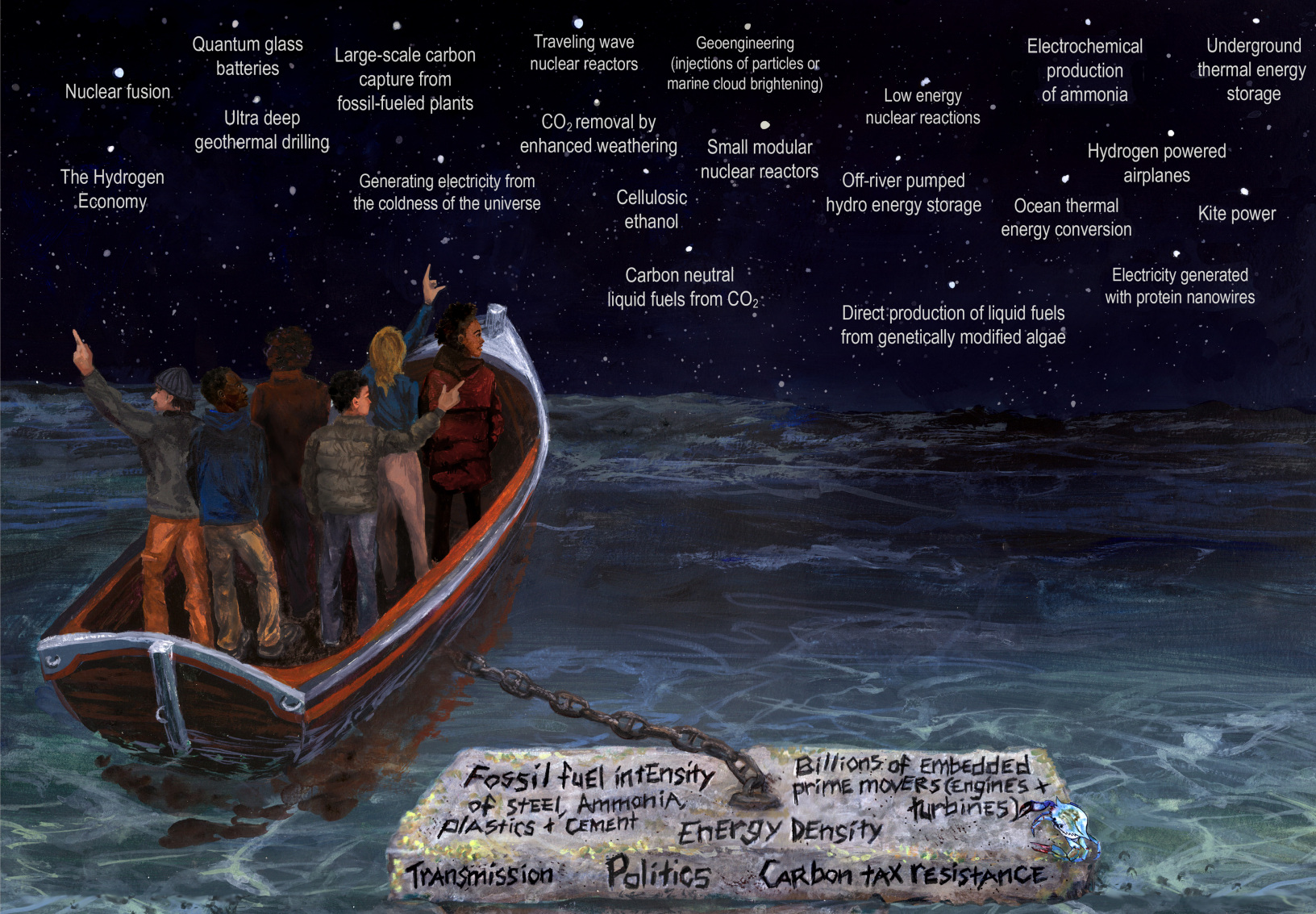


Tenth Annual Energy Paper



Nuclear fusion

Quantum glass batteries

Ultra deep geothermal drilling

The Hydrogen Economy

Large-scale carbon capture from fossil-fueled plants

Generating electricity from the coldness of the universe

Traveling wave nuclear reactors

CO₂ removal by enhanced weathering

Cellulosic ethanol

Carbon neutral liquid fuels from CO₂

Geoengineering (injections of particles or marine cloud brightening)

Small modular nuclear reactors

Off-river pumped hydro energy storage

Direct production of liquid fuels from genetically modified algae

Low energy nuclear reactions

Electrochemical production of ammonia

Ocean thermal energy conversion

Hydrogen powered airplanes

Electricity generated with protein nanowires

Underground thermal energy storage

Kite power



Tenth Annual Eye on the Market Energy paper: Front Cover

Stargazing. COVID lockdowns reduced global CO₂ emissions to levels last seen over a decade ago. While this decline is temporary, there's still a lesson to be learned: an unsustainable halt in economic activity and mobility was needed to make a material dent in global CO₂ emissions. In our tenth annual *Eye on the Market* energy paper, we take a look at when and how renewable energy transitions might accomplish the same thing. A lot of ideas flicker in the distance, but few are capable of being scaled and substantially commercialized in the foreseeable future.

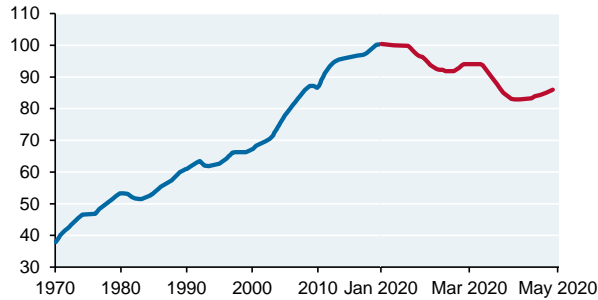
Topics in this year's paper include limits from de-carbonizing the grid alone; de-carbonization of steel and other industrial products; political and physical renewable energy bottlenecks; the scope of utility-scale energy storage, reforestation, and carbon sequestration required to make a difference; the impact of ride-hailing on emissions, and the never-ending hope for a hydrogen economy. We also review the financial, political and environmental risks to US energy independence, and whether a supply shock or stranded asset risk is the primary reason for the lowest oil & gas valuations in 90 years. We conclude with an exhibit on Trump and the environment.



Preface: the large but temporary impact of COVID on global energy consumption

One of the worst pandemics in 100 years had an understandably large impact on energy consumption given widespread adoption of lockdowns and other mobility restrictions. Estimates of real-time global CO₂ emissions showed a decline in May to levels last seen over a decade ago. However, this decline is almost certainly a temporary one. High frequency measures of China coal consumption are already back to pre-pandemic levels, the same is true for China oil demand as tankers line up on its eastern ports waiting to discharge oil for Chinese refineries, and China air traffic is down only 30% vs January. In the US, electricity production never fell more than 15% y/y during the pandemic, a full rebound is expected for US gasoline consumption by the second half of the year, and the EIA expects global liquid fuels consumption to reach pre-COVID levels by June 2021. Even so, there’s an energy lesson to be learned from the pandemic: an unsustainable halt in economic activity and mobility was needed to make a material dent in global CO₂ emissions. In our tenth annual energy paper, we take a close look at when and how renewable energy transitions might accomplish the same thing.

Global daily CO₂ emissions: history from 1970-2019, with daily estimates for 2020, Million tonnes CO₂/ day

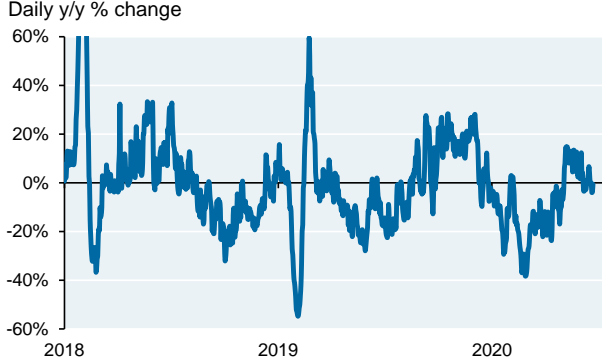


Source: Quéré et al, "Temporary reduction in daily global CO₂ emissions during the COVID-19 forced confinement" University of East Anglia. 2020.

COVID update

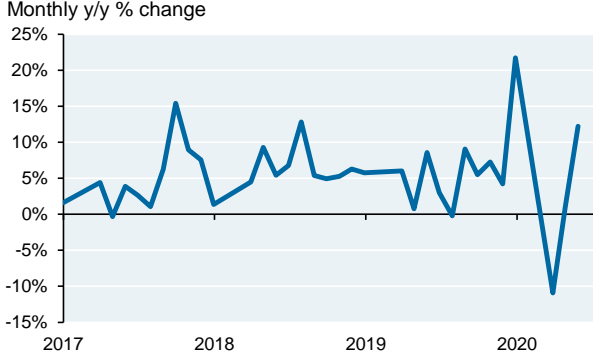
The epicenter of the US pandemic has shifted from the Northeast to several hotspot states spanning the Southern US from coast to coast. Until recently, while hotspot infections were surging, hospitalizations and deaths were not. Over the last week, hospitalizations in hotspot states have been rising as well. These outcomes are not a complete surprise; many hotspot states experienced the smallest declines in social distancing, measured by retail and restaurant tracking. For more information on the virus, vaccine development and market/economic impacts, see our virus analysis portal which can be found [here](#).

China coal consumption



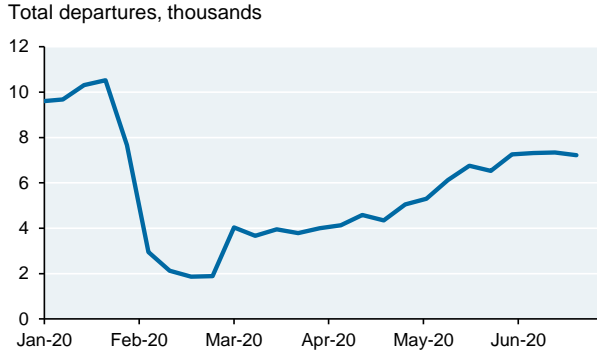
Source: cqcoal, Wind. June 24, 2020

China oil demand



Source: Bloomberg. May 2020.

Air traffic at China's 25 busiest airports



Source: Flightradar24. June 23, 2020.

World liquid fuels consumption



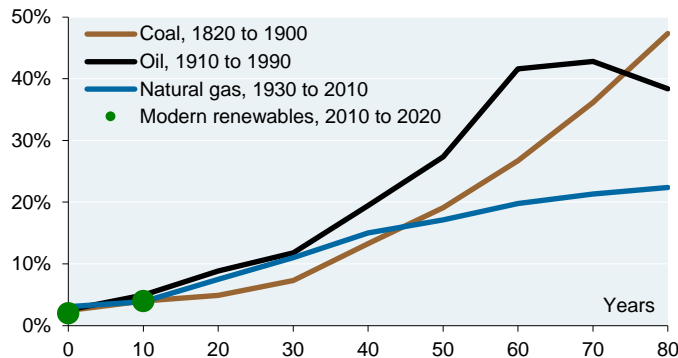
Source: EIA Short-term Energy Outlook. June 2020.



Executive Summary

When I began writing this piece ten years ago, I knew that I needed a technical advisor to shepherd me through the real world complexity of energy transitions. Vaclav Smil is one of the world’s foremost experts on such topics, and his guidance and insights have been invaluable. Over the last decade, Vaclav has described renewable energy as the fourth great energy transition (after mastery of fire, a shift from foraging to agriculture and domesticated animals, and a shift from biomass and human/animal labor to combustion of fossil fuels). However, he has also stressed the decades required for past energy transitions to unfold, illustrated in the first chart. In our discussions, he has also cautioned against embrace of faddish energy solutions that sound great on paper but which are difficult to scale (some are illustrated on this year’s cover), and has highlighted how energy efficiency gains are often offset by greater consumption. An example of the latter: a 75% decline since 1960 in jet aircraft fuel consumption per passenger-kilometer led to similar declines in ticket prices and a surge in ridership and related aircraft emissions.

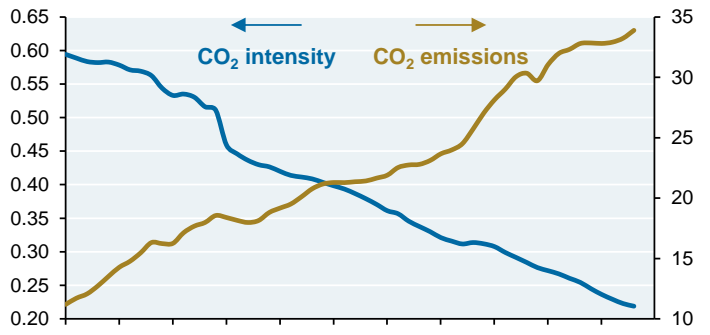
The last three energy transitions took ~40 years to reach 15%-20% shares, % of world primary energy consumption



Source: V. Smil (pre-1965 data), BP (post-1965 data), JPMAM. 2020.

Global CO₂ intensity declining, CO₂ emissions rising

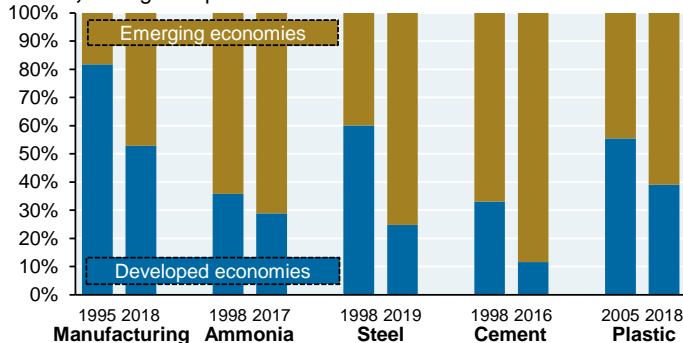
Tonnes of CO₂ / thousand \$2018 GDP (Intensity) / Billion tonnes (Emissions)



Source: BP Statistical Review of World Energy, Conference Board. 2019.

With that introduction, here’s where we stand now. While global CO₂ *intensity* has improved (the amount of CO₂ generated per unit of real economic growth has declined), the absolute *level* of global CO₂ emissions keeps going up. Recent emission increases mostly come from emerging economies, but remember the reasons why. **Developed countries have been de-industrializing for 25 years**, which has shifted carbon-intensive manufacturing of steel, cement, ammonia and plastics to the emerging world. In other words, emerging countries now produce industrial goods they need on top of what they also produce for the developed world. Any discussion of regional emissions and burdens should reflect these realities.

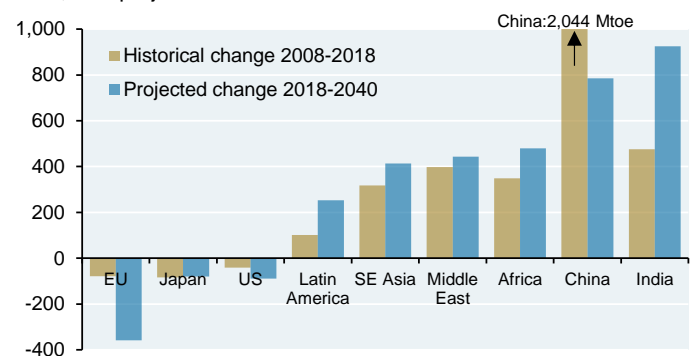
A shift in energy intensive manufacturing to the emerging world, % of global production



Source: UN Dept. of Social and Economic Affairs, Worldsteel, PlasticsEurope, USGS. 2019.

Primary energy use, past and future

Mtoe, with projections based on IEA Stated Policies Scenario



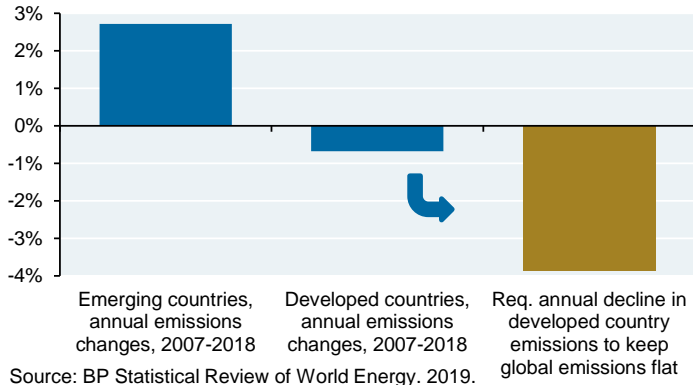
Source: International Energy Agency World Energy Outlook. 2019.



