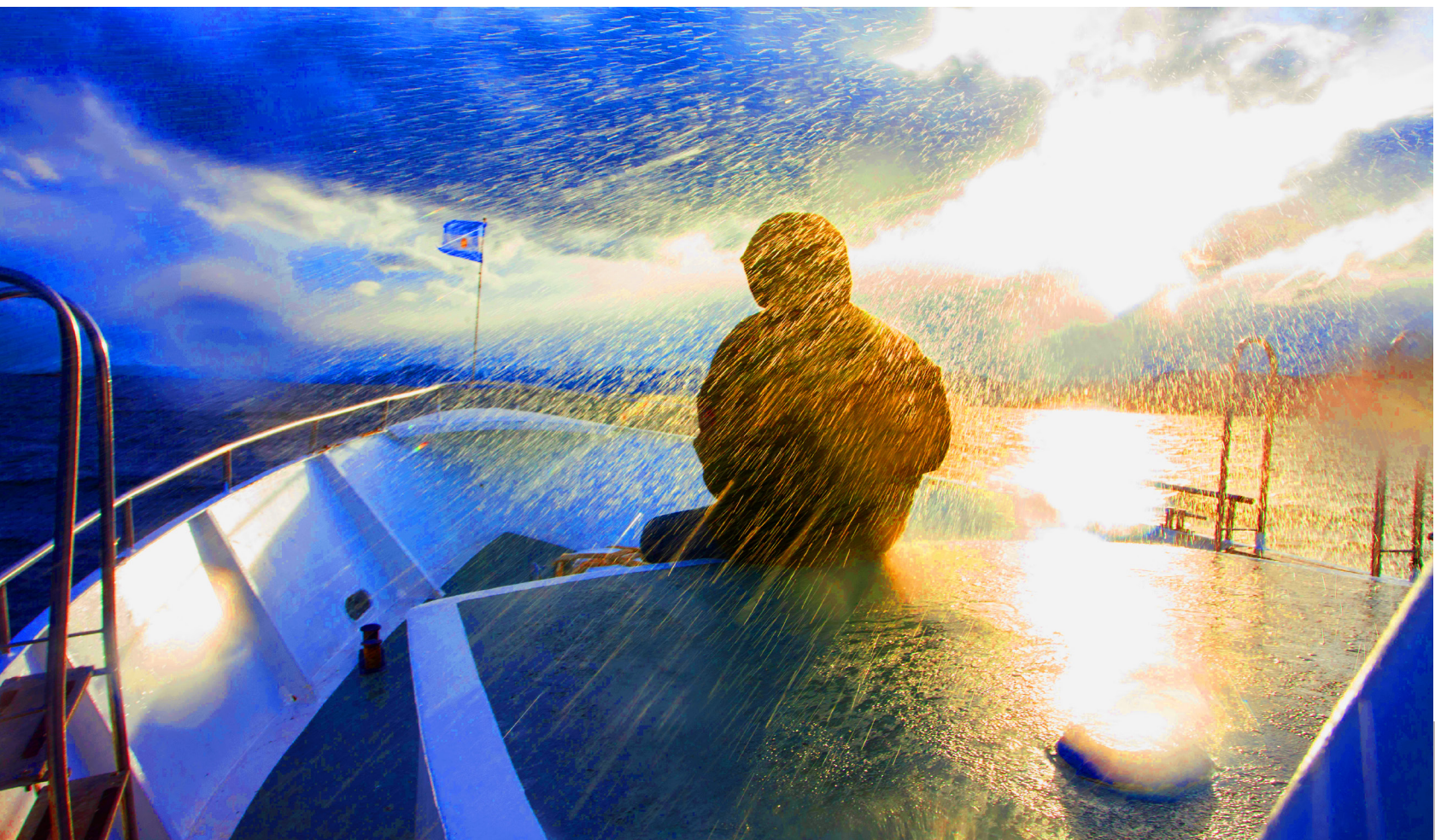


EYE ON THE MARKET • ENERGY OUTLOOK 2018

Pascal's Wager

J.P. MORGAN PRIVATE BANK



Pascal's Wager argues that belief makes more sense than disbelief when the worst outcome is a total loss. If so, supporting renewable energy makes sense even without knowing the true impact of greenhouse gas emissions on sea levels. However, energy transitions are gradual rather than sudden, defying the expectations of futurists. This year, we examine some timely examples: why climate goals can't be reached by simply decarbonizing electricity with wind and solar power; why natural gas will still be the fuel of the 21st century; the wide range of electric vehicle forecasts after last decade's misfires; the high-voltage transmission bottleneck in the U.S.; and how a group of academics thoroughly dismantled one peer's highly publicized and dreamlike vision of a renewable energy future. As a result, we also look at sea level rise, coastal exposures and flood mitigation infrastructure, which might be needed just in case. We conclude with the intersection between food, energy, urbanization and proposed changes to the U.S. Electoral College.

J.P.Morgan



First, a comment on Trumpism and markets. For investors, Trumpism looks like a combination of Ronald Reagan (deregulation, tax cuts), GW Bush (large fiscal deficits, conservative court appointments), Andrew Jackson (loyalty-based political patronage, laissez-faire economics), Herbert Hoover (protectionist tariffs, deportation of undocumented immigrants via the Mexican Repatriation of the early 1930's) and John F. Kennedy (singling out companies for attack as JFK did to US Steel in 1962, triggering a collapse in investor confidence and a 20% bear market). Other aspects of Trumpism, such as a first-year turnover rate of senior officials equal to the turnover rate of the prior four Presidents combined, have no modern parallel. For more details, please see this accompanying [brief note](#).

