
Population, millions



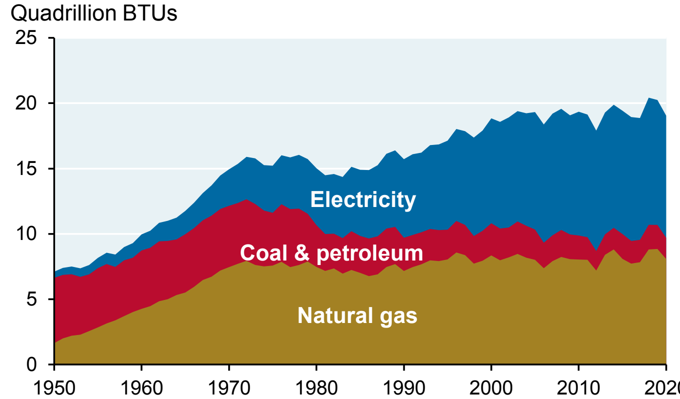
Source: BP, Census. 2019.

Age distribution of existing US nuclear reactors in 2035
Number of plants



Source: International Atomic Energy Agency. 2019.

Residential and commercial energy use by type
Quadrillion BTUs



Source: EIA. 2020.

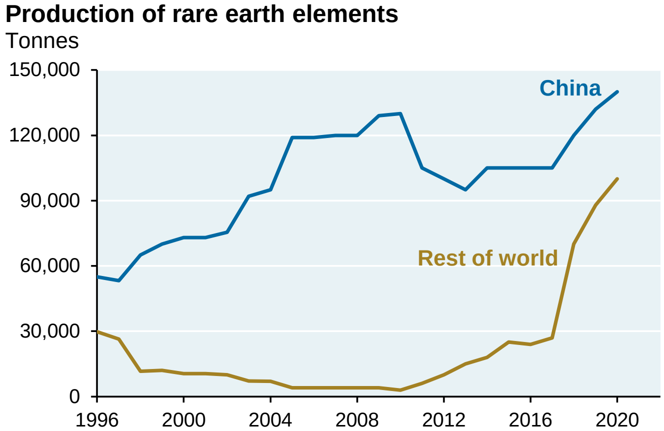
[8] China's rare earth metal diplomacy revving up again

For many years China had an effective monopoly on production of rare earth elements (REE) used to make rechargeable batteries, wind turbines and energy efficient light bulbs (and F-35 fighter jets and nuclear subs). While rest-of-world REE production has been rising, China still produces most of the "heavy" REEs that are scarcer; the light REEs are much more abundant. Almost 90% of China's REE exports go to 5 countries: Japan, US, Netherlands, South Korea and Italy. Demand for rare earth metals is expected to double by 2030 as renewable energy demands increase. While the value of global REE imports in 2019 was small ($1 billion compared to $1+ trillion in global oil imports), they are critical to a variety of renewable supply chains.

China has used rare earth metals diplomacy in the past: in 2010, China cut its REE export quotas by 37%. This led to a temporary ten-fold increase in REE prices per metric ton, a World Trade Organization ruling against China, a resumption of exports and a collapse in REE prices back to prior levels. But something happened that's worth noting: at the time, higher prices led to 200 new REE projects outside China. Many never survived since prices collapsed, but it does signify the ability of other countries to take on REE production and refining if it makes economic sense, and if they're willing to take on the inherent environmental risks. After a 2010 dispute with Japan over a fishing boat incident and China's decision to cut off REE exports for 2 months, Japan invested in Lynas Corp, an Australian company which survived and is the only supplier outside China able to process REE. Lynas now supplies Japan with one-third of its REE imports.

We may be in for a repeat of the 2010 episode. Chinese President Xi made a public visit to an REE facility in Jiangxi in 2019, and in 2021 China's Ministry of Industry and Information Technology proposed controls on production and export of REE. Responses: in 2018 a US rare earth mine in California reopened, a Texas REE processing facility was approved by the Dep't of Defense in April 2020, the EU has funded an initiative to recycle permanent magnet waste, an Australian company has raised financing for a project in Uganda, and Japan aims to reduce reliance on Chinese REE below 50% by 2025. **In other words, we might see another spike in global REE projects and prices if China is going to preserve its REE for domestic use or for use in trade disputes[34].**

Production of rare earth elements



Source: US Geological Surveys (1996-2021). 2020 estimates as of Jan 2021.