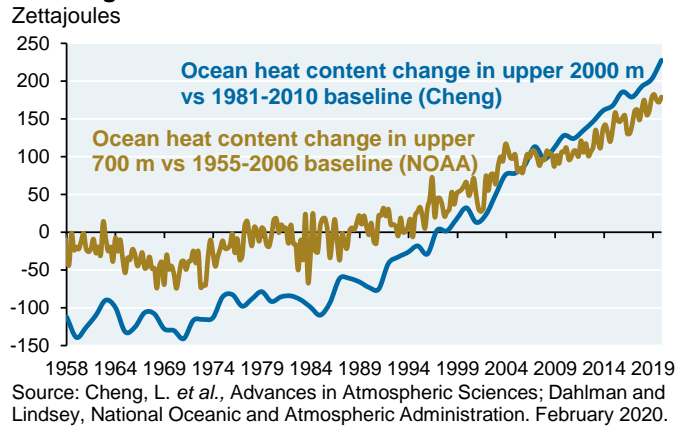
To reinforce the point on transfer of production to the developing world, consider **coal-fired electricity generation**. All the world's countries except China reduced net coal-fired generation capacity by 8 GW from January 2018 to June 2019. Over the same period, China *increased* such coal capacity by 43 GW, has another 121 GW under construction and is financing a quarter of all new coal projects across Asia. In other words, global reliance on cheap industrial and consumer goods exports from China comes at a substantial environmental cost.

Here's a simple exercise in CO₂ emissions math. Forget about *reducing* emissions; let's just think about keeping emissions *flat*. Emerging economy emissions increased by 3% p.a. since 2007 while developed world emissions declined by 0.7%. Let's assume that emerging economy emissions grow at the same pace and that the developed world has to emit less. **To keep global emissions flat, the developed world would need to reduce emissions by ~4% per year, which is 5x-6x faster than the current pace.** Whether that would be enough to keep oceans from continuing to heat up is unclear, but it would be a move in the right direction.

Required emission decline in developed countries to keep global CO₂ emissions flat: 5-6x faster than current pace



Warming oceans

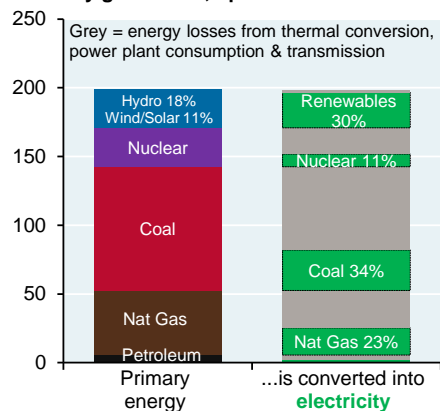




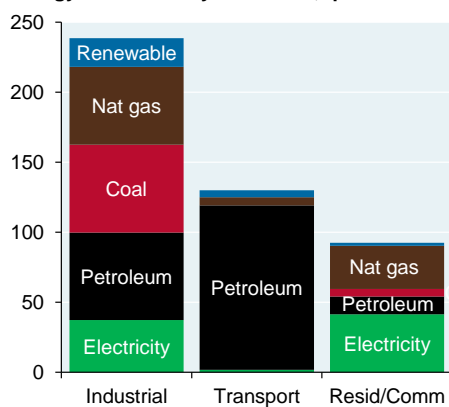
How might developed and developing countries accelerate the pace of de-carbonization? The visual below shows how primary energy is used to generate electricity on the left; and on the right; the composition of *all* energy consumed including electricity, broken down by end-user¹.

Global electricity generation, and its contribution to total energy consumed by end-users

Electricity generation, quad. BTU



Energy consumed by end-users, quad. BTU



Key Stats

- Electricity is just 17% of global energy consumed by end-users
- Decarbonization via renewables mostly confined to electricity, with some industrial use
- Renewables account for 30% of electricity, and 11% of total energy consumed by end-users
- Fossil fuels used in electricity generation represent 30% of all fossil fuel use
- Industrial sector is by far the greatest consumer of energy

Source: Energy Information Administration, J.P. Morgan Asset Management. 2019. As per BP/EIA convention, primary energy for nuclear power is derived by assuming 38% thermal conversion. For renewables, primary energy conversion only reflects transmission losses.

Key takeaways: so far, de-carbonization has mostly taken place on the grid. The 17% share of electricity in global energy consumption limits de-carbonization potential from the grid alone; electricity and de-carbonization will have to make substantial inroads in industrial use as well. While technologies are now available to achieve partial electrification of certain industrial processes, evidence of such transitions are very limited, even in jurisdictions with carbon taxes². **The electrification of industry must obey chemical and physical laws as well as economic ones**, which we discuss this year in Section 1.

On transportation, there's a *plan* in many countries for rapid electric vehicle adoption, but the jury is out regarding how fast it will occur. In 2019, the EV share of global light vehicle purchases was 2.5%, while in the US the EV share was 1.9% (both shares have risen from ~1.2% in 2017); that sounds more like a skirmish than a revolution to me.

And finally, the issue of carbon sequestration. After 20 years in development, carbon capture facilities only store 0.1% of global emissions every year, and there isn't even a viable blueprint yet for direct air capture or other forms of CO₂ mineralization at meaningful scales. Even something straightforward and beneficial like reforestation is often magnified way beyond its actual potential, a topic we discuss this year as well.

¹ Regionally, there are only modest differences in the charts above; see Appendix Table on page 34. Importantly, **electricity represents less than 25% of energy consumption in every major region.**

² There are roughly 60 carbon pricing initiatives around the world, covering 15% of global GHG emissions (note that carbon taxes and cap/trade systems only apply to a subset of a country's emissions; power and industry are usually included, while transport, buildings, waste and agriculture are often not). Carbon prices per tonne vary widely: \$2 (Japan, Mexico), \$18 (California), \$30 (EU), \$50 (France), \$120 (Sweden).



With that background, here are the topics discussed in this year's *Eye on the Market* energy paper on its tenth anniversary.

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Links to select topics from prior *Eye on the Market* energy editions

- [Germany and Energiewende: A dispassionate assessment \(2019\)](#)
- [Wildfires: anthropogenic climate change and risks for utilities in fire-prone areas \(2019\)](#)
- [Electric vehicles: a 2% or a 20% solution? \(2018\)](#)
- [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 \(2017\)](#)
- [Distributed solar power and utility billing changes which increase the cost \(2016\)](#)
- [US hydropower: how much potential for expansion? \(2016\)](#)
- [Nuclear power: skyrocketing costs in the developed world \(2014 and 2015\)](#)



Acknowledgements

Our energy *Eye on the Market* 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 interdisciplinary 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 one, *Growth*, was published by the MIT Press in September 2019 and the next one, *Numbers Don't Lie*, is coming out in September 2020) and more than 400 papers on these subjects and has lectured in North America, Europe, and Asia. In 2010, *Foreign Policy* magazine listed him among the 100 most influential global thinkers. 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.

We also appreciate feedback we received on various sections from scientists and researchers at the National Renewable Energy Laboratory, the Lawrence Berkeley National Laboratory, the Imperial College of London Centre for Environmental Policy, the Rockefeller University Program for the Human Environment, the Lund University Department of Human Ecology, Nanjing University, the Duke University Nicholas School of the Environment and the University of California Riverside Earth and Planetary Sciences Department.

Acronyms

BTU British thermal unit; **CCS** carbon capture and storage; **CHP** Combined heat and power; **CIS** Confederation of Independent States; **CO₂** carbon dioxide; **CSP** concentrated solar power; **E&P** exploration and production; **EIA** Energy Information Agency; **EPA** Environmental Protection Agency; **EV** electric vehicle; **FERC** Federal Energy Regulatory Commission; **FP** flowback and produced water; **GHG** greenhouse gas emissions; **GJ** gigajoule; **GW** gigawatt; **GWPC** Groundwater Protection Council; **HVAC** Heating, ventilation and air conditioning; **HVDC** high voltage direct current; **HY** high yield; **IAEE** International Association for Energy Economics; **IEA** International Energy Agency; **IFPEN** French Institute of Petroleum; **IPCC** Intergovernmental Panel on Climate Change; **IRENA** International Renewable Energy Agency; **ISO** independent system operator; **ITC** Investment Tax Credit; **kg** kilogram; **km** kilometer; **kW** kilowatt; **kWh** kilowatt-hour; **LBNL** Lawrence Berkeley National Laboratory; **LNG** liquefied natural gas; **m³** cubic meter; **MISO** Midcontinent Independent System Operator; **Mt** metric tonnes; **Mtoe** million tons of oil equivalent; **MW** megawatt; **MWh** megawatt-hour; **NGL** natural gas liquids; **NREL** National Renewable Energy Lab; **OECD** Organization for Economic Cooperation and Development; **OSHA** US Occupational Safety and Health Administration; **PEM** Polymer electrolyte membrane; **PPA** Power Purchase Agreement; **TWh** terawatt-hour; **USGS** US Geological Survey; **VMT** vehicle miles traveled



[1] The Ten Energy Commandments: on energy and de-carbonization

These have been useful in discussions with friends/family, but the conversations are not always easy.

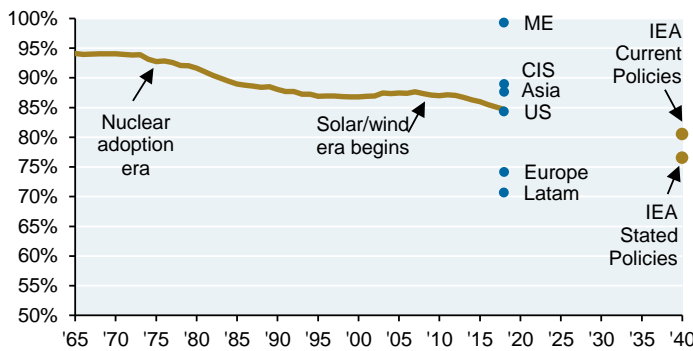
[i] *Thou shalt not conflate the speed of wind and solar cost declines with the speed of de-carbonization*

The world uses fossil fuels for 85% of its primary energy. The IEA expects this figure to continue to decline, fueled in part by Big Oil companies that are becoming Big Energy companies, investing as much as 15% of their capital spending on renewables in 2021. In 2021, renewable capacity is 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 projects³.

However, the IEA still projects that 70% of global primary energy consumption may be met via fossil fuels in 2040. Why don't rapid wind and solar price declines translate into faster rates of de-carbonization? As discussed in the Executive Summary, electricity accounts for less than 25% of primary energy consumption, which is almost exclusively where wind and solar are used; transportation and industrial uses are harder to de-carbonize; and even within the grid, transmission costs and politics are large obstacles (see [iv]).

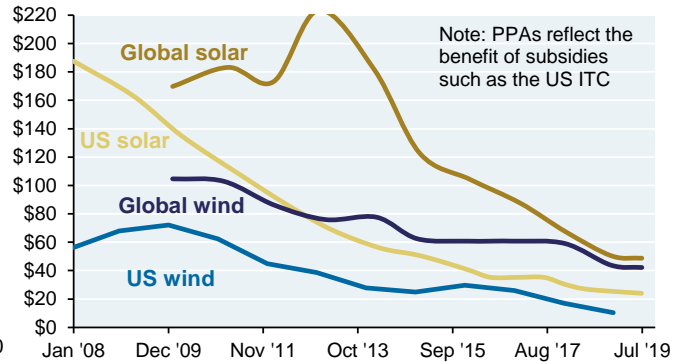
The world uses fossil fuels for ~85% of its energy

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



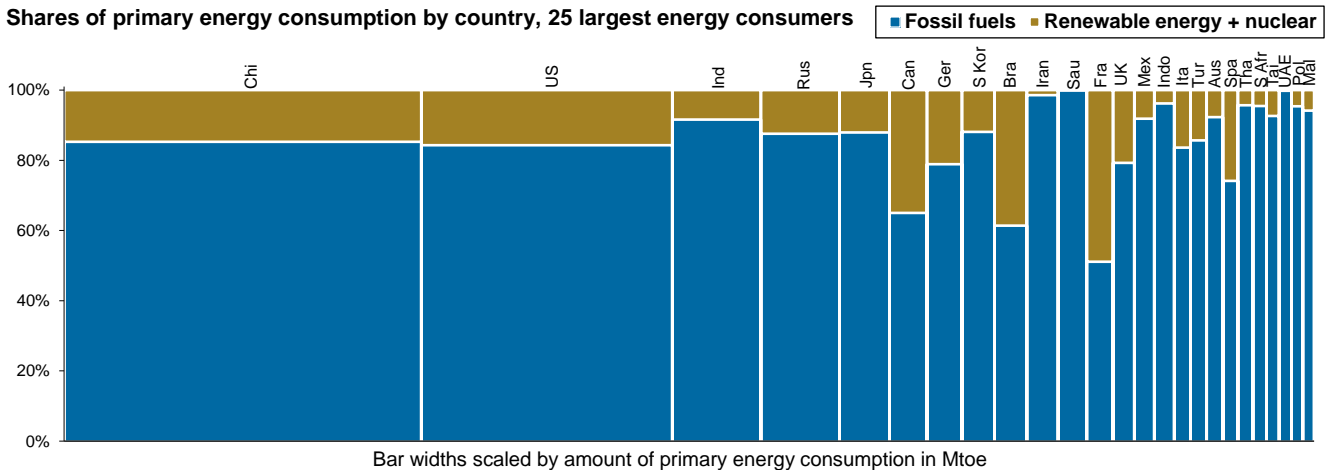
Source: BP Statistical Review of World Energy, IEA. 2019.

Average power purchase agreement prices for wind and solar, Real 2018 \$ per MWh



Source: Lawrence Berkeley National Laboratory, IRENA. 2020.

Shares of primary energy consumption by country, 25 largest energy consumers



Bar widths scaled by amount of primary energy consumption in Mtoe

Source: BP Statistical Review of World Energy. 2019.

³ Source: "Carbonomics: The Future of Energy in the Age of Climate Change", Michele Della Vigna, Goldman Sachs, December 2019. Michele and his team lay out a thesis of substantial carbon abatement and sequestration driven by carbon taxes. I am less sure what abatement prices would be for technologies that have not been commercially scaled, and believe that for more established technologies (electric buses, battery storage, biofuels, heat pumps), switching costs are often underestimated. But it's an interesting read, with a different point of view than mine.



[ii] *Thou shalt pay a heavy price to electrify industry, when it can be done at all*

As illustrated above, the industrial sector is the largest fossil fuel end-user. Could some industrial processes be electrified to eventually use more renewable energy as the grid is de-carbonized? Examples include sectors which use fossil fuels primarily for “process heat” (see table). However, even for sectors with high potential for electrification, it could be an expensive transition. In addition to upfront switching costs, industrial companies would face costs per unit of energy that are **3x-6x higher for electricity compared to the cost of direct natural gas combustion**. Electric heating efficiency gains vs natural gas could offset part of the cost, but not all of it. A carbon tax would change these dynamics; it remains to be seen if countries will adopt them at levels required to engineer faster transitions.

Industrial sectors with "high" potential for electrification

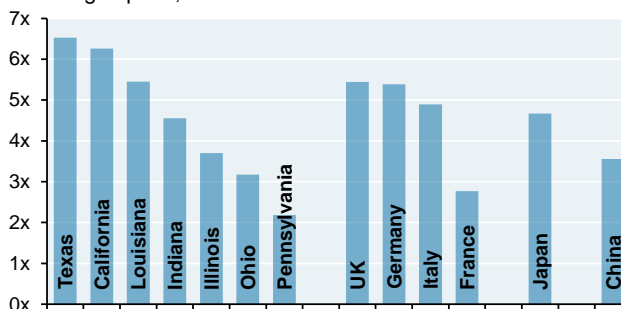
Sector	Heat requirement	Fuel consumption shares:		
		HVAC	Heat	CHP
Primary metals excl. steel	1200°C	6%	75%	7%
Fabricated metal	430°C-680°C	20%	61%	7%
Machinery	730°C	46%	39%	4%
Secondary steel	1425°C-1540°C	4%	87%	0%
Wood products	180°C	10%	50%	14%
Vehicle parts (drying)	150°C	31%	33%	12%
Plastics and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

CHP refers to "combined heat and power", a process by which waste heat from combustion provides additional power. Sectors above have low CHP shares; sectors with higher CHP shares are harder to electrify.