The market-friendly aspects of Trumpism were delivered in 2017; this year, investors have to deal with the rest. The US corporate sector is in good shape when looking at strong profits growth, high profit margins and rising stock buybacks, but falling valuations justifiably reflect concerns about what comes next from the White House, as well as a Fed that may double the Fed Funds rate to 3.5% by the end of 2019. I still expect positive single digit equity returns this year as offsetting forces work their way through markets, but the range of uncertainty around that figure has widened a lot over the last month.

For the last seven years, we have written an annual **energy paper** that covers 5 topics of interest to us and to many of our clients. Vaclav Smil at the University of Manitoba has served as our technical advisor since its inception, and his insights and guidance have been invaluable to us. This year, our topics include examples of how energy transitions are gradual rather than sudden, defying the expectations of futurists:

- Why climate goals can't be reached by simply decarbonizing electricity with wind and solar power
- Why natural gas will still be the fuel of the 21st century
- The wide range of electric vehicle forecasts after last decade's misfire
- The high voltage transmission bottleneck in the US
- How a dream team of researchers thoroughly dismantled Mark Jacobson's highly publicized vision of a 100% renewable grid

As a result, we also look at sea level rise, coastal exposures and flood mitigation infrastructure, which might be needed just in case. We conclude with the **US Electoral College**, which is under siege again, but best left just the way it is for reasons related to food, energy, urbanization and national security.

Michael Cembalest
JP Morgan Asset Management



Pascal's Wager

Executive Summary

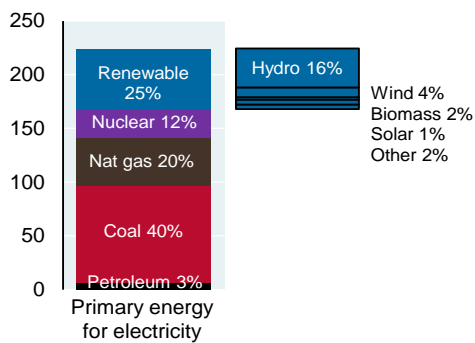
Impressive wind and solar power milestones have been reached in the last few years: ongoing declines in capital costs, power auction prices well below 10 cents per kWh, rising wind capacity factors and rising capacity additions which in 2016 exceeded non-renewable new capacity for the 4th year in a row. These trends, shown in chart form on page 7, are the by-product of scale, innovation and plenty of subsidies.

There's a "but", and it's a fairly big one: electricity **is less than 20%** of global energy consumption. Unless progress is made reducing fossil fuel use by industry and transport, decarbonization goals might not be met in timeframes often cited. If so, outcomes argue for more flood mitigation investment, and a greater appreciation of the critical role that natural gas will play over the next century. Let's take a look.

The first chart shows **primary energy** used to generate electricity, measured in "quads" (quadrillion BTUs). In 2017, the renewable share reached 25%. Hydroelectric power accounted for 16%; wind and solar combined accounted for 5%, up from 0.5% in 2004.

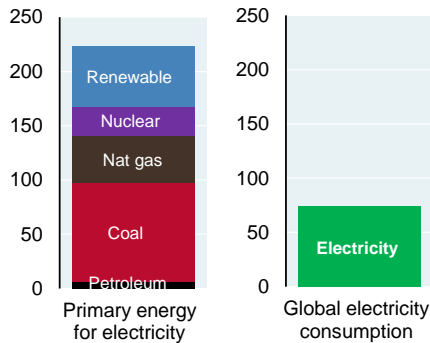
The second chart shows **how electricity gets generated**: 225 quads of primary energy are required to generate 75 quads of electricity. Where did the rest go? 150 quads are lost to thermal conversion¹, power plant consumption and transmission.

Primary energy for electricity: 25% renewable, mostly from hydropower with growing shares from wind...
quadrillion BTU, global



Source: Energy Information Administration, IEA, JPMAM. 2017.

...thermal conversion and transmission losses reduce end-user electricity to 1/3 of its primary energy inputs...
quadrillion BTU, global



Source: Energy Information Administration, JPMAM. 2017.

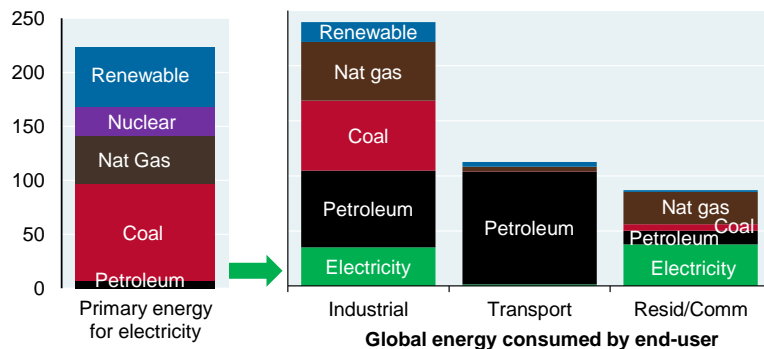
¹ **Thermal conversion** losses vary by technology and age. Most US coal plants have thermal efficiency rates of 32%-38%, while natural gas combined cycle power plant efficiency rates are closer to 50%, with record ratings of about 60% for the latest additions. Of the factors mentioned above, thermal conversion is by far the biggest source of energy loss, accounting for 90% of the gap between primary energy and electricity consumed.