Rare earth production and reserves (tonnes)

	Mine production				Reserves	
	2019	%	2020	%	2020	%
United States	28,000	13%	38,000	16%	1,500,000	1%
Australia	20,000	9%	17,000	7%	4,100,000	4%
Brazil	710	0%	1,000	0%	21,000,000	18%
China	132,000	60%	140,000	58%	44,000,000	38%
India	2,900	1%	3,000	1%	6,900,000	6%
Russia	2,700	1%	2,700	1%	12,000,000	10%
Vietnam	1,300	1%	1,000	0%	22,000,000	19%
Other countries	31,166	14%	40,600	17%	4,320,000	4%
World total	218,776	100%	243,300	100%	115,820,000	100%

Source: US Geological Survey. 2021. 2020 estimates as of January 2021.

Light REEs: Lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium and scandium
Heavy REEs: Terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium and yttrium

[34] **China's use of trade in diplomatic disputes**. After Australia called for an international inquiry into the origins of COVID-19, China responded by raising trade barriers on imported Australian barley, timber, sugar, seafood, wine and coal. But *not* iron ore, since China is highly dependent on Australia for that.

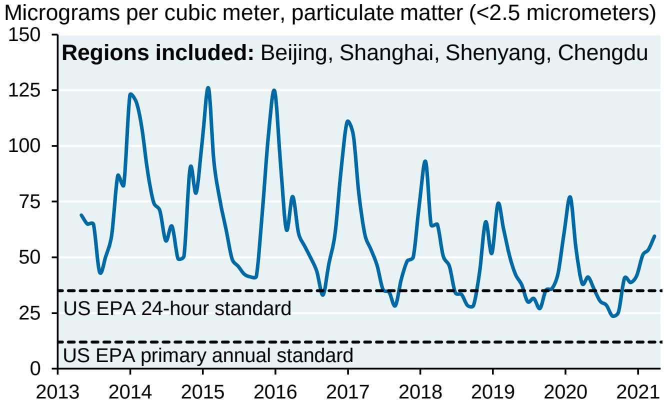
[9] China: how new laws on residential heating systems actually lead to greater GHG emissions

Due to its low price and high heat value, coal is a primary winter heating fuel in Northern China. In rural communities, coal-fueled "kang" bed-stoves have been around for almost 2,000 years. However, without desulfurization and denitrification, kang bed-stove combustion of coal releases sulfur dioxide, nitrogen oxide and other air pollutants directly into the atmosphere. In the Beijing/Tianjin/Hebei region, annual rural coal consumption can exceed 40 million tons, contributing to ~15% of that region's overall sulfur dioxide, 4% of its nitrogen oxide and 23% of its airborne nanoparticles. The first chart illustrates the huge seasonal swing in Central and Northern China air quality in winter when coal usage rises, and how particulate matter surges above recommended limits in Western countries. An alternative air quality measure shows that in some Northern China regions, air quality sometimes registers as "terrible" or "poisonous" in winter months.

The problem: direct combustion of coal for heat is more efficient than combustion of coal to make electricity to power electric heaters, and China's grid is still highly reliant on coal. On the right, we show the estimated heating efficiency of kang bed-stoves (62%) compared to the efficiency of China's electricity grid (38%, net of transmission losses). Also: China's electricity grid is 65% reliant on coal. Putting the pieces together, a 2020 paper estimated that for every 1 kg of coal consumed by a kang bed-stove, 1.9-2.2 kg of coal would be needed to indirectly power an electric heater in the same home[35]. The authors estimate 200 million metric tons of additional CO_2 emissions this year in China simply due to the shift from kang bed-stoves to electric heating (around 2% of China's overall CO_2 emissions). As per the chart on the left, the policy may be helping to reduce particulate matter as intended, along with other decarbonization steps.