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

Sectors such as chemicals, pulp/paper and food take advantage of **combustion waste heat** for power (“CHP: combined heat and power”). They are harder to electrify since producers would need to then purchase the part of their energy needs previously obtained at little to no incremental cost, or redesign the entire process. Sectors such as glass, brick and cement require temperatures in excess of 1400°C, and are also harder to electrify since they are non-metallic, non-conductive solids.

The four industrial pillars of modern society are steel, cement, ammonia (for fertilizer) and plastics; each relies on fossil fuels as raw materials and/or for process heat at very high temperatures. Production of these pillars is expected to keep rising, though at a slower pace than during China’s industrialization era.

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

Industrial use of fossil fuels to generate process heat

Construction materials (cement, bricks, tiles, glass, kiln-dried timber)
Production of petrochemicals, synthesis of plastics, food/beverage
Smelting of iron ores in blast furnaces

Global production (million tonnes)

Product	2000-2018		2018-2050		2050 E
	2000	CAGR	2018	CAGR E	
Steel	848	4.3%	1,817	0.6%	2,170
Cement	1,660	5.2%	4,100	0.4%	4,682
Ammonia	132	1.5%	171	1.6%	281
Plastics	190	3.6%	359	2.6%	818

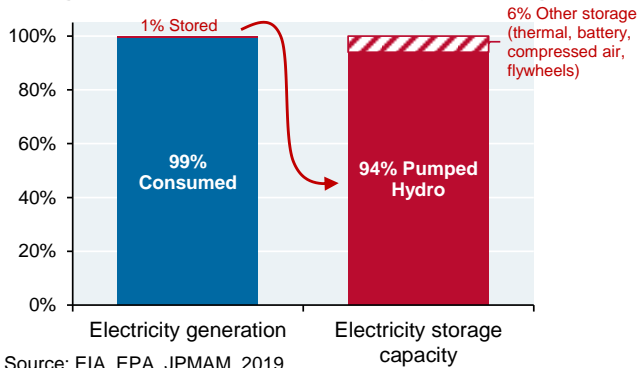
Source: Energy Transitions Commission, USGS, World Steel Association, PlasticsEurope. 2019. CAGR = compound annual growth rate.



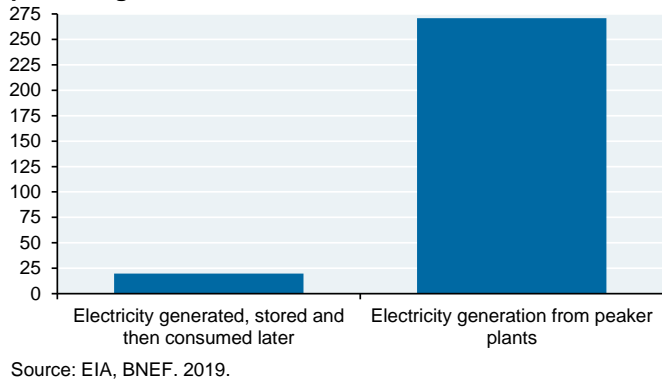
[iii] Thou shalt toil mightily to store energy that you produce

Some de-carbonization proposals for the grid entail substantial over-building of wind and solar power with the goal of storing excess electricity generation to draw upon later, allowing natural gas peaker plants to eventually be retired. However, long-term utility-scale energy storage via electrochemical batteries is an industry that is still in its infancy. **Less than 1% of US electricity generation was stored in 2019, and almost all of this storage occurred in decades-old pumped hydro facilities (see below) rather than in batteries.** A much larger storage buildout would be needed to displace natural gas peaker plant generation, which is currently 10x the amount of stored-and-then-dispatched electricity. There are plenty of “**hockey stick**” forecasts for electrochemical battery deployment, as there were for electric vehicles a decade ago and which turned out to be way too high. Due to the complexities around reimbursement and cost recovery allowances for utilities that invest in storage, some battery storage forecasts are likely to be too high as well.

Only 1% of US electricity generation is stored, and most storage is via decades-old pumped hydro storage



Much larger storage buildout needed to reduce peaker plant usage, TWh



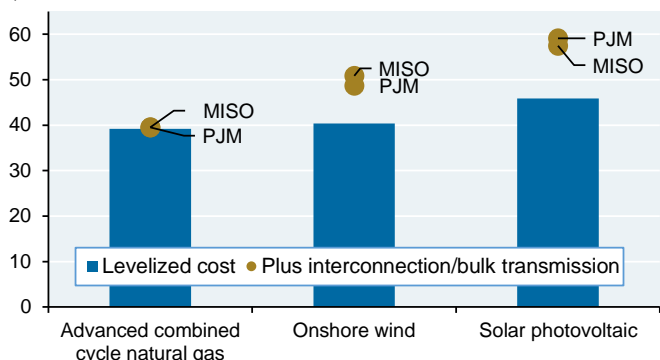
Seneca pumped storage and hydroelectric facility, Warren County, Pennsylvania



[iv] Thou shalt confront thy neighbor regarding his NIMBY policy on renewable energy deployment

Lawrence Berkeley National Labs recently released a study of renewable transmission costs⁴ in light of the distance from many wind and solar projects to urban demand centers. The chart below shows levelized electricity generation costs in the blue bars, plus estimates of transmission interconnection costs and “bulk” long-distance transmission costs (the latter only for wind and solar, since the majority of bulk infrastructure for natural gas already exists). A renewable energy future must contend with these incremental costs, but that might not be the hardest part...there’s also the **politics**, as explained below. Like the US, Germany is also struggling with cost and political obstacles in bringing power from its northern wind sites to southern population centers, and already has the highest electricity costs in Europe.

Levelized cost of electricity, with & without transmission
\$/MWh



Source: EIA, Gorman *et al.*, Lawrence Berkeley Laboratory. 2019. Transmission costs include LBNL estimates for local interconnection costs in MISO and PJM regions, plus their national estimates for bulk transmission costs derived from projects in California, Texas and the Midwest. Bulk costs represent the majority of total transmission cost.

Operational Fuel Security Analysis
ISO New England, January 2018

“Energy shortfalls due to inadequate fuel would occur with almost every fuel-mix scenario in winter 2024/2025, requiring frequent use of emergency actions to keep power flowing and protect the grid. Emergency actions that would be visible to the public range from requests for energy conservation to load shedding (also known as rolling blackouts or controlled outages that disconnect blocks of customers sequentially)...The study results suggest that New England could be headed for significant levels of emergency actions, particularly during major fuel or resource outages.”

“No Hampshire”. The proposed 1 GW Northern Pass transmission line connecting Hydro-Quebec to Southern New England was supported by Massachusetts regulators and its Department of Energy Resources to reduce reliance on fossil fuels and use hydropower instead. However, a New Hampshire siting committee unanimously **rejected** the proposal since it worried that the 192-mile transmission line would disrupt streets and harm tourism. Concessions by the project group to bury 52 miles of the route and set aside 5,000 acres of preservation/recreation land were insufficient to change the outcome. In July 2019, the New Hampshire Supreme Court rejected the proposal. **The grid regulator ISO New England warned that the region’s power system may soon be unable to meet electricity demand and maintain reliability without rolling blackouts or controlled outages** (see box above). According to the IPCC, lifetime hydropower CO₂ emissions are 5% of natural gas emissions, yet some opponents of the Northern Pass Project still cited its emissions as a reason for rejecting it.

⁴ “Improving estimates of transmission capital costs for utility-scale wind and solar projects to inform renewable energy policy”, *Energy Policy*, Gorman, Mills and Wisser (LBNL), December 2019.



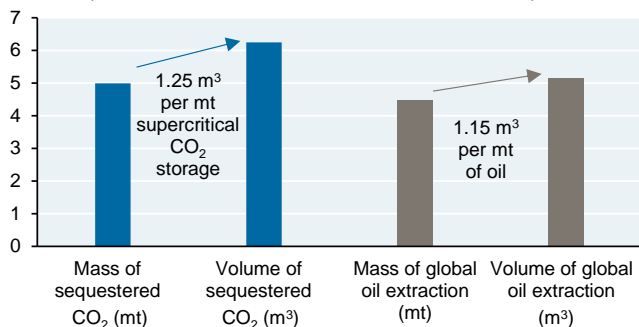
[v] Thou shalt not perpetuate false narratives on carbon capture and storage (CCS)

Despite almost 20 years of endless hype, by the end of 2019, CCS facilities captured and stored just 0.1% of global CO₂ emissions. Put aside issues of cost overruns, failures of bellwether projects, the US Dep't of Energy withdrawing support for large projects, cancellations in Europe, legal uncertainties about liability and the ~30% energy drag on coal facilities required to perform CCS in the first place. Let's assume that all of these obstacles are solved via innovation and legislation.

The bigger problem is the scope required to make a difference. Global CO₂ emissions from fossil fuels were ~33 bn metric tons in 2019. To store just 15% of this amount (5 bn metric tons), a CCS compression, transportation and storage industry would have to handle 6 bn cubic meters of CO₂ every year by volume. How much is that? For context, that's more than the 5 bn cubic meters of oil that's produced, transported and refined each year around the globe. In other words, **CCS infrastructure would have to be even greater than the one used for the world's annual oil consumption just to sequester 15% of global emissions.** There are applications where CCS makes sense (enhanced oil recovery and small amounts of commercial CO₂ demand). But as a big picture solution to CO₂ emissions, CCS buildout requirements are daunting.

To capture 15% of CO₂ emissions, CCS infrastructure would have to be larger than the global oil ecosystem

Billions (metric tons for mass, cubic meters for volume)



Source: BP, IEA, JPMAM. 2019. Mt = metric tons, m³ = cubic meters

What about carbon mineralization?

Carbon mineralization is an alternative form of carbon capture and 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. 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 CO₂ emissions from fossil fuel combustion were removed from the atmosphere (to mineralize 15% of global CO₂ emissions, more magnesite would need to be mined every year than annual global mining of coal and iron combined⁵). 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 CO₂ (mixed in water) into basalt rocks, and in which the carbon mineralization reaction can occur in just a year or two⁶. However, while you don't have to mine and move rocks in this version, you **do** need to move the CO₂ to where the rocks are... which brings us back to the chart above on the need for a massive build-out of carbon capture infrastructure (pipelines, compression, storage etc) to make even a small difference.

⁵ "Carbon Sequestration via Mineral Carbonation: Overview and Assessment", Howard Herzog, MIT.

⁶ Read about Iceland's CarbFix2 project if you want to learn more.

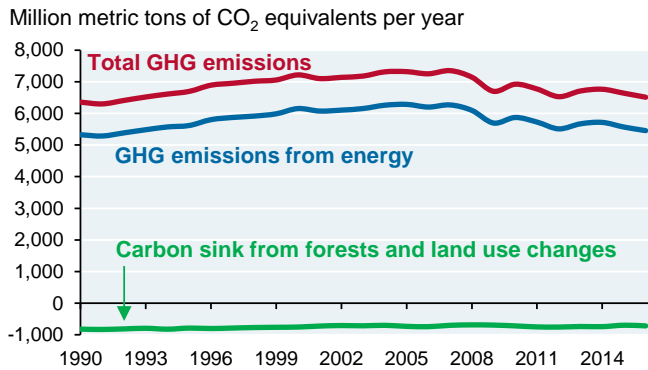


[vi] Thou shalt replenish the earth with trees, but not overestimate their impact

US forests comprise roughly 750 million acres, which is one third of all US land area (including Alaska and Hawaii). This amount of forest acreage has not changed much over the last 100 years, and offsets ~10% of annual US GHG emissions each year. Reforesting areas cleared due to wildfires/insect outbreaks and planting trees in previously unforested areas (“afforestation”) will help, but be realistic about the achievable benefits. Assuming 2.5 metric tons of CO₂ sequestered per year per acre of forest⁷, ~130 **million** acres would have to be planted to offset another 5% of US GHG emissions, bringing forested land area back to the level it was in 1850 (despite a 6-fold increase in US population since then). Reforesting that many acres of private and public land would be a *major* undertaking; as shown below, the US Forest Service has been reforesting just over 100 **thousand** acres per year, which is three orders of magnitude smaller.

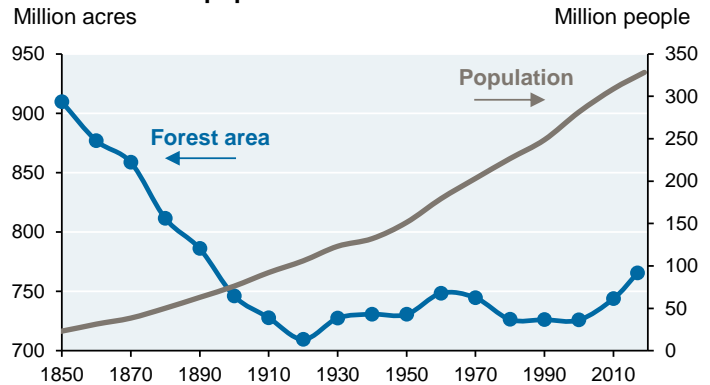
Remember as well that some amount of reforestation is needed just to offset acreage lost to (a) aging US forests which absorb less carbon over time, (b) CO₂ released from wildfires, which has averaged 60 - 80 million metric tons per year since 2013, and (c) the impact of severe hurricanes, one example being Hurricane Michael which destroyed 3 million acres of trees in Florida in 2018.

US forests offset 10% of annual GHG emissions



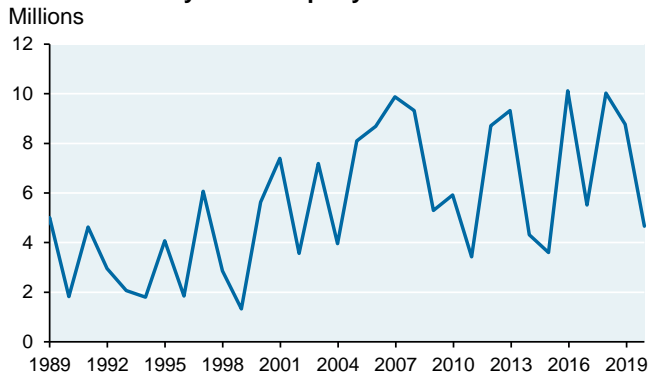
Source: US EPA. 2017. Total emissions include agriculture, waste and industrial processes such as chemical, metal and mineral production.

Forest area and population trends in the US



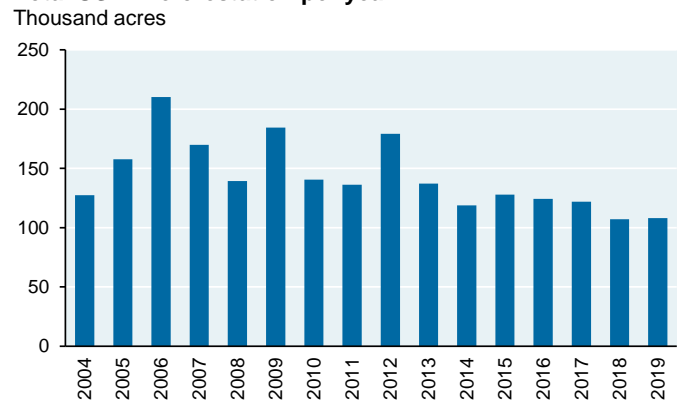
Source: United States Department of Agriculture. 2019.

Acres burned by wildfires per year in the US



Source: National Interagency Fire Center. 2019.

Total USDA reforestation per year



Source: USDA Reforestation and Timber Stand Improvement Reports. 2019.