While fossil fuels are used to generate electricity, they're also used to power combustion engines, for heating/smelting and as raw materials. In the third chart, we break down global energy consumption into the three major users of energy (industry, transportation and residential/commercial), and their energy sources. **The charts below highlight the limits of decarbonization via electricity alone:**

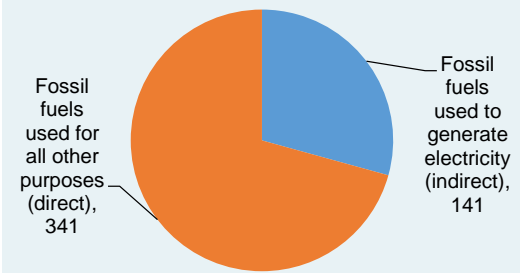
- Electricity is only 17% of global final energy consumption, and is consumed almost entirely by industrial and residential/commercial users (a very small amount is used by electrified rail)
- Electricity accounts for less than one third of global fossil fuel use
- While coal usage still exceeds natural gas, coal displacement by gas is one of the most important emission reduction trends of the 21st century, assuming methane leakage rates below ~3%²
- The industrial sector is the largest user of energy and is heavily reliant on direct fossil fuels use (for reasons we discuss on page 5), and transportation is almost 100% reliant on petroleum products

...at which point electricity only represents 17% of total energy consumed, the remainder being direct energy use
quadrillion BTU, global



Source: Energy Information Administration, JPMAM. 2017.

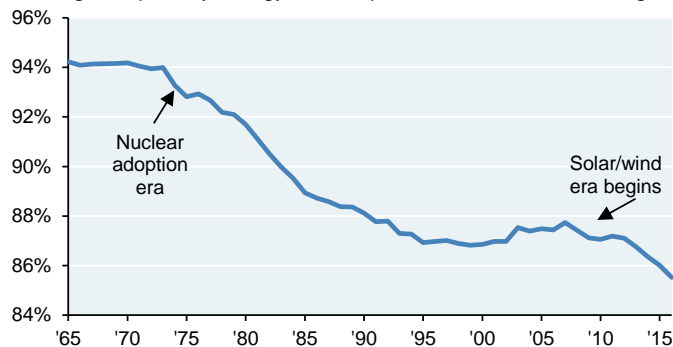
Electricity accounts for less than one third of global fossil fuel consumption
quadrillion BTU, global



Source: EIA, IEA, JPMAM. 2017.

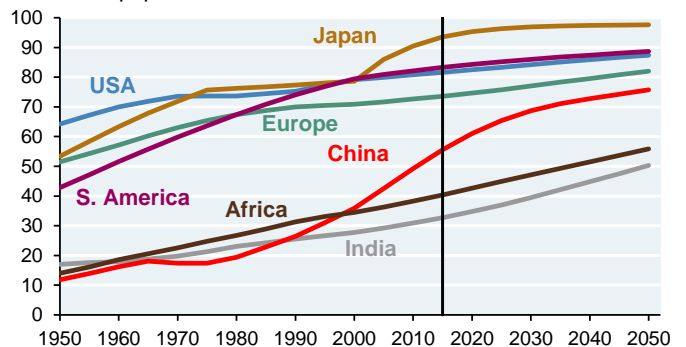
- Fossil fuels accounted for ~85% of global primary energy consumed³ in 2016. That figure is now gradually declining with the onset of the solar/wind era
- Energy solutions need to be designed for increasingly urbanized societies, rendering discussions about so-called "off-the-grid" approaches even less relevant

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. 2016.

Living for the city: global urbanization trends
% of total population



Source: World Bank World Development Indicators. 2015, forecast to 2050.

² "The environmental case for natural gas", International Energy Agency, November 2017

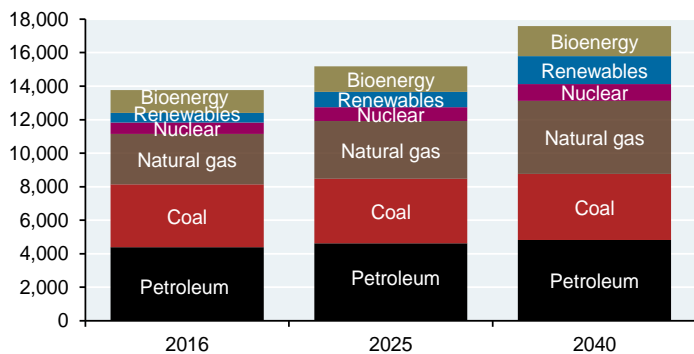
³ The BP chart excludes "traditional biomass", which refers to wood, charcoal and straw used for heat. If these energy sources were included as renewable, the fossil fuel figure would drop to ~78%. However, as explained in the note on the bottom of page 4, traditional biomass isn't really "renewable" in the modern sense of the word.