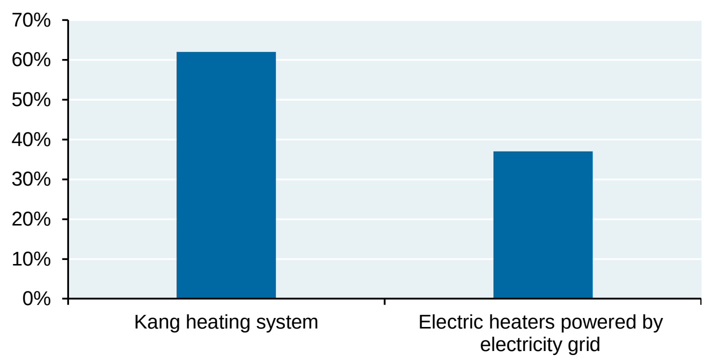
Urbanization and further penetration of renewables on the grid will solve part of this problem in China, but there's a broader issue at work here. "Electrification of everything" can improve air and water quality in countries with substantial rural combustion of fossil fuels, and provides a means to eventually use greener power on the grid. **However, electrification before grid decarbonization can improve some environmental issues while at the same time making others worse.**

China particulate matter
Micrograms per cubic meter, particulate matter (<2.5 micrometers)



Source: Bloomberg, EPA, JPMAM. March 31, 2021.

Efficiency of Chinese heating systems
%



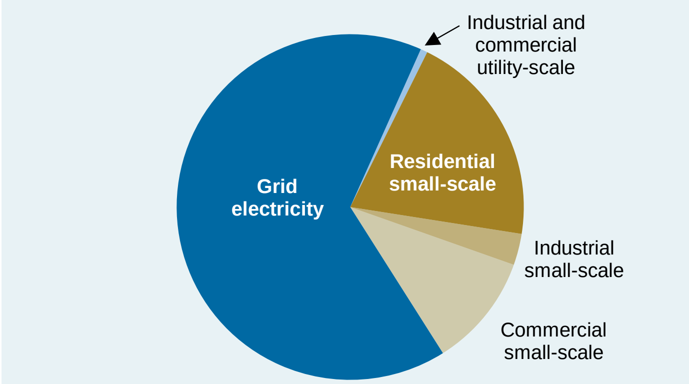
Source: Kammen, UC Berkeley; Zheng, North China Electric Power University. November 2020.

[35] "*Exploring the trade-offs between electric heating policy and carbon mitigation in China*", Kammen et al, Nature Communications, 2020.

[10] US solar power: distributed small-scale generation is growing, but customers face headwinds

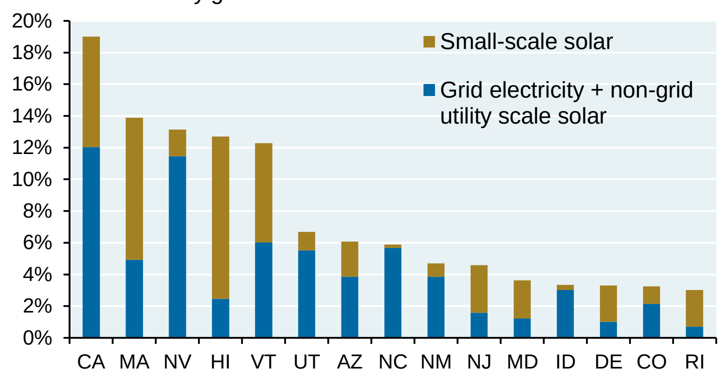
US solar power is still a small contributor at 2.8% of electricity generation and 1.2% of primary energy. Wood MacKenzie expects solar generation to double by 2025, but that's still single digits in share terms. On a national level, utility-scale solar power on the grid accounts for 2/3 of solar generation while small-scale distributed solar on residential, commercial and industrial rooftops accounts for the rest. In some states, distributed solar accounts for more generation than grid solar (MA, HI, VT, NJ, MD). In the third chart, we show solar capacity factors by state; fixed-tilt is an upper limit proxy for distributed rooftop solar.