⁷ Obviously depends on the species and location; triangulated from *Journal of Forestry*, EPA and USDA reports.

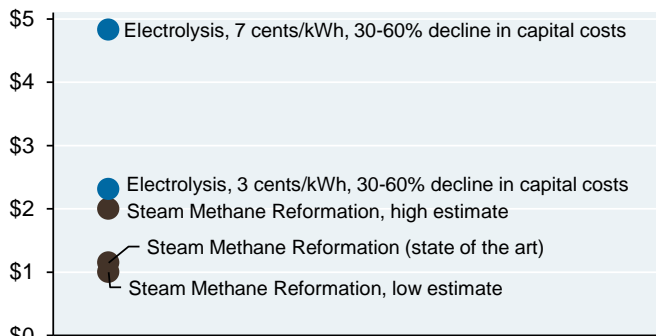


[vii] *Thou shalt not make unto thee graven images of a hydrogen economy...yet*

The “green hydrogen” economy is based on the notion that hydrogen is a fuel that can be used to generate heat and power; that electrolysis can split water into its component molecules to produce oxygen and hydrogen; and that renewable electricity can be used to power the electrolysis required. However, due to the high costs of electrolysis, 95% of commercially available hydrogen is **currently** produced via steam methane reformation (SMR) of fossil fuels. Might that change one day, so that renewable-driven electrolysis could create “green” hydrogen?

- In February of this year, the US Department of Energy released a study⁸ on the potential for hydrogen production using electrolysis instead of SMR. They estimated possible future hydrogen costs by (a) varying the price of electricity, which is by far the largest component of electrolysis costs, and (b) assuming 30%-60% declines in upfront electrolyzer capital costs as production increases
- DoE future cost estimates range from **\$4.5 - \$5.0 per kg of hydrogen** assuming electricity costs of 7-8 cents per kWh, and assuming a large decline in electrolyzer capital costs. This would still be well above current state-of-the-art SMR hydrogen costs of just **\$1.15 per kg** using current nat gas prices
- If electricity costs fell to 3 cents per kWh (i.e., in the range of current wind and solar PPAs but without incorporating utility costs for transmission infrastructure), the DoE estimated that hydrogen production costs could fall to **\$2.0 - \$2.5 per kg** of hydrogen, which is closer to but still above current SMR costs. This scenario would require co-located renewable energy dedicated to hydrogen production
- **Bottom line:** in the absence of a substantial carbon tax, further electricity and capital cost declines are required for green hydrogen costs to converge with fossil-fuel hydrogen costs⁹. In addition, to meaningfully impact energy consumption, existing turbines, engines, heating systems and other industrial equipment that now rely on natural gas would need to be replaced or upgraded to rely on hydrogen instead. That’s another real-life obstacle that hockey stick forecasts often fail to incorporate

Electrolysis vs Steam Methane Reformation as a means of producing hydrogen, \$/kg



Source: US Department of Energy. February 2020.

Hydrogen blasts from the past

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

⁸ DoE base case: electrolyzer capital costs decline by 30%-60% to \$460 per kW (\$342 for the electrolyzer stack and the rest for storage, compression and other auxiliary systems required). Source: “Hydrogen Production Cost From PEM Electrolysis”, US Department of Energy, David Peterson et al, February 2020.

⁹ **A 2019 hydrogen analysis from IRENA came to conclusions that were similar to the US DoE.** For green hydrogen to become competitive with SMR hydrogen, IRENA estimates that upfront capital costs would need to fall by 75%, and that electricity costs would need to be around 2 cents per kWh.



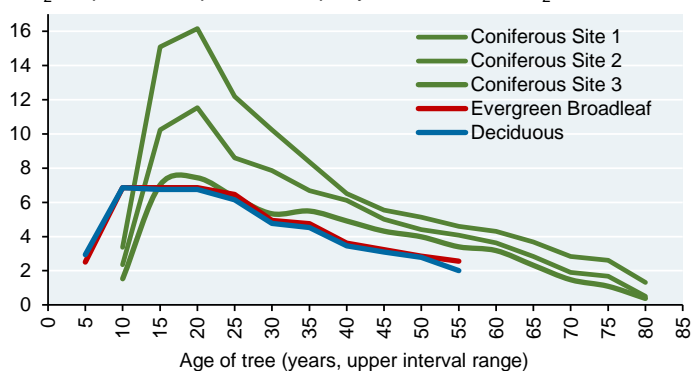
[viii] *Thou shalt not equate “emissions foregone” and “emissions sequestered”*

Voluntary Carbon Markets refer to companies or individuals purchasing voluntary emission reduction credits, also known as VERs or “carbon offsets”. Corporate or individual purchasers of VERs seek to offset their own emissions, and are typically different from those purchasing offsets as part of a regulated cap and trade system. What is an offset exactly? Well, that’s a good question. Technically, it’s a credit you buy to offset a metric ton of CO₂ equivalent that you either emitted (or might emit in the future) by driving, flying etc. The offset would presumably render you “carbon neutral”. However...

There are two kinds of VERs. Some are derived from projects that actually **sequester** (i.e., remove) carbon from the atmosphere on a long term basis, while others are based on projects that **avoid or prevent growth in future GHG emissions**.

Currently viable versions of **sequestration** include forestry projects and related efforts (restoration of peat swamps in Indonesia, for example). Forestry carbon offsets are usually granted by accrediting agencies only when they occur and are verified, which takes time given how long it takes for certain species to grow, and given pest and wildfire risk. Forestry projects are also subject to sovereign risk in emerging countries where they’re often based; some UN reforestation “REDD” projects were reportedly compromised when trees were harvested despite payments made to protect them, with little accountability for the parties involved. Another challenge: local communities in emerging countries tend to prefer tree species that are valued for construction and furniture use, and are less welcoming of native faster-growing species with less perceived utility. Furthermore, exotic non-native species may have faster growth rates, but threaten biodiversity and bring risk of unintended ecological consequences¹⁰.

Examples of tree sequestration by type and age
CO₂ sequestration per hectare per year, tonnes of CO₂



Source: Research Institute for Sustainable Humanosphere, Kyoto Univ. 2015.

The second type (mitigation) includes capture of methane from landfills, dairy farms and coal mines; managing nitrogen fertilizer on farms; and switching to more energy efficient cookstoves. To reiterate, these projects do not sequester carbon; they **slow the rate at which emissions would otherwise have grown in the future**.

The size of the VER market is small. In 2018, only \$300 million of VERs were purchased globally (a small fraction of regulated carbon trading markets). VER projects funded in 2018 offset 98 million tons of CO₂, which was 0.3% of global CO₂ emissions. It will be interesting to see if the VER market can accommodate growing interest from airlines¹¹; air travel accounts for 2.5% of all CO₂ emissions, which is much larger than 2018 VER project sequestration. There’s no reason why VER projects cannot expand, but oversight will be critical to maintain additionality, ownership, permanence and “no leakage” standards.

VERs traded at ~\$3.5 per metric ton in 2017 and 2018, compared to \$50 that the Environmental Defense Fund cites as the true social cost of carbon, and compared to the \$75 price that the IMF estimates as necessary to accelerate energy transitions. In other words, VERs are inexpensive for purchasers but also reflect a world that has not incorporated the true cost of carbon into pricing mechanisms.

¹⁰ “Choosing species for reforestation in diverse forest communities: social preference versus ecological suitability”, Chechina and Hamann, University of Alberta, 2015.

¹¹ In 2019, **Shell** began offering some customers nature-based carbon credits to offset emissions generated by its share of oil extraction, refining, distribution and use. **BA** and **Air France** announced they will offset emissions from domestic flights, while **EasyJet** announced it will offset all emissions from use of jet fuels immediately.



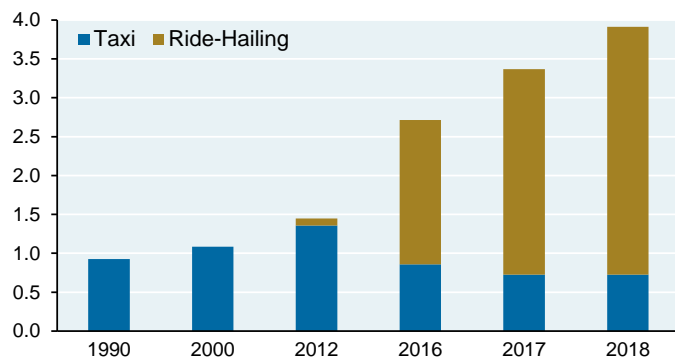
[ix] *Thou shalt not falsely extol the environmental benefits of ride-hailing services*

What’s the impact of ride-hailing services on vehicle miles traveled and GHG emissions? The answer from several recent studies is straightforward: after accounting for people who would have taken public transport, biked or walked instead, and those who would not have traveled at all, there’s a **substantial net increase in estimated vehicle miles traveled and emissions from ride-sharing**, possibly as large as 60%-80% compared to a world with no ride-sharing at all¹². Part of the issue: driver “dead-heading”, which refers to the time/distance ride-share drivers travel while waiting for passengers and commuting.

The charts tell the story: the surge in rides nationally and in NYC after the onset of ride-hailing apps; the increased emissions per trip-mile of ride-hailing trips; and estimates of ride-hailing miles traveled compared with what they replaced by trip category. As per the third chart, ride-hailing is only estimated to *reduce* emissions in a scenario of electric ride-hailing cars, further de-carbonization of the grid and rider pooling¹³. California and the City of Chicago have begun to implement penalties and incentives to promote ride-hailing electrification, rider pooling and use of mass transit (which in many cities has suffered declines in ridership). But the convenience of personalized ride-hailing may make it difficult to dislodge.

US ride-hailing and taxi ridership

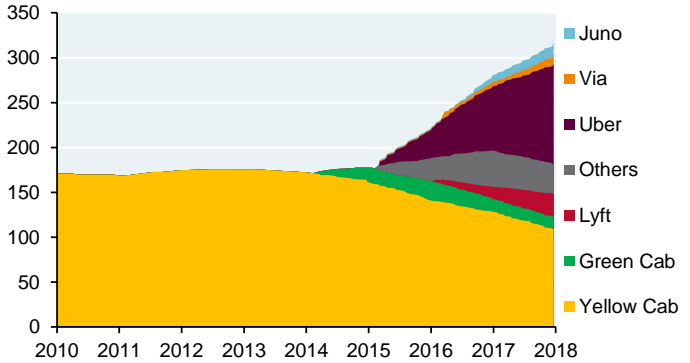
Annual ridership, billions



Source: "Ride-Hailing's Climate Risks", Union of Concerned Scientists. 2020.

Volume of rides in New York City

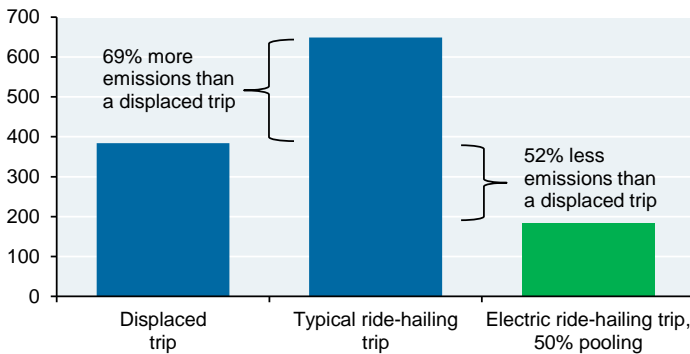
Millions of trips



Source: Barclays Research. December 2019.

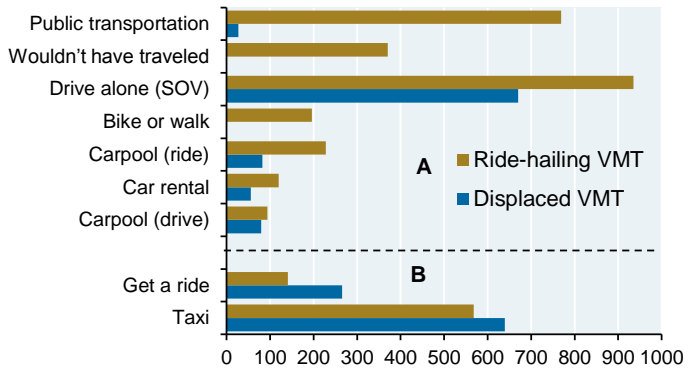
Ride-hailing emissions

Emissions per trip-mile (g CO₂ equivalent)



Source: "Ride-Hailing's Climate Risks", Union of Concerned Scientists. 2020.

Total vehicle miles traveled by ride-hailing services versus displaced choice of transportation



Source: National Renewable Energy Laboratory. September 2018.

¹² Sources for this section include:

"Ride-Hailing Climate Risks", Union of Concerned Scientists, 2020

"The impact of ride-hailing on vehicle miles traveled", National Renewable Energy Laboratory, September 2018

"The New Automobility: Lyft, Uber and the Future of American Cities", Schaller Consulting, 2018

¹³ Even in California, only 1% of ride-hailing vehicles were in EVs in 2018. Around 15% of ride-hailing trips are pooled.



[x] Thou shalt read Shakespeare: “The fault lies not in our stars, but in ourselves”

There is some irony to Americans being fascinated by the uncertain premise of geologic carbon storage and carbon mineralization at meaningful scales. Why is that? Americans emit close to the highest levels of CO₂ per capita on the planet, and could more readily achieve emissions reductions through behavioral changes rather than through carbon capture schemes. The table shows three totally hypothetical scenarios of behavior switching (cars, housing and food) that in aggregate could substantially reduce US emissions if they all took place as described.

The table is not meant to suggest that such transitions would be easy; they would require large penalties or incentives, and habits are very hard to change. But such changes, as well as other ones dealing with consumption, heating/cooling temperature preferences and transportation patterns, could be a more reliable way for the US to reduce emissions in the near term.

Topic	Scenario assumptions	Annual emissions decline (MMT)	Key assumptions	
Cars	US drivers transition to cars with developed world gas mileage, and reduce half the US miles driven per capita gap vs Europe	624	US mileage	27.4 mpg
			Developed world mileage	41 mpg
			US miles driven per capita	16,000
			OECD Europe miles driven per capita	8,000
			CO ₂ emissions per gallon of gasoline	8,887 grams
			Number of US passenger vehicles	240,000,000
Housing	US home sizes converge to the upper end of European averages, reducing consumption of electricity, natural gas, propane and fuel oil	92	Affects 50 million US housing units above:	2,000 sq ft
			Largest average dwelling sizes in Europe: (Belgium, Denmark, Netherlands, Switzerland)	1,400 sq ft
			CO ₂ intensity of nat gas, propane and fuel oil	53 - 73 kg of CO ₂ / MM btu
			CO ₂ intensity of US electricity generation	0.99 pounds of CO ₂ / kWh
Food	US consumption of animal-based foods decreases by 50%, substituted with plant-based foods*	210	Emissions based on University of Michigan Center for Sustainable Systems, Scenario #3, Feb 2020, "Implications of future US diet scenarios on GHG emissions", Martin Heller et al	
Total annual CO₂ savings		925	18% of total annual US emissions	

* Emissions results from this scenario were similar to a no-beef diet partially offset with added amounts of chicken, fish and pork.

Sources: EIA, EPA, Bureau of Transportation, ICCT, IEA, Eurostat, USDA, University of Michigan, Carnegie Mellon (EIO-LCA)

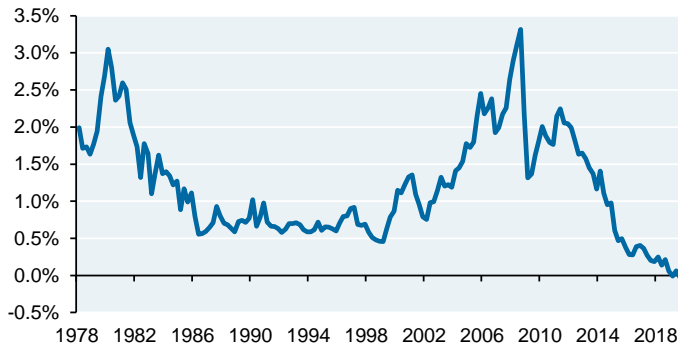


[2] Peak US energy independence? Roadblocks in the Shale Revolution

Whether the US energy deficit is measured in dollar terms or in energy terms, US reliance on foreign energy supplies ended 2019 at its lowest level in 60 years¹⁴. Nixon and his successors could only dream of this kind of energy independence, which was a constant US policy objective for decades.