Where does that leave us? Even if renewable sources rose to 50% of electricity generation from 25%, fossil fuels could still represent ~70% of total energy use unless transport and industry decarbonize as well. On transportation, the International Energy Agency has one of the most optimistic electric vehicle forecasts we've seen (see page 10). However, its New Policies Scenario for 2040 **does not show substantial decarbonization of global energy use**. In their scenario, while coal use plateaus and renewable energy doubles, **natural gas meets most of the world's growing energy demand**. Petroleum doesn't decline either, despite the anticipated rise of EVs. When including bioenergy⁴, the renewable share expands from 14% in 2016 to just 20% by 2040. While CO₂ emissions grow more slowly in this scenario, they still increase vs current levels.

IEA: Renewables at 20% of primary energy by 2040

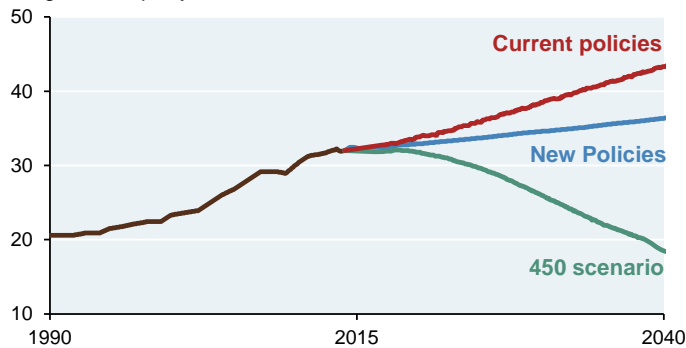
Global primary energy use by source, mm tonnes of oil equivalents



Source: International Energy Agency New Policies Scenario. 2017.

Global CO₂ emissions from primary energy demand

Gigatonnes per year



Source: International Energy Agency. 2016.

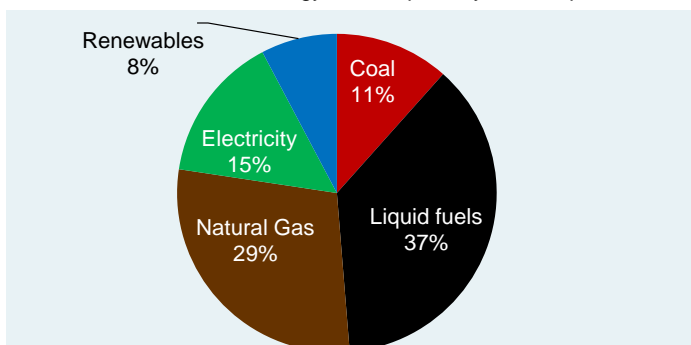
⁴ **The bioenergy question.** Bioenergy currently provides 10% of the world's primary energy. It may sound "green", but around 2/3 of bioenergy is consumed in developing countries for cooking and heating, using open fires or cookstoves with considerable negative impact on health (smoke pollution) and environment (deforestation). The remainder represents modern bioenergy used for heat, and smaller amounts used for transportation and electricity. Even modern forms of biomass energy are not as green as you might think, as we covered in last year's paper. **So, most current bioenergy practices are quite different from hydro, wind and solar. Including bioenergy as "renewable" is not straightforward, which is why we break it out.**



The industrial sector and the slow pace of decarbonization

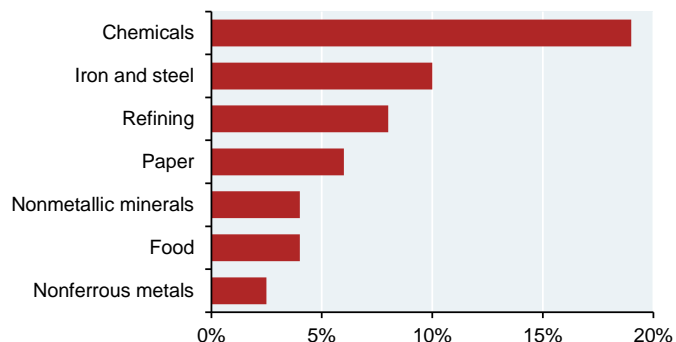
Only 15% of OECD industrial energy use is derived from electricity; the rest is mostly direct consumption of fossil fuels. What does the industrial sector do with all these fossil fuels? The bar chart and tables show examples: oil refining and the manufacture of chemicals, iron, steel, paper and food form the backbone of modern society. These processes are hard to decarbonize as they require two things: **fossil fuels for raw materials, and also for process heat at sustained high temperatures.** While in principle electricity *could* provide some of the latter, there has been only modest progress to-date.

Industrial sector: electricity only 15% of energy use
OECD industrial sector energy consumption by source, percent



Source: Energy Information Administration. 2016.

OECD industrial sector energy consumption by product
% of total



Source: Energy Information Administration. 2016.

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 and beverage industries |
| Smelting of iron ores in blast furnaces |



That's why **Pascal's Wager** comes to mind. According to the French philosopher, if you believe in God and he does not exist, you experience a "finite loss". But if you do *not* believe in God and he *does* exist, you experience "infinite loss". Consider the following theories:

- Greenhouse gas emissions impact temperatures, which in turn impact sea level rise
- Efforts to substantially decarbonize via wind and solar power will fall short of climate-related goals

Maybe that's right, and maybe it isn't. However, the **infinite** loss case (you don't believe but the theories are true) is much worse than the **finite** loss case (theories are wrong but you prepare anyway). As a result, after looking at electric vehicles and other renewable energy topics this year, we also examine flood mitigation projects in coastal cities, which may be needed just in case. We conclude with thoughts on the intersection between food, energy, urbanization and proposed changes to the US Electoral College: maybe drafters of the US Constitution had more foresight than they're being given credit for.