US solar generation by source



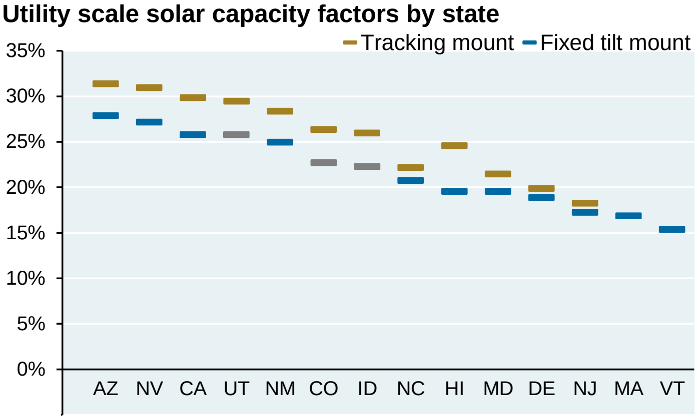
Source: Energy Information Administration, JPMAM. 2019.

Top 15 states by solar share of electricity generation
% of total electricity generation



Source: Energy Information Administration, JPMAM. 2019.

Utility scale solar capacity factors by state



Source: Lawrence Berkeley National Lab, JPMAM. 2019. Gray bar = estimate.

Select reimbursement approaches by state

AZ initial 30% below ToD retail rate, reimbursement declines over time; **CA** full ToD retail rate; if positive net balance at end of year, reimbursed at 3-4¢ per kWh; monthly transmission charge; **HI** wholesale rate (~50% of retail rate) plus monthly transmission charge; **MA** full retail rate, 60% of retail rate for positive export balance; **MD** full retail rate; **NJ** full retail rate, avoided cost for positive export balance; **NM** utility-dependent (full retail rate or net avoided cost); **NV** 75%-95% of retail rate; **UT** full retail rate; **VT** full retail rate, 10%-20% below retail rate for positive export balance

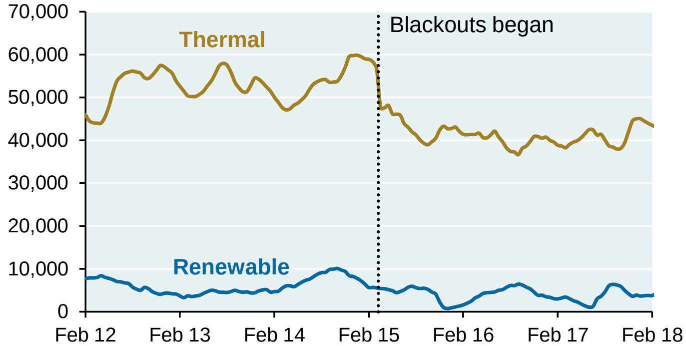
Many states no longer reimburse solar customers at the full retail rate irrespective of time of day. Many now pay a fixed discount to the retail rate, or a time-of-use amount which depends on the time of day (ToD), or a wholesale rate. Some utilities take an even more localized approach, only maintaining generous incentives for customers in places with strained, over-utilized transmission grids. Falling compensation rates increase the value of distributed storage to such customers, allowing them to forgo electricity purchases at higher prices; but this has its own payback period due to the additional capital cost of storage capacity.

Less generous reimbursement approaches have been adopted since (a) many solar customers flood the grid with electricity when it's abundant, reducing its value; and (b) customers that export solar need in some way to bear a greater cost of transmission upgrades that are often required to accommodate two-way electricity flows. According to a study of industrial solar customers in California, changes to net metering rules reduced electricity savings by 30% and substantially lengthened payback periods.

Epilogue: Last words on the Texas power outage and why I write this paper each year

Here's a chart on the outage and a table showing ERCOT's seasonal resource adequacy assessment.

Electricity generation in Texas
Megawatt hours



Source: EIA. February 22, 2021. Renewable includes wind, solar and hydroelectric. Thermal includes natural gas, coal and nuclear.

ERCOT seasonal resource adequacy assessment: winter worst case, gigawatts

	Coal	Nuclear	Gas	Wind
Total capacity	13.6	5.2	48.4	25.0
Expected offline	2.8	1.1	10.0	23.2
Expected online	10.8	4.1	38.3	1.8
Minimum during crisis (Feb. 15)	7.6	3.8	27.5	0.6
Underperformance	**3.2**	**0.3**	**10.8**	**1.1**

Source: ERCOT 2020 SARA report, EIA, JPMAM. 2021.