US net energy deficit, in dollar terms

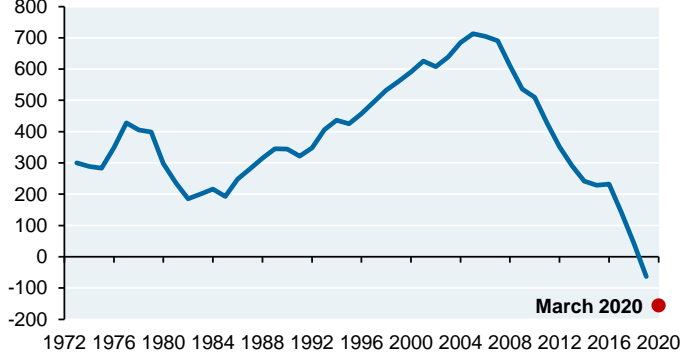
Energy imports - energy exports, % of GDP



Source: Bureau of Economic Analysis, Haver Analytics, JPMAM. Q1 2020.

US net energy deficit, in energy terms

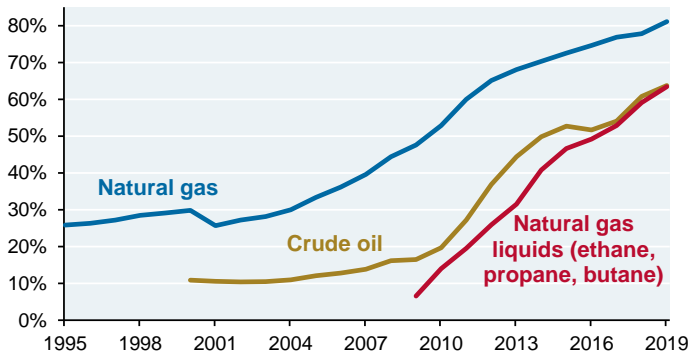
Net imports of oil, natural gas and coal in million tonnes of oil equiv.



Source: EIA, JPMAM. March 2020.

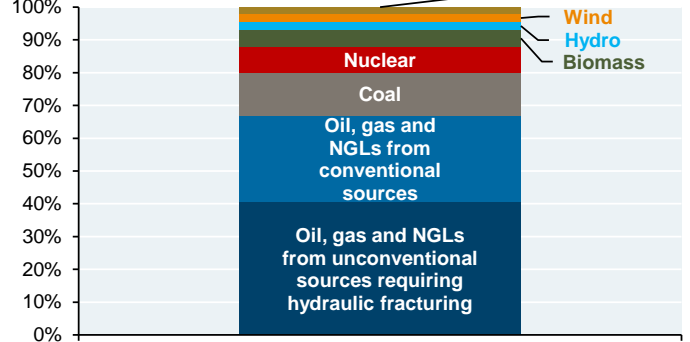
However, US energy independence is highly reliant on hydraulic fracturing: between 65%-80% of all US natural gas, crude oil and natural gas liquid production was derived from fracturing operations in 2019. As a result, hydraulic fracturing accounted for 40% of all US primary energy consumption as well. Looking ahead, the independence shown above may be at risk due to financial and environmental factors.

Percentage of US oil and gas production derived from hydraulic fracturing through year-end 2019



Source: EIA, US Department of Energy, JPMAM. 2019.

Hydraulic fracturing accounted for 40% of all US primary energy consumption in 2018



Source: EIA, BP, Society of Petroleum Engineers, S&P Platts, JPMAM. 2018.

¹⁴ Here's an illustrative statistic: US net oil imports as a % of US oil consumption declined from a peak of 60% in 2006 to 14% in 2018, **the lowest level since 1958**.



Financial pressures

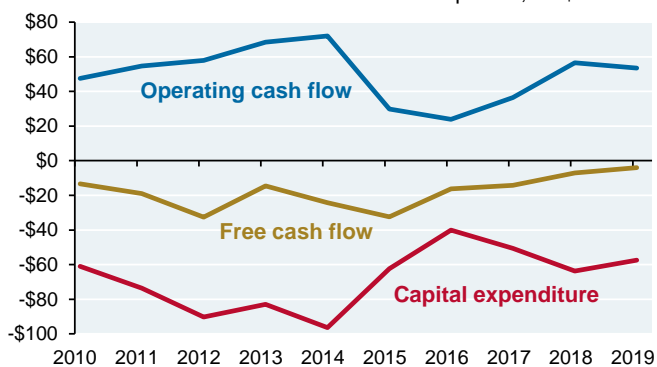
Even before the COVID pandemic, investing in the US shale revolution was something of a train wreck. Let's focus on a 29-stock universe¹⁵ of companies associated with the US shale boom from 2010 to 2019:

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

Note that this all happened despite 8%-9% of US natural gas production now being exported via LNG terminals, which was supposed to be a catalyst for higher US natural gas prices (it wasn't). This poor financial performance led to a collapse in shale sector stock prices, an exodus of capital and a spike in bankruptcies. Debt and equity issuance by E&P companies fell by 60% from 2014 to 2019. By the end of 2019, the industry shake-out started to translate into better relative equity performance for the S&P 500 E&P sector...and then COVID hit, after which the relative gains were lost again (red circle, third chart). Due to COVID, leverage of US independent producers has now doubled with plenty of debt coming due every year from 2021 to 2025¹⁶. The survivors are likely to have to rely on internally generated cash flow instead.

Shale revolution: a revolution in supply, not profit

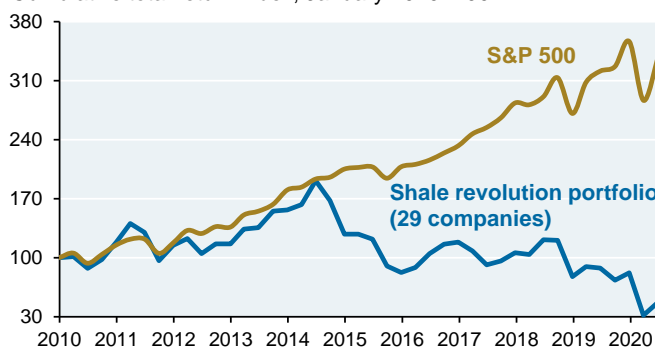
Select cash flow measures for 29 shale companies, US\$ billions



Source: Bloomberg. 2019.

The shale collapse

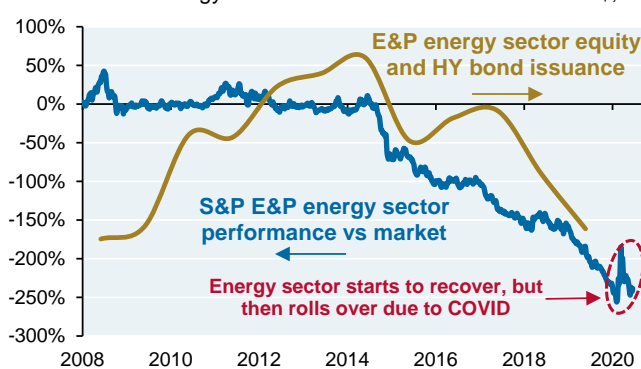
Cumulative total return index, January 2010=100



Source: Bloomberg. June 26, 2020. Shale revolution portfolio is market cap weighted and rebalances quarterly.

E&P sector relative performance and issuance

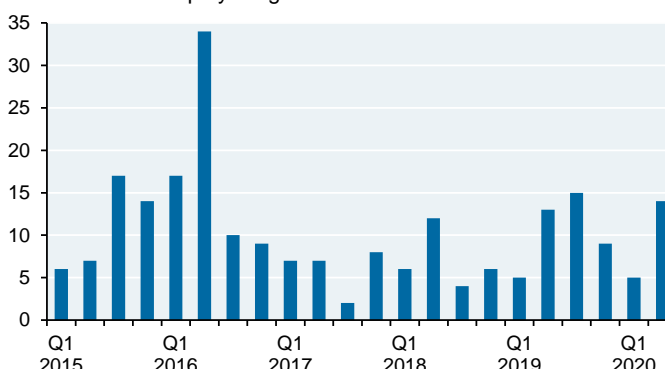
S&P 500 E&P energy sector - S&P 500 total return US\$, billions



Source: Bloomberg. June 26, 2020.

North American oil and gas producer bankruptcy filings

Number of bankruptcy filings



Source: Haynes and Boone Oil Patch Bankruptcy Monitor. May 31, 2020.

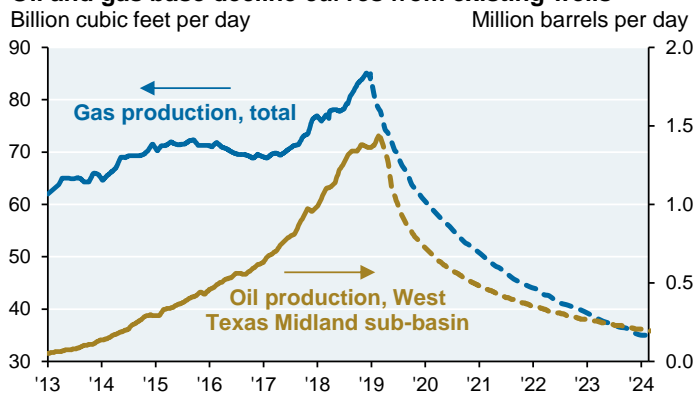
¹⁵ The 29 companies in our shale revolution universe: Anadarko, Antero, Apache, Cabot, Callon, Carrizo, Chesapeake, Cimarex, Concho, Continental, Denbury, Diamondback, EOG, EQT, Hess, Laredo, Marathon, Matador, Murphy, Noble, Oasis, PDC, Pioneer, QEP, Range, SM, Southwestern, Whiting and WPX.

¹⁶ "Global energy analyzer: Supercycle on the Horizon II", C.Malek, JP Morgan European Equity Research, June 2020



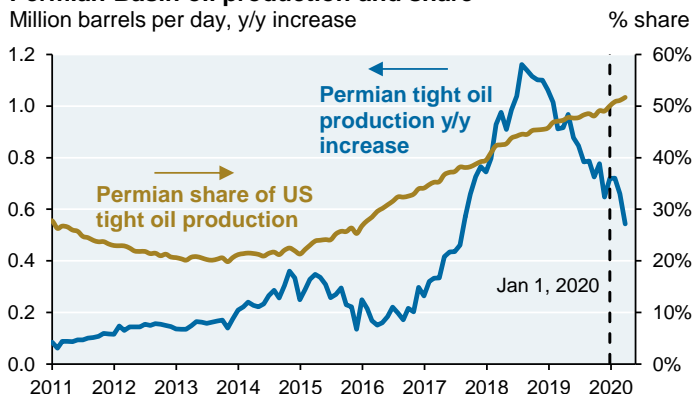
The shale boom has been characterized by rapid growth in production and by rapid decline rates of individual wells (the first chart shows illustrative decline rates of existing wells). As long as the shale industry is growing, new well production replaces lost production of aging wells. But at a time of scarcer capital, new wells might not be financed and constructed as fast. **Even before COVID** (dotted vertical line in the charts below), the industry shake-out was seen in declining Permian Basin production growth, in a falling oil and gas rig count, and in declining E&P capital spending expectations.

Oil and gas base decline curves from existing wells



Source: IHS Markit, Antero Resources, JPMAM. 2019.

Permian Basin oil production and share



Source: EIA. April 2020.

Number of US oil and gas rigs



Source: Baker Hughes, Bloomberg. May 29, 2020.

E&P year ahead capital spending expectations



Source: Federal Reserve Bank of Dallas. Q1 2020.

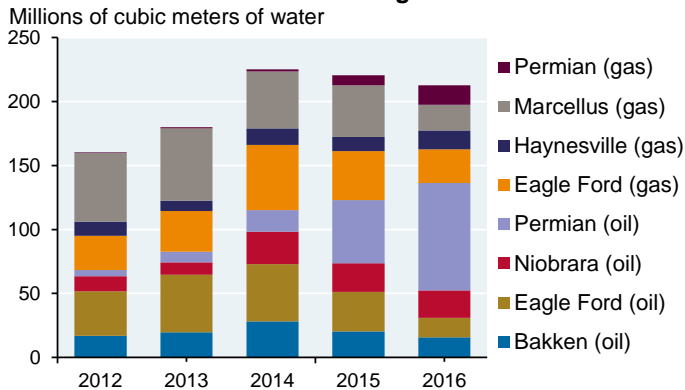
We expect some of the “base” decline from existing shale wells to be replaced by new wells; the harder question is by how much. Operating and development costs have declined, well productivity has improved and there are large sunk costs in Appalachia (i.e., lease agreement options) that may compel many producers to keep drilling irrespective of lifecycle economics. Furthermore, if the onshore shale boom fades, we might see a revival of US *offshore* oil & gas production in the Gulf of Mexico. US oil production is also very sensitive to price: \$55-\$65 oil prices could add 1-3 mm bpd to US production when compared with JP Morgan’s \$40 base case WTI price forecast. **Even so, the US may now be close to peak oil and natural gas production and peak energy independence given financial pressures on the shale industry, and environmental pressures discussed next.**



Environmental pressures

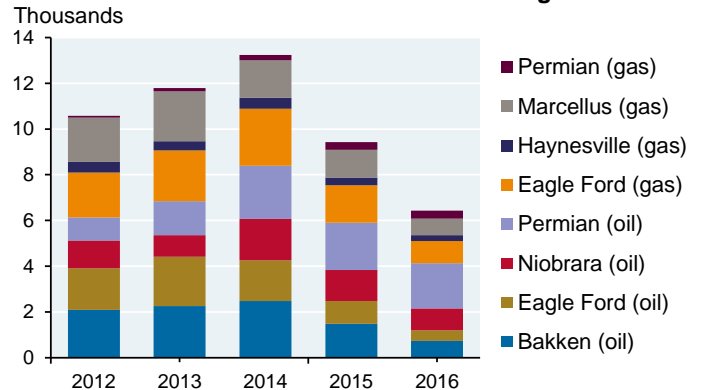
The word “hydro” is part of “hydraulic fracturing” for a reason. Water requirements for fractured wells are 8x-10x higher than for conventionally drilled wells. Water demand rose as the shale revolution unfolded, with only a modest decline from peak levels in 2014 to 2016. There are a lot of factors driving water demand, so it’s important to distinguish them. Water demand is a function of the number of wells drilled, and the lateral length of wells which increased by 20%-30% from 2011 to 2016. So, some degree of increased water demand simply reflects more wells and longer distances from the wellhead.

Water use in select shale oil and gas basins



Source: Kondash *et al.*, Science Advances. August 2018.

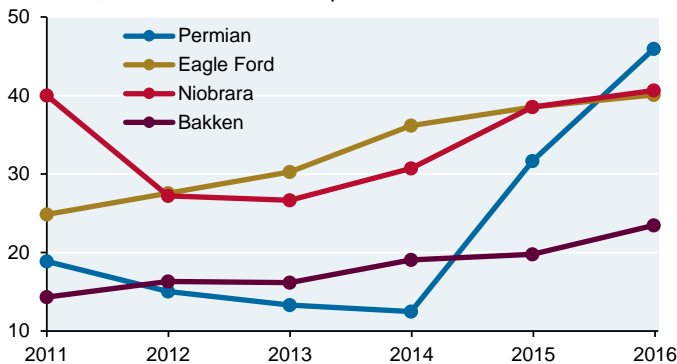
Number of new wells drilled in select oil and gas basins



Source: Kondash *et al.*, Science Advances. August 2018.