Table of Contents

| | |
|---|------------------------------------|
| Comments from our technical advisor Vaclav Smil, and links to prior years' topics | Page 8 |
| [1] Electric vehicles: a 2% or a 20% solution? | <u>Pages 9-15</u> |
| Projections of electric vehicle penetration are soaring as policymakers and manufacturers prepare for the EV revolution. But will EVs be a 2% or 20% solution by 2030? Also: a look at the payback period for a hypothetical Tesla semi EV truck | |
| [2] High voltage direct current lines: China leads, US lags | <u>Pages 16-18</u> |
| While China invests in high voltage direct current lines to facilitate greater penetration of renewable energy, US progress is slower due to legal, environmental and financial obstacles | |
| [3] Renewable Rap Battle: a scathing critique of a widely publicized energy solution | <u>Pages 19-22</u> |
| Stanford's Mark Jacobson argues for a grid entirely powered by wind, solar and hydro, a proposal which has gotten a lot of publicity. However, in a sharply worded rebuttal, a team of researchers analyzed Jacobson's proposal and thoroughly dismantled it, finding it to be riddled with implausible assumptions. An important lesson for laypeople regarding the visions of futurists and the binding constraints of the real world | |
| [4] Better safe than sorry: sea level rise, coastal exposure and flood mitigation | <u>Pages 23-28</u> |
| The latest projections of sea level rise, assessments of coastal exposure and the mechanics and cost of flood mitigation infrastructure, including in lower Manhattan | |
| [5] Maybe the Constitutional framers were right: who feeds and powers an increasingly urbanized world? | <u>Pages 29-32</u> |
| Once again the US Electoral College is under siege; the connection between food, energy, national security and urbanization suggest that it's best left just the way it is | |
| Sources and acronyms | <u>Pages 33-34</u> |



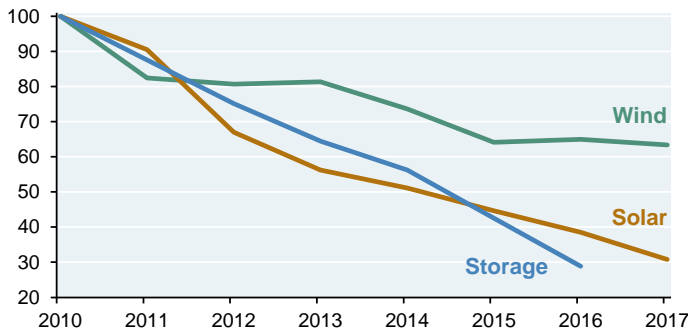
Executive Summary supplementary materials: renewable energy milestones

The last few years have seen impressive declines in the capital cost of solar power, energy storage and to a lesser extent, wind. The impact of these changes can be seen in several ways:

- wind and solar reaching 5% of global electricity generation in 2017 (up from 0.5% in 2004), alongside 16% from hydropower
- wind and solar power auction prices converging below \$100 per MWh (10 cents per kWh); the latest US leveled wind power purchase agreements have reached 2 cents per kWh according to the DoE
- continued growth in US and global renewable energy capacity additions, which in 2013-2016 exceeded non-renewable capacity additions
- increases in US wind capacity factors by vintage year, which reflect larger rotor diameters, higher hub heights and locations with better wind speeds

Declining upfront capital costs of wind, solar & storage

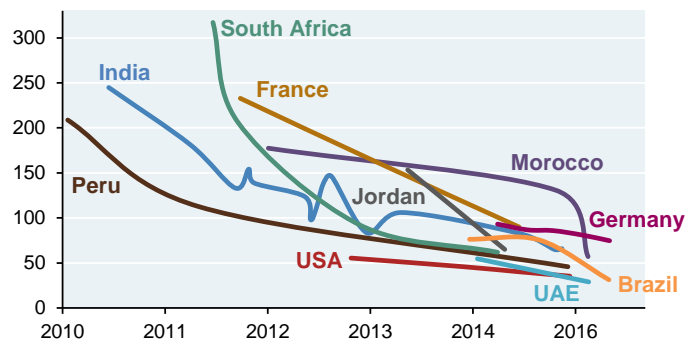
Index of upfront capital costs, 2010 estimates = 100



Source: EIA, NREL, Lazard, UBS, Nykvist, et. al. December 2017. Storage proxied by electric vehicle battery packs.