Now let's look at what some politicians, regulators and journalists had to say about this.

"Bad Takes Department": some people blamed the Texas power outage primarily on wind

"This is what happens when you force the grid to rely in part on wind as a power source. When weather conditions get bad as they did this week, intermittent renewable energy like wind isn't there when you need it."
– U.S. Representative Dan Crenshaw (Texas Tribune)

"We should never build another wind turbine in Texas."
– Sid Miller, Texas agriculture commissioner (Texas Tribune)

"The windmills failed, like the silly fashion accessories they are, and people in Texas died."
– Tucker Carlson, Fox News (Austin American-Statesman)

"*[The outages] are proof that green energy is not ready for primetime. [In sub-freezing temperatures], wind and solar just don't work for power.*" – Larry Kudlow, Fox News (Austin American-Statesman)

"*The cold-driven February 2021 shortage in Texas was caused by over-reliance, not under-reliance, on weather-dependent renewables like solar panels and wind turbines.*" – Michael Shellenberger (energy journalist)

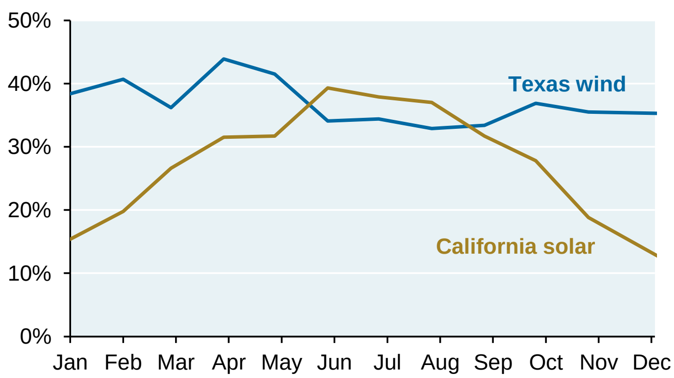
In my view, these are highly inaccurate diagnoses of the outage given the following readily available information:

- The decline in Texas natural gas generation was four times larger than the decline in wind
- ERCOT *said* the outage was primarily due to natural gas supply issues due to freezing of gathering lines and failure of electric pumps. The table above shows the underperformance by fuel type according to ERCOT's own worst-case risk assessment analysis prepared in 2020
- **Texas has a "critical loop" problem**: many of its natural gas production sites, compression facilities and hubs are **electrified** instead of using natural gas to power their operations. As a result, if their electricity is cut for some reason, it creates a **downward spiral** since these facilities can no longer supply natural gas to power plants, creating the need for even greater outages that affect more natural gas operators. This is what happened during the outage when Texas utility Oncor cut power to dozens of natural gas facilities
    - ➢ There's an easy solution here: natural gas operators are supposed to file a form so that they are on a "critical infrastructure list". However, as reported in the Texas Tribune, many natural gas operators hadn't filled out the form or didn't even know it existed (!!). After the outage, Oncor added 168 natural gas facilities to its critical list, a five-fold increase from January of this year

- Another problem: in Texas, natural gas pipelines are **contractually obligated to prioritize residential customers** while power plants usually don't have contracts that guarantee supply. When demand for natural gas spiked during the cold weather, most residences received uninterrupted natural gas while many power plants didn't
  - Remarkably, the president of the North American Electric Reliability Corporation (NERC) said this: "Our gas system, quite frankly, is designed for industrial use and space heating. **It's not designed to serve large power plants**. We don't think of gas as the same criticality as we do power. That makes sense, except when you realize a power system without reliable gas supply is not that useful"
- NERC and the Texas Public Policy Foundation warned years ago that ERCOT's load vs its capacity reserve margin was too small
- Texas relies heavily on just-in-time production of natural gas and has less gas storage than other states with high shares of gas-powered electricity generation; more gas storage should be the easiest fix rather than more costly winterization of equipment
- Texas decided years ago not to participate in the Tres Amigas interconnection project which could have provided backup power from Western and Eastern grids. One reason Texas reportedly declined to participate: it would have required the state to be regulated by FERC (national) instead of ERCOT (state)