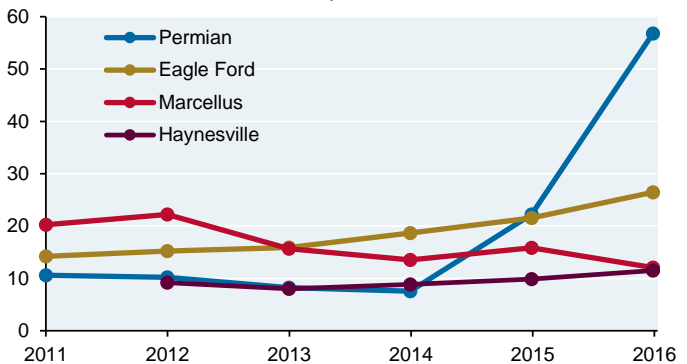
Since changing well numbers and wellhead distances affect water demand levels, our preferred measure of shale industry water intensity is “liters of water per gigajoule of energy”. As shown below, **water intensity** rose for many shale oil locations from 2011 to 2016, and also for shale gas wells in the Permian¹⁷.

Median water use intensity for hydraulic fracturing of oil
Liters/GJ, first 12 months of well production



Source: Kondash *et al.*, Science Advances. August 2018.

Median water use intensity for hydraulic fracturing of gas
Liters/GJ, first 12 months of well production



Source: Kondash *et al.*, Science Advances. August 2018.

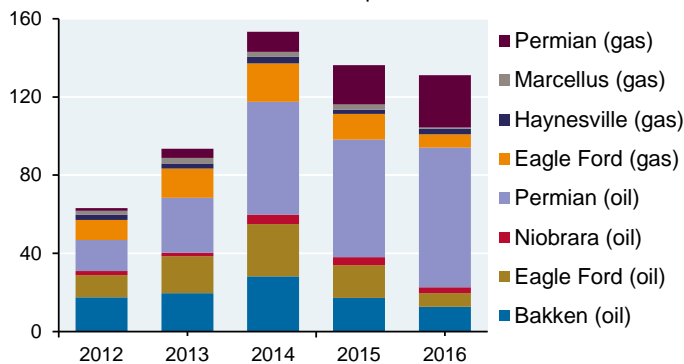
¹⁷ While most electricity *generation* doesn’t take place in water-stressed areas, **~50% of natural gas extraction does occur in water-stressed areas**. Natural gas water usage is at least less intense than for coal. From 2013 to 2016, for every MWh of electricity generated with natural gas instead of from coal, there was a reduction of 1 m³ in water consumption and 40 m³ in water withdrawal. In terms of toxicity, however, **it’s a toss-up between produced water from fracturing and coal mine water drainage**. The former is often toxic (see next page), and so is the latter: many coal mines are abandoned and not sealed, so they fill up with rain and continuously discharge acidic, polluted water. Furthermore, storage of coal combustion residuals in coal ash ponds can leach heavy metals and radioactive material into groundwater. Source: Environmental Research Letters, Kondash and Vengosh, Dec 2019.



Water demand is only half the story regarding environmental issues. After the fracturing process is over, operators are left with flowback and produced (FP) wastewater that has to be dealt with. “Flowback” refers to return of water originally injected into the well, while “produced” water refers to water that exists naturally in these formations and which surfaces along with high concentrations of dissolved inorganic and sometimes radioactive substances. The chart on the left shows FP water trends, while the chart on the right shows management practices used to dispose of it. Of the two wastewater types, produced water accounts for ~90% of total volume, which may limit possibilities for beneficial reuse.

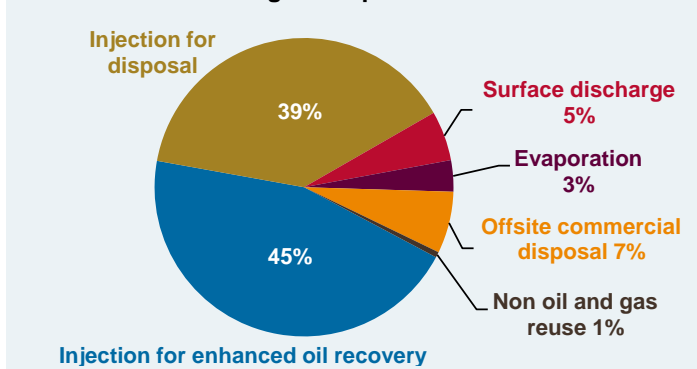
The FP water challenge is complex; in some locations, volumes are higher but reinjection is easier/cheaper for geological reasons. In other locations, FP volumes are lower but reinjection is more complex and expensive. While overall FP volumes declined from 2014 to 2016, FP water per well more than doubled from 2012 to 2016. As with overall water demand shown earlier, the Permian is at the epicenter.

Flowback/Produced water in shale oil and gas basins
Millions of cubic meters of FP water produced over first 12 months



Source: Kondash *et al.*, Science Advances. August 2018.

Produced water management practices



Source: Groundwater Protection Council, “Produced Water Report: Regulations, Current Practices and Research Needs”, June 2019.

It is beyond the scope of this paper to review all the environmental consequences of the shale industry’s water demand and wastewater treatment needs. The Groundwater Protection Council produced a 300-page report in 2018 that goes through some specifics¹⁸, and we also covered the EPA’s fracturing study (and objections from the EPA’s own Science Advisory Board) in 2017. The debates are intense; as water scarcity becomes more of an issue and as states deal with environmental impacts of fracturing, **its cost and complexity may rise in the handful of states that account for 90% of shale oil and gas production.** Wood Mackenzie estimated that water management costs could add \$6 to the cost of producing a barrel of oil, possibly curbing future Permian oil supply by 400,000 barrels per day by 2025.¹⁹

¹⁸ GWPC 2019 “Produced Water Report: Regulations, Current Practices and Research Needs”

¹⁹ Wood Mackenzie press release, “Permian produced water: slowly extinguishing a roaring basin?” June 11, 2018.



Possible consequences for US oil & gas from a Biden presidency and a Democratic sweep²⁰

Federal government could block new oil & gas leases on Federal lands

- A halt to *new* offshore and onshore leases on Federal land in Permian and Bakken basins would be likely, while it's less likely that *existing* Federal leases would be rescinded. Oil production on Federal lands is ~25% of total production, and offshore Gulf production is ~10% of total production.

Climate-related financial regulation could further restrict the industry's access to capital

- Publicly-traded energy companies are likely to be required to disclose climate risks, and banks may be required to incorporate climate risks in stress test capital ratios. It is less likely that financial institutions would be subject to energy related portfolio limits, or be forced to divest

Executive Branch could deny fossil fuel infrastructure projects and/or LNG export permits

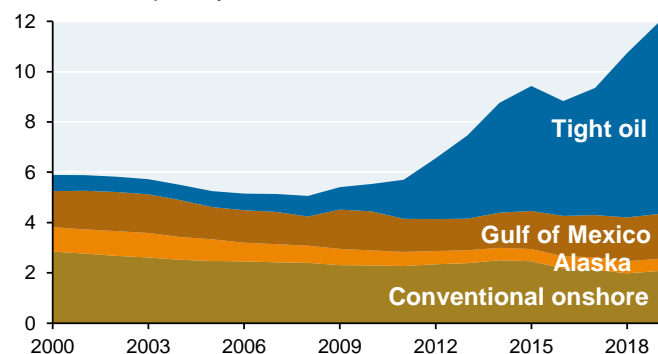
- Biden pledges to evaluate Federal infrastructure projects based on climate pollution potential and GHG impact. Biden originally did not sign the "No Keystone XL" pledge, but now promises to revoke the permit. Other possible outcomes: expand scope of Clean Water Act
- Biden may use the threat of fossil fuel export bans to extract concessions from the oil & gas industry, but so far has resisted calls to declare a climate emergency

Congress could subject hydraulic fracturing to stricter review and regulation

- A 2005 bill exempted hydraulic fracturing from being subject to Federal standards set by the 1974 Safe Drinking Water Act (the "Halliburton loophole"). If the exemption were repealed, fracturing would require EPA approval, giving the Administration greater discretion to delay or block permits

US oil production by type

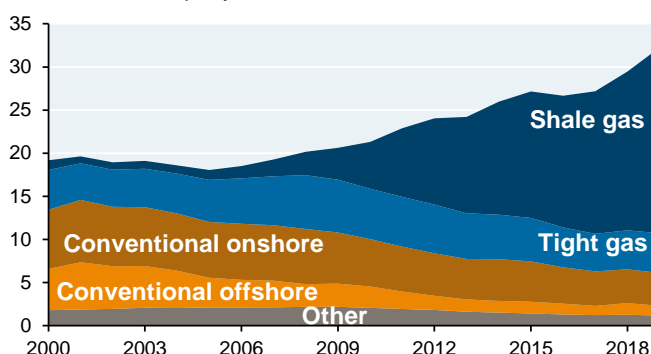
Million barrels per day



Source: EIA. 2019.

US dry natural gas production by type

Trillion cubic feet per year



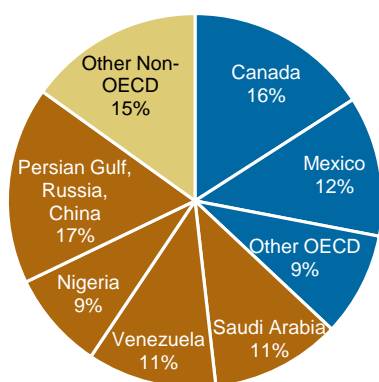
Source: EIA. 2019.

²⁰ The likelihood of passage of some provisions mentioned on this page are based on research by Rapidan, a Maryland-based energy and political consulting firm.

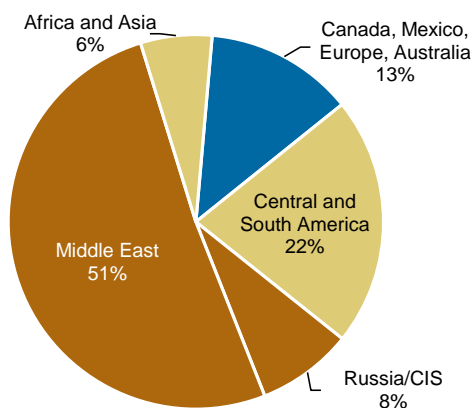


What might US energy dependence look like if financial and environmental pressures constrain the US shale industry before substantial de-carbonization of transport and industry takes place? From a US geopolitical, military and economic perspective, it's not a pretty picture. The first chart shows US oil imports by country in 2005, the year of peak US oil imports. The second two charts show proven reserves by country for oil and natural gas. In essence, these are the countries the US would need to rely on for its imported oil & gas needs. If US energy independence is lost, regaining it through renewable energy could take, at the minimum, the rest of my lifetime²¹.

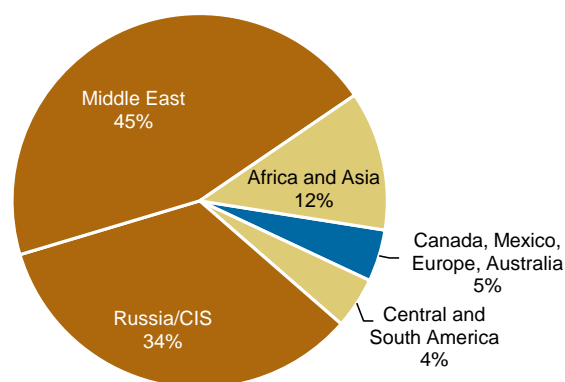
Peak US oil imports, 2005



Proven oil reserves, 2018



Proven natural gas reserves, 2018



Source: BP Statistical Review of World Energy, EIA, J.P. Morgan Asset Management, 2019.

²¹ **In the IEA's "Sustainable Development Scenario", the US gets much closer to energy independence by 2030 through large declines in fossil fuel usage. However, its core assumptions include the following. You can decide whether you consider this scenario in the realm of the possible:**

- US primary energy use declines to 1992 levels despite a 40% population increase from 1992 to 2030
- solar generation grows by a factor of 5.5x, wind generation grows by a factor of 3x
- nuclear generation is unchanged (no decommissioning)
- coal use for power/heat declines by 90% (industrial sector switches to solar thermal and geothermal energy)
- electric vehicles sales reach 47% from today's 2% levels
- oil use declines by 24% due to electric vehicles, and ICE gasoline/diesel mileage per gallon improves by 40%
- truck CO₂ emissions per tonne of freight declines by 33%
- energy intensity of buildings declines by 30%



Section 2 Appendix: no free lunch (the environmental impact of renewable energy)

While environmental consequences of oil and gas on climate and groundwater systems have been widely studied, scientists are only just beginning to assess **environmental impacts of a world highly reliant on renewable energy instead**:

- A renewable energy future will require massive amounts of cobalt, copper, lithium, graphite, cadmium and rare earth elements for solar panels, batteries, electric vehicle motors, wind turbines and fuel cells. One study cited increases in materials demand of 87000% for EV batteries, 1000% for wind power, and 3000% for solar cells and photovoltaics by the middle of the century
- Even with modest production of these minerals to-date, their extractive and smelting industries have left a legacy in many parts of the world of **“environmental degradation, adverse impacts to public health and biodiversity damage”** (B. Sovacool)

The renewable waste issues of the future:

- IRENA estimates that toxic solar panel waste (which contains lead, cadmium and chromium) could rise from 250 *thousand* tonnes in 2016 to 78 *million* tonnes by 2050
- By 2030, 11 million tonnes of spent lithium-ion batteries are projected to be discarded, with few systems in place to recycle them
- Fiberglass wind turbine blades are built to withstand hurricane force winds and cannot easily be crushed, recycled or repurposed, at least not so far; retired ones mostly end up in landfills, or in Europe, burned. The US might face 720,000 tons of wind turbine blade disposal over the next 20 years

I have not seen anyone suggest that environmental consequences of a renewable energy future would be anywhere near as corrosive on the environment as one based on fossil fuels. Even so, a renewable energy world may be much less “green” than currently perceived.

Sources:

“Sustainable minerals and metals for a low-carbon future”, B. Sovacool, Science Magazine, January 2020

IRENA Solar Photovoltaic Panel End-of-Life Management report, 2016

World Economic Forum Global Battery Alliance

“Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development”, Manberger and Stenqvist, Energy Policy, August 2018



[3] Mountains vs Molehills, 2020: de-carbonizing steel production and deep geothermal energy

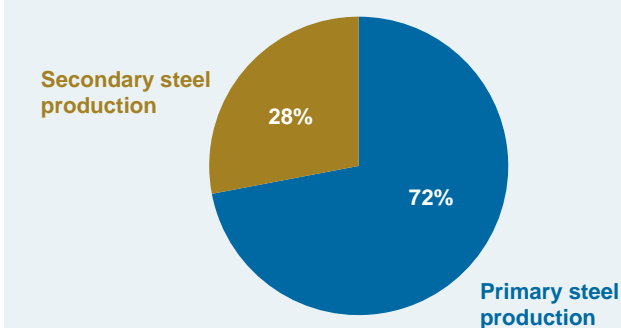
Last year, we added a section called “Mountains vs Molehills” to assess the real-world de-carbonization potential of new ideas frequently mentioned in the media and on green energy blogs. This year we have another installment: **de-carbonization of steel production, and ultra-deep geothermal energy.**

Topic #1: De-carbonizing steel production, Bill Gates and concentrated solar power

The idea for this topic started with an article on a Bill Gates-funded solar power startup and how it could “fix” a huge carbon emissions problem²². The article described a concentrated solar power (CSP) plant which reached 1,000°C through the use of reflectors calibrated via artificial intelligence, and how this energy could be used to “create steel, cement and petrochemicals” (instead of using fossil fuels). **Ok then. Let’s break this down for steel,** the largest industrial source of global CO₂ emissions.