Global solar auction prices converging below \$100/MWh

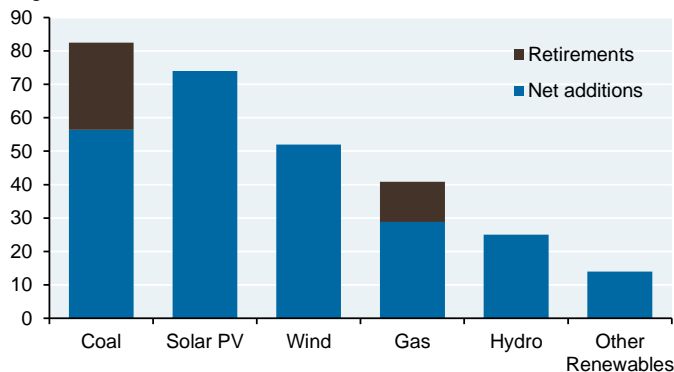
US\$/MWh



Source: International Renewable Energy Agency. 2017.

2016 Global electricity capacity additions by fuel

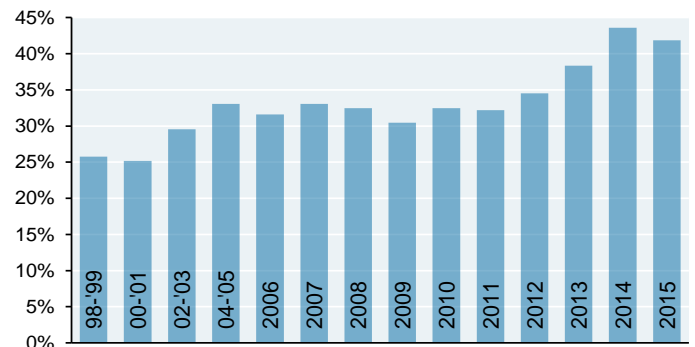
Gigawatts



Source: IEA, Renewable Energy Policy Network, 2016.

US wind capacity factors by project vintage year

%



Source: Department of Energy, Berkeley National Laboratory. 2016.



Why all the focus on decarbonization?

I asked Vaclav to articulate for our clients why decarbonization is an important initiative. His response is useful context for both those who are convinced by consensus views on climate science, and also for those who are still on the fence:

“Underlying all of the recent moves toward renewable energy is the conviction that such a transition should be accelerated in order to avoid some of the worst consequences of rapid anthropogenic global warming. Combustion of fossil fuels is the single largest contributor to man-made emissions of CO₂ which, in turn, is the most important greenhouse gas released by human activities. While our computer models are not good enough to offer reliable predictions of many possible environmental, health, economic and political effects of global warming by 2050 (and even less so by 2100), we know that energy transitions are inherently protracted affairs and hence, acting as risk minimizers, we should proceed with the decarbonization of our overwhelmingly carbon-based electricity supply – but we must also appraise the real costs of this shift. This report is a small contribution toward that goal.”

Acknowledgements: our technical advisor Vaclav Smil

As always, our energy *Eye on the Market* was overseen by **Vaclav Smil**, Distinguished Professor Emeritus in the Faculty of Environment at the University of Manitoba and a Fellow of the Royal Society of Canada. His inter-disciplinary research includes studies of energy systems (resources, conversions, and impacts), 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 40 books (the latest ones, *Energy Transitions* and *Energy and Civilization* were published last year) and more than 400 papers on these subjects and has lectured widely 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, and is described by Bill Gates as his favorite author.

Select topics from prior *Eye on the Market* energy editions (hyperlinks)

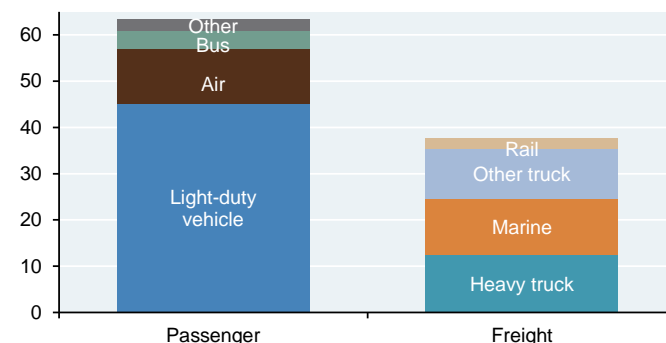
- [Cost/emissions tradeoffs of high-renewable grids \(2017\)](#)
- [Hydraulic fracturing \(2017\)](#)
- [Forest biomass \(2017\)](#)
- [College campus energy use \(2017\)](#)
- [Distributed solar power and billing changes \(2016\)](#)
- [US hydropower capacity \(2016\)](#)
- [Nuclear power \(2014 and 2015\)](#)



[1] Electric vehicles: a 2% or a 20% solution?

While the share of renewable power generation has grown tenfold since 2004, the world still uses fossil fuels for 85% of its primary energy. Without displacement of direct fossil fuel use in transportation and industry, climate goals may not be reached within desired timeframes. Since road transportation accounts for 50% of global oil consumption, a key component of decarbonization is the speed of electric vehicle (EV) adoption. Forecasters are now jockeying for position with geometric projections. However, the transition to EVs is likely to be gradual, once again confounding the expectations of futurists.

World transportation energy consumption by mode
Quadrillion Btu



Source: Energy Information Administration. 2016.

| Global consumption of oil products | mtoe* | % of total |
|------------------------------------|-------|------------|
| Road transportation | 1,823 | 50% |
| Feedstocks | 588 | 16% |
| Other transportation (air, marine) | 539 | 15% |
| Heating | 313 | 8% |
| Industry | 303 | 8% |
| Agriculture | 116 | 3% |

Source: IEA Statistics, 2015. Mtoe = million tons of oil equivalents

Let's start with public policy and manufacturer goals. The table on the left shows countries that have announced dates by which internal combustion engine (ICE) sales are banned, and countries with less binding EV sales targets. Automakers have announced EV sales targets as well.