I understand concerns about large shares of wind power. It's intermittent, requires new transmission lines and suffers from energy density problems that we describe elsewhere. And in contrast to normal years when Texas wind generates high capacity factors in winter, Texas wind output collapsed this February. However, as shown in the table on the prior page, **a wind decline was something ERCOT had planned for; the larger and sudden collapse in natural gas generation was not**. As a result, the outage is primarily a natural gas story and to say otherwise indicates to me that someone has an agenda they're pushing. The Texas outage and its misdiagnoses are one reason I write this paper every year: as long as there's misinformation[36] about energy out there (whether accidental or intentional), there's still more work to do. See you next year.

Texas wind vs California solar capacity factors by month
%, 2019 capacity factor



Source: EIA. 2019.

[36] **Misinformation in Texas was not confined to energy in 2021**. Two of the more absurd election lawsuits were filed in Texas this year. They rhyme with contentions that wind was the primary issue in the Texas power outage.

[1] An original jurisdiction Supreme Court case filed by Texas AG Paxton which alleged that other states violated Texas rights by using non-legislative means to change election rules. UT professor Stephen Vladeck called the suit the "craziest" lawsuit filed during the election season, and election law expert Rick Hasen at UC Irvine characterized it as "the dumbest case I've ever seen filed on an emergency basis at the Supreme Court".

[2] The lawsuit filed by Texas Rep Gohmert which petitioned the US District Court for Eastern Texas to grant VP Pence the "exclusive authority and sole discretion under the 12th Amendment to determine which slates of electors for a State, or neither, may be counted". Constitutional scholar Ned Foley at Ohio State described the suit as "breathtaking and preposterous"; even the Trump DoJ described it as a "walking legal contradiction".

"What about…" Answers to client energy questions

What about low energy nuclear reactions which are supposed to produce energy at room temperature?

Currently, LENR does not meet our commercialization test. I will write about it when/if a commercial application gives off substantial levels of heat without radiation. There's still plenty of skepticism: in May 2019, researchers from British Columbia, MIT, Maryland, Lawrence Berkeley National Laboratory and Google revisited LENR and failed to find evidence of fusion or heat.

What about that Saudi green hydrogen plant under construction?

Saudi Arabia is building a hydrogen plant powered by 4 GW of wind and solar to produce 650 tonnes of green hydrogen daily in 2025. Most hydrogen is used today in oil and gas refining to remove sulfur or to produce ammonia, 80% of which is used as fertilizer. The Saudi plant's green hydrogen output will be just 0.3% of global "brown" hydrogen generated via steam reformation of natural gas. Some people envision hydrogen used in stationary fuel cells for backup electricity generation. So, now let's look at it this way: assuming 60% round trip fuel cell efficiency, the Saudi facility's output could instead be used to generate 4.74 TWh per year. That would represent just 1.3% of Saudi electricity consumption and 0.018% of global electricity consumption.

What about sustainable aviation fuels and renewable natural gas?

Sustainable aviation fuels (SAF) are made from used cooking oils, solid waste and food waste. They're expensive to produce given the aggregation and distillation required, and currently cost 2x regular jet fuel. In 2019, less than 200,000 metric tons of SAF were produced globally, equal to less than 0.1% of commercial airlines jet fuel consumption. Even if all announced SAF projects were completed, volumes would reach just ~1% of expected global jet fuel demand in 2030[37]. So, nothing to get too excited about yet.

Same goes for renewable natural gas (RNG). US RNG volumes are 200-300 mm gallons per year. According to Platts, potential from US landfills is 2.9 billion gasoline gallon equivalents (GGE) per year, while NREL estimates potential at 4.8 billion GGE per year from landfills, agricultural waste, wastewater and other organic waste. In 2019, 142 billion gallons of gasoline were consumed in the US. So, even if RNG from all landfills and other sites were channeled into central processing facilities, RNG could offset ~2.5% of annual US gasoline demand. Similar percentages apply to renewable diesel made from animal fats, waste and used cooking oils on a global scale. Germany has been converting waste to energy as well using biogas from crops, waste and landfills to generate electricity. This is not cheap, nearly 20 cents/kWh compared to 9 cents/kWh for onshore German wind.