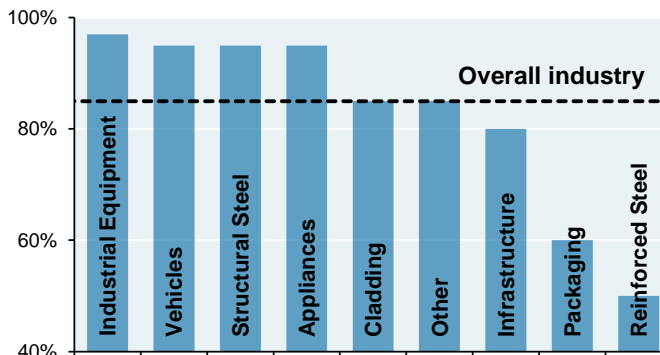
- Steel is created two ways: producing it from cast iron made from iron ore and coke (“primary” production), or by melting down scrap steel in an electric arc furnace (“secondary” production). The global split is 70% primary and 30% secondary. While US steel production is more skewed to electric arc furnaces (around 70% of US output in 2018), the US only represents 5% of global steel production
- For secondary production, steel has a melting point of 1,370°C – 1,540°C, so 1,000°C is still a few hundred degrees away from what’s needed. Even so, let’s assume that the new CSP plants reach higher temperatures (as some reflector operations have); in that case, secondary steel production *could* be de-carbonized via electricity produced solely via solar/other renewable energy
- However, given the long lives of structures made from steel, rising demand for steel in Asia and Africa where there is little scrap to recycle, and the fact that most scrap steel is *already* recycled (see chart, right), **primary steel production is likely to remain the dominant method of creating steel** and also remain a carbon-intensive activity for the foreseeable future

Global solid steel production



Source: IEA, “Tracking Industry”. May 2019.

Steel recycling rate by product



Source: ArcelorMittal Global R&D, Worldsteel. 2016.

²² “A Bill Gates-backed startup wants to fix a huge carbon emissions problem”, CNET, November 19, 2019



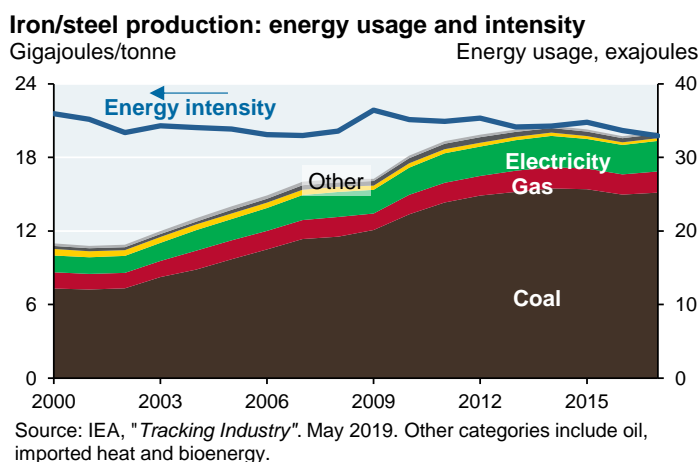
Why is primary steel production so carbon-intensive? As per the table below, the two most carbon-intensive primary steel production processes are:

- *The conversion of coking coal into coke at temperatures of 1,000°C in coke ovens.* Most emissions in this stage result from carbonization of coal at high temperatures (specifically, from combustion of coke oven gas that is about 50% methane, carbon monoxide and ethylene). The conversion process eliminates volatile compounds in coal and produces a purer form of more porous carbon
- *The iron-making process, during which iron ore (oxides), coke and limestone are fed into a blast furnace.* Hot air is blown into the furnace, at which point the coke burns, stripping the oxygen from iron oxide to produce carbon monoxide, carbon dioxide and molten “pig” iron. A small amount of limestone is used as a “flux” to absorb impurities

Some CO₂ produced in these stages can be recycled into ammonia and methanol production, but the amounts are small relative to overall emissions. Energy intensity of iron and steel production and its reliance on coal hasn’t changed much in recent years. While some countries like Sweden produce steel more efficiently at 16 GJ of energy per tonne, they are offset by less efficient producers like China (~20 GJ/t).

CO ₂ emissions, integrated steel-making	
Kg of CO ₂ emissions per tonne of steel produced	
Coal and coking	990
Iron ore sintering	15
Blast furnaces (iron-making)	610
Basic oxygen furnace (steel-making)	85
Total	1700

Source: "Assessment on the energy flow and carbon emissions of integrated steelmaking plants", Energy Reports, He et al, January 2017



As a result, de-carbonization of primary steel production requires new approaches that produce iron from its ores without using any coke or natural gas. There are ideas afoot: ArcelorMittal announced a demonstration plant to produce steel by using hydrogen instead of coal. The hydrogen would enable “**direct reduction**” of iron ore (in essence, hydrogen would be used as the reducing agent for iron oxide instead of carbon). The concept is interesting, but...

- The plant’s initial output of 100,000 tonnes is 0.01% of 2018 global steel production (1.8 bn tonnes)
- ArcelorMittal first plans to use hydrogen obtained via **fossil fuel steam methane reformation** (see page 13) to allow for “economical operation”. It will only run on “green” hydrogen produced from renewable electricity sources when it is “available in sufficient quantities”
- Bloomberg New Energy Finance often makes exponential growth forecasts for de-carbonization technologies of all kinds, and hydrogen-produced steel is no exception: last fall, BNEF estimated that half of global steel output could be produced via green hydrogen by 2050! We ran this forecast by a Swedish steel industry expert who described it as **highly implausible**. Blast furnace steel plants have useful lives of 50+ years, and it’s rare for them to be replaced beforehand. Construction of hydrogen reduction plants from scratch will take decades, even if the exact design is ready to go...which it isn't. Sweden has shovels in the ground for a demonstration plant to get the iron ore reduction chemistry right (since every iron ore can behave differently), and is targeting **2045** for full operation



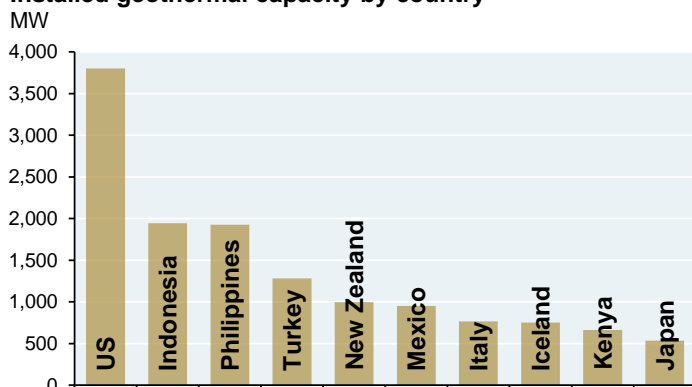
Mountain vs Molehill Topic #2: Ultra-deep geothermal energy

Geothermal energy has been used in hot baths since antiquity, for space heating in Boise, Idaho since 1892, for virtually all houses in Reykjavik since the 1930s, and for electricity generation since 1904 in Larderello, Italy. Before getting into “ultra-deep” geothermal power, let’s walk through the footprint of existing geothermal energy today.

Geothermal energy has a small presence. Its output in 2018 was only 0.1% of global primary energy consumption, split roughly 50/50 between electricity production and heat (many sources don’t even break geothermal out as a separate category, and combine it with things like wave power)²³. Around half a GW of new capacity came online in 2018, bringing the global total to 13.3 GW. Most additions occurred in Turkey and Indonesia, with the rest scattered about the US, Africa and Asia. There are two ways of generating electricity by using geothermal energy: binary cycle and dry-steam. In a binary cycle plant, geothermal fluid vaporizes another fluid with a lower boiling point than water that then spins a turbine, while in conventional dry-steam/flash plants, geothermal steam is used directly to power the turbine.

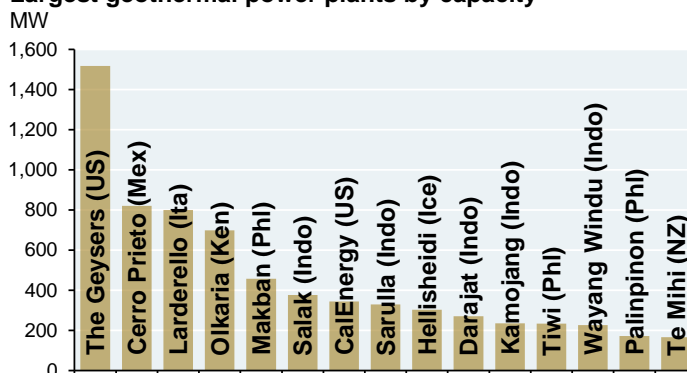
As shown below, the world’s largest geothermal plants have well depths of ~2 kilometers, and access reservoirs with average temperatures of 250-300°C.

Installed geothermal capacity by country



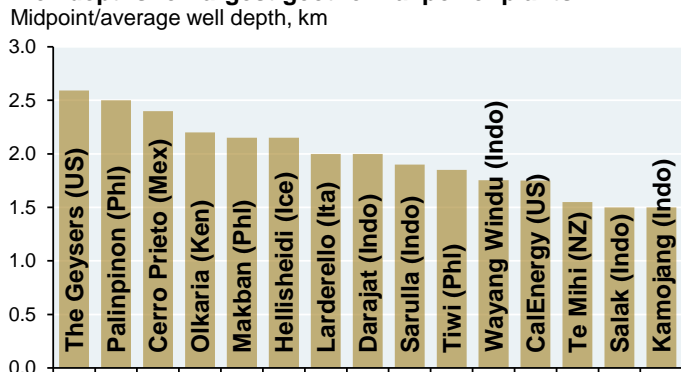
Source: BP Statistical Review of World Energy. 2019.

Largest geothermal power plants by capacity



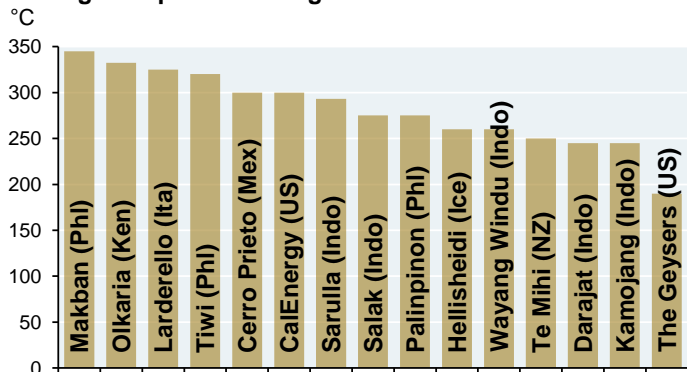
Source: Proceedings from World Geothermal Conference, OpenEI, individual company releases. 2020.

Well depths for largest geothermal power plants



Source: Proceedings from World Geothermal Conference, OpenEI, individual company releases. 2020.

Average temperatures of geothermal reservoirs



Source: Proceedings from World Geothermal Conference, OpenEI, individual company releases. 2020.

²³ REN21 Renewables 2019 Global Status Report



With that backdrop, let's discuss "ultra deep" geothermal energy. At 5-7 kilometers below the surface of the earth, there are geothermal reservoirs measured at 400°-500° C and at 200+ bars of atmospheric pressure. In these locations, water exists as "supercritical fluid". Such fluids *in theory* could deliver 5x-10x more power than traditional geothermal plants and rival the power derived from nuclear power plants. If so, the increased power could offset some of the increased drilling costs required to access such depths, if they were achieved. The concept has led to press articles such as "*Supercharged Geothermal Energy Could Power the Planet*", which asserted that "heat contained in the upper three kilometers of the earth's crust would be enough to meet the world's energy demand thousands of times over"²⁴. Yes, but....let's take a closer look.

The most well-known deep geothermal projects in the world are **Iceland Deep Drilling Projects 1 and 2**²⁵. They are still in the exploratory field-test phase since development of valves, coatings, casings and sensors that can withstand the intense temperatures and pressures involved, and the corrosive materials surfaced during the process, are still ongoing.

- The first well, IDDP-1, had to be completed in 2009 before reaching supercritical fluid depths since molten magma flowed into the well at 2,100 meters. However, above the magma intrusion, superheated steam at 452°C and at 40-140 bars of pressure was measured during a 2-year flow test, capable of generating 35 MW of power (8x-10x higher than a conventional geothermal well). At the time, IDDP-1 was the hottest producing geothermal well in the world. Eventually, its master valves failed and the superheated steam flow had to be quenched with cold water. The flow was quenched, but the thermal shock caused the well casings to buckle beyond repair, and IDDP-1 was abandoned
- In 2017, the IDDP-2 project team drilled to depths of 4,500 m, reaching a different field that is recharged by seawater and which contained supercritical conditions of 600°C and 350 bars of pressure. This project represented the first of its kind in terms of drilling into geothermal reservoir rocks at these extreme temperatures. Flow tests have begun and will be carried out over the next few years, even through IDDP-2 has already sustained casing damage which could restrict certain development options at deeper levels
- The ultimate goal of the IDDP project: generate power from supercritical geothermal resources which would be used not just in Iceland but in Scotland as well. The IceLink plan entails a 1,200 km high-voltage underwater DC cable to Scotland to interconnect Iceland's electric grid to those of the UK and beyond. Laying such a cable in deep Atlantic waters would be another unprecedented achievement: today's longest underwater HVDC cable is 580 km in shallow waters between Norway and the Netherlands

In other words, deep geothermal power is in the very early stages of development. We're intrigued about the concept of deep geothermal as baseload power, but are realistic about the physical materials and geological challenges ahead (including risks of seismic activity). We met with a company that's trying to solve some drilling challenges via an "electric pulse plasma-based drill" designed to reach temperatures of 6,000° C. As the plasma drill descends, it would be followed by a continual casing that would conduct water on the way down, and supercritical steam on the way back up. The intense heat from the drill bit would presumably vaporize everything in its path, and the company developing it believes that drilling costs would remain linear with depth (in contrast to traditional deep drilling techniques whose costs rise geometrically with depth). **However**, its efforts are in their infancy, and their estimates of plasma drilling costs have to be taken with a giant grain of salt until proven in more than just early field studies.

²⁴ New Scientist.com (a weekly science and technology publication), October 17, 2018

²⁵ "*The IDDP Success Story*", Proceedings of the World Geothermal Congress, Gudmundur Friedleifsson et al, 2020



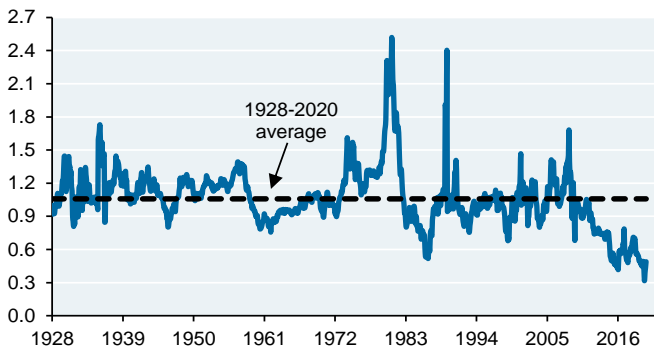
[4] Oil & gas equity market underperformance: stranded asset risks or supply shock?

Even before COVID, the US oil & gas sector traded at the largest valuation discount vs the market in decades, and its performance has been trounced by investments in renewable and other clean energy stock benchmarks. Both developments are illustrated in the first two charts. The big picture question: **did oil & gas stocks underperform primarily due to expectations of widespread carbon taxes and billions of barrels/BTUs of stranded oil and gas reserves that the world will have little use for anymore?**

Mark Carney from the Bank of England believes this, and estimated that global markets could decline by \$20 trillion once energy transitions risks are fully recognized by investors²⁶. And in mid-June of this year, **British Petroleum wrote off \$18 billion in assets**, citing both lower near-term oil demand due to the coronavirus, and a reduction in BP's medium-term expectations for oil prices from \$70 to \$55 per barrel. In its announcement of one of the largest industry writedowns in many years, BP also cited the tendency for governments to direct COVID stimulus packages toward more climate-friendly initiatives and away from anything related to fossil fuels.

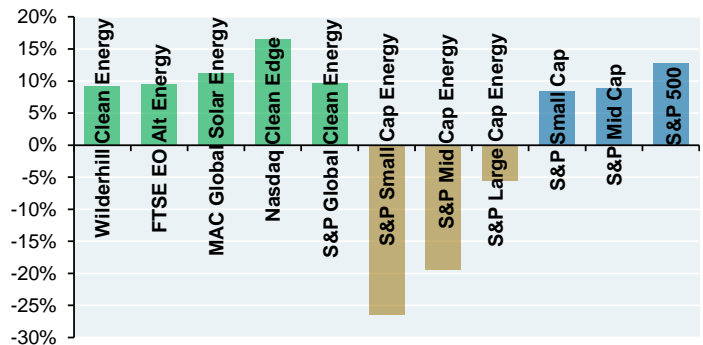
Energy sector valuations at all-time lows vs the market

Energy stocks price to book divided by market price to book



Source: Empirical Research Partners. May 2020. Equal-weighted portfolio.