Government policy goals

| Country | Announced goal for vehicle sales | 2017 light vehicle sales (MM) |
|-------------|--|-------------------------------|
| China | ICE ban pending; cap-trade policy targets EV sales of 5% by 2020 | 28.3 |
| U.S. | No stated goal | 17.2 |
| Japan | EVs 30% of sales by 2030 | 5.1 |
| Germany | End ICE sales by 2030 | 3.7 |
| India | End ICE sales by 2030 | 3.2 |
| U.K. | End ICE sales by 2040 | 2.9 |
| France | End ICE sales by 2040 | 2.5 |
| Brazil | EVs 30% of sales by 2030 | 2.2 |
| Italy | EVs 30% of sales by 2030 | 2.1 |
| Canada | EVs 30% of sales by 2030 | 2.0 |
| South Korea | EVs 30% of sales by 2030 | 1.8 |
| Mexico | EVs 30% of sales by 2030 | 1.5 |
| Netherlands | End ICE sales by 2025 | 0.5 |
| Norway | End ICE sales by 2025 | 0.2 |

Source: IEA Global EV Outlook, Vox, Clean Energy Ministerial, Focus2move. 2018.

Company policy goals

| Company | Announced electric car ambitions | 2016 light vehicle prod. (MM) |
|----------------|-------------------------------------|-------------------------------|
| Chinese OEMs | 4.5mm annual EV sales by 2020 | 11.9 |
| Toyota | 5.5mm annual EV sales by 2030 | 10.2 |
| Volkswagen | 2-3mm annual EV sales by 2025 | 10.1 |
| Renault-Nissan | 1.5mm cumulative EV sales 2020 | 8.9 |
| Hyundai | 38 new electric models by 2035 | 7.9 |
| GM | 1mm annual EV sales by 2026 | 7.8 |
| Ford | 40 new electric models by 2022 | 6.4 |
| Honda | 2/3 of 2030 sales to be EVs | 5.0 |
| Fiat-Chrysler | No stated goal | 4.7 |
| Daimler | 0.1mm annual EV sales by 2020 | 2.5 |
| BMW | 15-25% of BMW group sales by 2025 | 2.4 |
| Volvo | 100% EV sales by ~2024 | 0.5 |
| Tesla | 0.5mm EV sales by 2018, 1mm by 2020 | 0.1 |

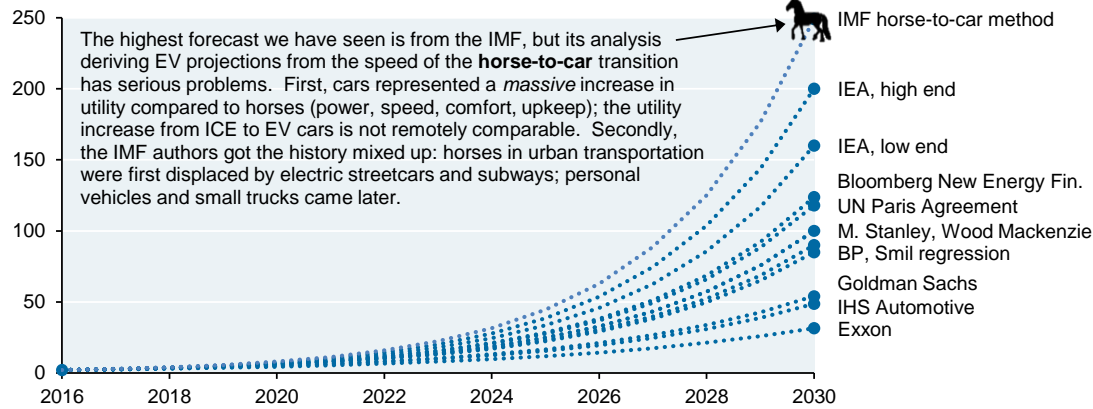
Source: IEA Global EV Outlook, OICA, Reuters, NYT, Bloomberg, listed companies. 2018.



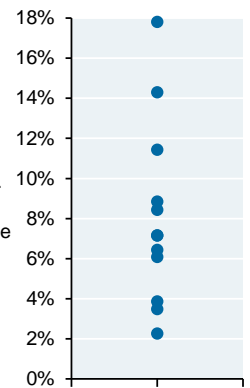
How fast? Governmental agencies, economists, research analysts and futurists have all chimed in with EV projections. As shown below, there's a very wide range of projections for the global EV fleet size by the year 2030⁵. Assuming a global fleet of 1.4 billion cars in 2030 (up from ~1 billion today), the projections range from 2% to 20% of the future projected fleet⁶. In most cases, these projections continue growing at a rapid pace to 2040 and beyond.