Renewable energy solutions that contribute 1%-3% of a given fuel supply after a decade or more of investment at high cost entail carbon reductions that **could much more readily be achieved** by retiring old, less energy-efficient equipment, pricing kilometers flown or driven closer to their true all-in cost, investing in lighter vehicle materials and most of all, putting curb weight limits on sport utility vehicles as their adoption spreads globally.

What about electrifying the world's container ships?

The first one was scheduled to begin operating in 2020 but was delayed by COVID. Its specifications: capable of carrying 120 twenty foot equivalent units (TEUs) at a speed of 6 knots for 30 nautical miles. Compare that to Maersk's Triple-E class ships which carry 150x as much cargo over distances 400x greater at speeds 3x-4x faster. What would it take to make an electric version of Maersk's ship, matching its speed and performance? Even when incorporating the higher efficiency of electric motors, using today's state of the art electric batteries with 300 Wh/kg of energy density, **the electric version of the Maersk ship would have to dedicate 40% of its cargo capacity to the batteries themselves (obviously an economic non-starter)[38].** Or to put it another way: an electric ship whose batteries and motors weighed no more than the fuel and diesel engine in today's container ships would need battery energy densities to improve by 10x vs current levels. Final bit of context: in the past 70 years, energy densities of the best commercial batteries haven't even quadrupled.

[37] "*Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation*", Kevin Soubly et al, McKinsey/WEF, 2020.

[38] Smil, V. 2019. "*Electric container ships are a hard sail*". *IEEE Spectrum* March 2019:22.

What about MSCI's carbon accounting idea for portfolio investors: a ratio of emissions to sales?

MSCI's carbon accounting approach for portfolio investors uses an intensity measure based on the **ratio of a company's emissions to sales**[39]. I understand what its creators are trying to do: if a company grows revenues while keeping its carbon footprint the same, this may indicate that the company has figured out how to improve its energy efficiency. **Sorry, but I still have a lot of questions.**

- Two pharmaceutical companies have the same emissions footprint, except Company A is in the US and charges a lot more for the same exact drugs that Company B sells in Germany, whose gov't negotiates drug prices as part of its single payer system. **If I sell Company B stock and buy Company A stock, my portfolio carbon accounting will improve for no climate-related reason at all, right?**
- I manage a fund that invests in companies that produce cement, steel, glass, rubber and plastic; in other words, the materials that make modern energy-efficient megacities possible. Company A is an industrial company in France, while Company B makes the same products and is located in Italy. I sell my Company B stock and buy Company A stock. My portfolio carbon accounting improves since France's grid is more reliant on nuclear power while Italy is more reliant on fossil fuels. **Should Company B be "penalized" by capital allocators due to something completely outside the company's control?**
- I'm a small cap manager with a 3% tracking error budget vs the Russell 2000, while Firm B's budget is 7%. This allowed Firm B to run a larger underweight to energy than I did from 2019 to 2020. **Is Barron's going to write an article on small cap managers saying that I don't pay enough attention to climate issues like Firm B does, even though the results are the by-product of temporary sector preferences?**
- A recession hits and the revenues of the companies in my portfolio drop by 20% while their emissions drop by 5%. **Are my stakeholders going to ask me if I have lost my focus on climate issues?**

There's a lot of good that can come from more accurate accounting of emissions. In our asset management business, we use quantitative and qualitative signals to inform our climate judgments of companies. Many simplified accounting formulas don't separate climate issues that companies control vs ones they don't, and may convey signals to investors that are not in line with sustainable decarbonization goals.

[39] The formula is based on the ratio of Scope 1 emissions plus Scope 2 emissions, divided by the company's sales. **Scope 1** refers to direct emissions, for example resulting from on-site fossil fuel combustion. **Scope 2** refers to indirect emissions, for example resulting from purchase of electricity from a utility. See "*Carbon footprinting methodology for underwriting portfolios*", CRO Forum (Netherlands), April 2020; and "*MSCI Carbon Footprint Index Ratios Methodology*", MSCI, January 2018.

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