Renewable and traditional energy stocks vs the broad market, 2013-2020, Annualized total return



Source: Bloomberg. Date range: Jan 1, 2013 to Jun 26, 2020.

World liquid fuels consumption

Million barrels per day



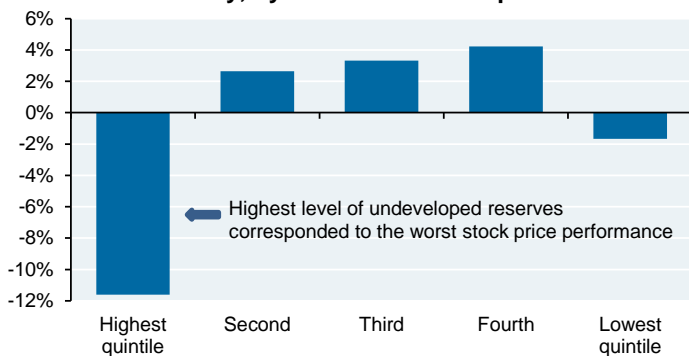
Source: EIA Short-term Energy Outlook. June 2020.

²⁶ "Firms ignoring climate crisis will go bankrupt, says Mark Carney", The Guardian. October 13, 2019.



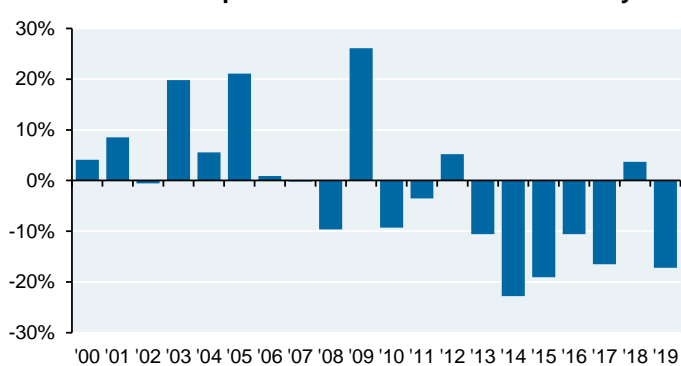
Researchers from UCLA and Simon Fraser University have come to similar conclusions on stranded asset risks, at least as it relates to oil & gas stock prices and the impact of additional reserves. In a “stranded asset” world, the more reserves a company finds, the worse off its stock price would be for having invested to obtain them. Using a sample of 679 North American oil firms from 1999 to 2018, they found that reserve growth had a *negative* effect on firm value, and that this negative effect was stronger for producers with higher extraction costs²⁷. When they looked at the details, **they found that negative effects were mostly due to growth in undeveloped reserves.** Other papers found similar results²⁸: the highest quintile of undeveloped reserves led to the weakest stock price performance, an effect which was particularly pronounced over the last 5 years. Finally, companies that spent less on reserve accumulation outperformed, usually since they used free cash flow to buy back stock.

Average annual energy producer stock price returns vs the overall industry, by value of undeveloped oil reserves



Source: Empirical Research Partners. 2019.

Stock price returns for energy producers with highest value of undeveloped oil reserves vs overall industry



Source: Empirical Research Partners. 2019.

²⁷ “Stranded Fossil Fuel Reserves and Firm Value”, Simon Fraser University and UCLA. November 2019.

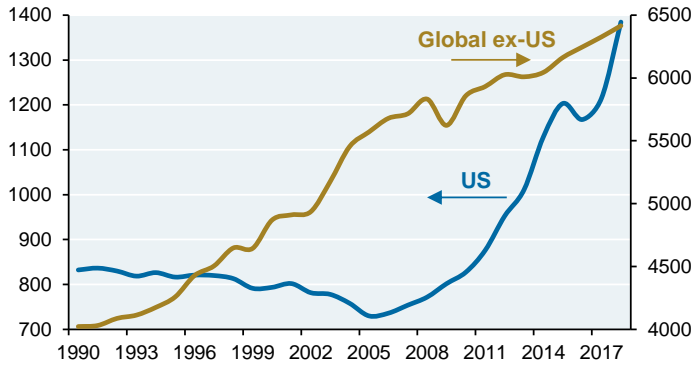
²⁸ Empirical Research Partners, “Energy Bear Market Blues” (December 2019) and “Energy: Buy the 93-year Low” (January 2020).



Even so, the US supply glut may be just as good an explanation for the dreadful performance of US oil & gas stocks. The US shale revolution began in 2005, after which US oil and gas production almost doubled in 13 years. When measured in energy terms, it was the **second largest positive oil and gas supply shock in modern history**, surpassed only by the USSR production boom from 1969 to 1982. And as shown in the second chart, only a small portion of US supply growth was exported; most of it was consumed in the US, resulting in a sharp decline in imports.

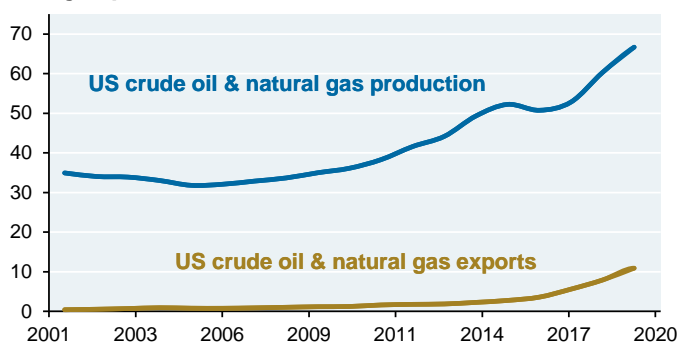
US and global oil and natural gas production

Million tonnes of oil equivalent



Source: BP Statistical Review of World Energy. 2019.

Most of the shale boom reduced imports, rather than being exported, Quadrillion BTUs

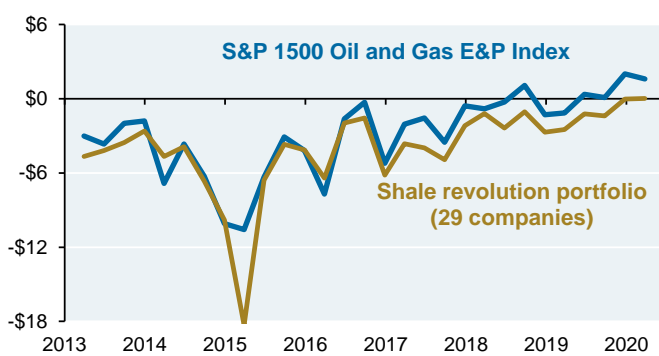


Source: EIA. 2019.

In the earlier section on US energy independence, we illustrated how shale producers and capital providers didn't focus on profitability, and how the shale industry generated year after year of negative cash flow. The sector had only just begun to regain profitability when the COVID pandemic hit. It's hard to find a similar episode of consistently negative free cash flow in the history of US corporate finance: **an entire decade of a sector foregoing profitability to focus on revenue growth.** It happened with casinos and airlines, but not this pervasively across all companies, and not for this long.

Energy sector free cash flow

US\$ billions



Source: Bloomberg. Q1 2020.

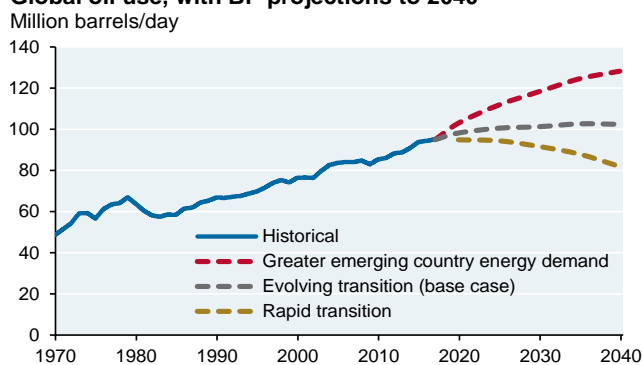
Industry Group	Years of consecutive negative free cash flow
S&P 1500 Oil and Gas E&P	13 (2006 - 2018)
Shale industry (29 stocks)	12 (2008 - 2019)
S&P 1500 Airlines	9 (1999 - 2007)
S&P 1500 Automobile manufacturers	4 (2005 - 2008)
S&P 1500 Casinos & Gaming	3 (1996 - 1998)

Source: Bloomberg, Factset. JPMAM. 2019.



Which argument is the right one? It may come down to what happens to oil demand. Projections of peak oil demand incorporate population growth, changes in energy intensity, changes in the energy mix and penetration of electric vehicles. In BP’s “evolving transition” estimates, global oil consumption persists at current levels until 2040. This scenario assumes that oil consumption rises due to increased prosperity in emerging countries, and is offset by policy changes that improve energy efficiency and boost EV penetration to 15% globally²⁹. **If this view turns out to be right, 2020 would be too soon for the “stranded asset” theory to be the primary driver of oil & gas stock prices; poor industry cash flow and the supply glut would be equally sensible explanations for oil & gas underperformance.**

Global oil use, with BP projections to 2040



Source: BP Energy Outlook. 2019.

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.

What could substantiate the stranded asset theory? The IEA models a “Sustainable Development” Scenario (see footnote 19 on page 23 for details) which entails a large decline in primary energy use, and substantial increases in renewable energy growth, electric vehicle penetration and energy efficiency. This scenario is designed to limit global warming to 1.8° C relative to the pre-industrial era; energy-related CO₂ emissions are assumed to peak immediately and fall to zero by 2070. **If the world jumps onto this trajectory, stranded oil & gas asset risks would be substantial.** As shown in the bottom table, large portions of current oil, gas and coal proven reserves³⁰ would be stranded in this scenario. In contrast, under the “Stated Policies” Scenario³¹, cumulative oil and gas extraction by 2070 is estimated to be *greater* than current proven reserves, so no oil & gas assets would be stranded at all. Only coal reserves still end up being stranded in this case, an outcome which markets are pricing in already.

²⁹ There are well-known investors who apparently agree with this thesis: **Berkshire Hathaway** is investing \$10 billion in Occidental Petroleum to facilitate its acquisition of Anadarko.

³⁰ While **proven reserves** are generally estimated by incorporating the commercial viability of extracting them, JP Morgan European Equity Research applied higher return thresholds and distinctions on carbon density, and estimated that proven reserves could be roughly half of the BP estimates shown above.

³¹ The IEA **Stated Policies** case is not a standstill scenario, and includes current policy intentions and targets that have already been announced.



[5] Maiming the Swamp: Trump and the Environment

White boxes implemented as of January 2020, shaded boxes pending

Elimination of methane reporting requirements for oil & gas companies	Rescinded water pollution regulations for fracking on Federal lands	Rejection of proposed ban on pesticides linked to developmental problems in children
Partial removal of methane flaring limits on public lands	Scrapped rule requiring mining companies to prove ability to finance clean-up costs	Reversed rule requiring braking system upgrades to trains hauling flammable liquids
Transfer of emissions regulatory control from Federal Govt to State Agencies	Reduced importance of GHG emissions in FERC pipeline environmental reviews	Ended OSHA program designed to reduce risks of lung disease from silicosis
Revoked right of California to set its own vehicle emissions limits	Lifted ban on oil and gas drilling in Arctic National Wildlife Refuge	Relaxation of rules aimed to improve safety at hazardous chemical plants
Loosening of rules regarding toxic emissions from industrial polluters	Loosened offshore drilling regulations including reduced testing requirement for blowout prevention	Scaled back pollution protections for tributaries and wetlands
Loosened rules regarding oil refinery monitoring of benzene and other pollutants	Lift freeze on coal leases on public lands	Revoked rule preventing mining companies from dumping debris into local streams
No more enforcement of rules on hydrofluorocarbon emissions from air conditioners and refrigerators	Streamlined approval process for oil & gas drilling in national forests	Withdrew proposed rule to reduce pollution from sewage treatment plants
Directed agencies to no longer report social cost of carbon	Open marine protected areas in Atlantic and Pacific Oceans to commercial fishing	Exempt certain power plants from rules limiting toxic discharge into local waterways
Revoked prior Executive Order to reduce Federal Govt GHG emissions	Revoked flood standards for Federal infrastructure projects	Extend lifespan of unlined coal ash basins leaking contaminants into groundwater
Relaxation of rules requiring repair of oil & gas methane leaks	Revoked directive that Federal agencies minimize impact on water and wildlife when approving development projects	Double time allowed for removal of lead pipes from high lead water systems
Weaker fuel economy standards for cars and light trucks	Elimination of climate and conservation policies at Dept of Interior	Scrapped rules requiring a doubling of energy efficient light bulbs
Eminate requirement for new coal plants to capture GHG emissions	Weakening of Endangered Species Act	Announced plan to stop funding UN program helping lower income countries to reduce GHG emissions
Weaker rules regarding coal plant mercury emissions	Relaxation of fishing season length and catch rate rules	Limit EPA studies that rely on confidential patient data that cannot be made public
Limits on community challenges to EPA-issued pollution permits	Relaxation of salmon protections to free up water for farmers	Relax standards requiring more energy efficient residential furnaces and commercial water heaters

Sources: Harvard Law School Environmental Regulation Rollback Tracker, Columbia Law School Climate Deregulation Tracker, Brookings Institution, Federal Register, Environmental Protection Agency, Interior Department, US Chamber of Commerce, NY Times, J.P. Morgan Asset Management. January 2020.



Appendix Table: key electricity and primary energy statistics by country/region

Electricity

Region	Primary energy used for electricity (quad. BTUs)	Electricity consumed ¹ (quad. BTUs)	Electricity share of primary energy	Electricity share of consumed energy	Renewable share of primary energy used for electricity
World	248.4	80.3	13%	18%	31%
US	37.7	12.9	13%	17%	18%
OECD	99.0	33.5	13%	18%	33%
OECD Europe	34.5	11.5	14%	19%	47%
Japan	8.5	3.2	16%	21%	24%
Canada	6.5	1.8	12%	16%	75%
Non OECD	149.4	46.9	12%	17%	30%
China	72.7	23.2	15%	23%	31%
India	15.4	4.4	12%	18%	22%
Brazil	6.1	1.9	11%	15%	88%
Mid East	9.2	3.3	9%	11%	9%
Russia	11.3	3.1	10%	13%	18%

Primary and delivered energy

Region	Total primary energy (quad. BTUs)	Total consumed energy ¹ (quad. BTUs)	Consumed energy: industrial sector (quad. BTUs)	Consumed energy: transport sector (quad. BTUs)	Renewable share of consumed energy ²
World	627.0	453.5	238.7	122.4	11%
US	99.9	75.1	26.4	28.2	7%
OECD	249.8	183.8	75.2	60.1	10%
OECD Europe	83.7	59.4	22.6	18.9	14%
Japan	19.9	15.2	7.7	3.3	9%
Canada	15.9	11.4	6.2	2.8	16%
Non OECD	377.2	269.7	163.4	62.4	11%
China	152.7	101.5	70.6	15.5	10%
India	36.2	25.0	16.3	4.9	14%
Brazil	16.6	12.5	6.7	4.3	36%
Mid East	38.2	31.1	17.7	7.9	1%
Russia	31.6	23.3	13.3	4.8	3%

Fossil fuels

Region	Fossil fuel share of elec. generation	Fossil fuel share of primary energy	% of fossil fuels used for electricity
World	57%	80%	29%
US	60%	82%	27%
OECD	47%	76%	24%
OECD Europe	29%	68%	18%
Japan	70%	84%	36%
Canada	11%	61%	7%
Non OECD	65%	82%	31%
China	65%	81%	38%
India	75%	82%	39%
Brazil	9%	50%	7%
Mid East	90%	97%	22%
Russia	62%	86%	26%

Source: JPMAM, US Energy Information Agency "International Energy Outlook", 2019.

- Consumed energy is equal to primary energy consumption net of thermal conversion losses in power plants, power plant energy consumption and transmission losses
- Includes renewable share of electricity generation, plus renewable energy directly used by industrial, transportation and building sectors



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