Electric vehicle projections for the year 2030: from 2% to 20% of the global fleet

Global fleet size, million EVs



2030 EV penetration
% of global fleet size

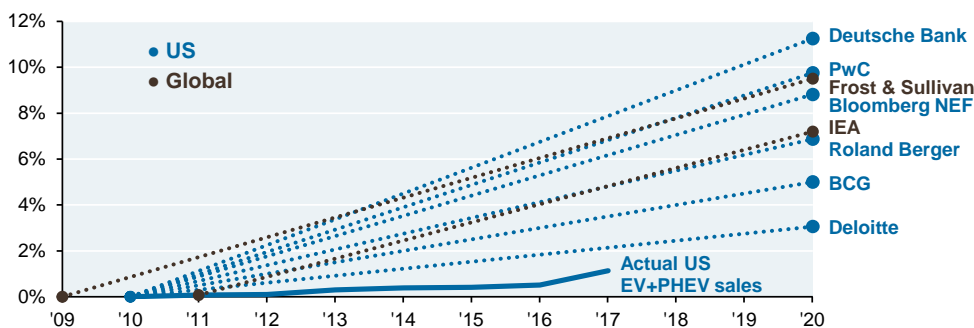


Sources: IEA, IHS, BNEF, MS, GS, UN, Wood Mackenzie, BP, Smil, Exxon, IMF. 2018.

When looking at these projections, it's worth recalling the **overly optimistic EV projections made by some of the same forecasters a decade ago** (see below). Yes, these forecasts took place before the decline in lithium ion battery prices, before subsidies for EV buyers and before government targets were established. However, they're still useful as a reminder that many forecasters vote with their hearts instead of their minds, and often don't incorporate real-life barriers to product displacement. Cars are not smartphones: they have higher upfront and ongoing maintenance costs, complex supply chains, refueling requirements and higher standards for performance and safety. The EV revolution is now upon us, but the important question for investors is the pace. The median forecast is ~125 million EVs by 2030; I'm taking the "under" rather than the "over".

Prior generation of electric car projections out of sync with reality

EV+PHEV sales as % of total car sales



Source: DOE, BEA, hybridcars.com, and listed organizations. 2017. Note: global EV+PHEV sales in 2016 were also around 1.1%.

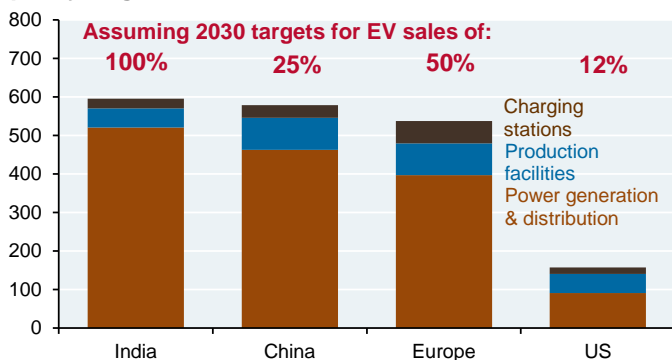
⁵ The World Economic Forum forecast is derived differently: by electrifying fleets, taxis and other public transport rather than personal vehicles (which are on the road less than 5% of the time), 35% of US vehicle miles travelled could be electrified by 2030, even though the vehicle stock might remain 85% internal combustion engine cars.

⁶ We assumed a lower growth rate (2.8%) for light vehicles to 2030 compared to the historical 2005-2015 growth rate (3.8%) given the potential impact of more efficiently used autonomous cars.



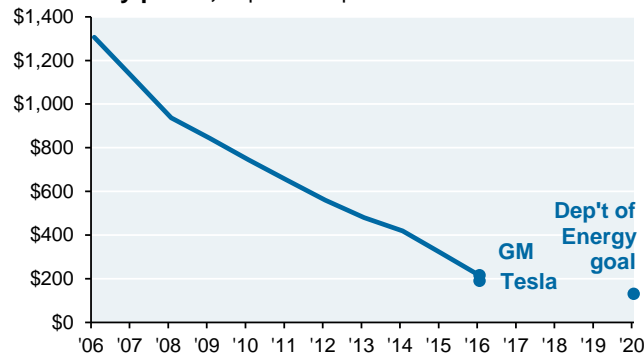
Why might the EV revolution occur at slower speeds rather than faster ones? First, related infrastructure needs are not just charging stations and production factories. Large power generation and transmission investments would be needed as well. According to one analysis we have seen, India, China and Europe would face a combined \$1.7 trillion in required capital investment. These are imprecise estimates, but could be quite large and require tough decisions in aging societies with growing unfunded pension and healthcare costs.

Total investment required through 2030 to meet EV policy targets, US\$ billions, cumulative



Source: Bridgewater Associates. February 2018.

Lithium ion energy storage costs: EV battery packs, capital cost per kWh



Source: Nykvist, et. al, Albertus et al. January 2018.

Another challenge: how far can lithium ion battery costs fall? There has been a sharp decline in the capital cost of lithium ion battery packs over the last decade to around \$200 per kWh. The US Department of Energy has a stated goal of \$100 per kWh on a cell basis (around \$130 for the pack) in the next few years, a level often cited as the point at which mass-marketed EVs could reach parity with some ICE vehicles. However, in a January 2018 paper, ARPA researchers concluded that the DoE target could be hard to reach using current battery design⁷. While they outline manufacturing processes and materials that might reduce costs, these approaches do not yet meet required performance standards. This DoE table compares current and future possible technologies:

Vehicle energy storage technology overview

Current technology: lithium ion battery (graphite/NMC)

| | |
|--------------------|---|
| Current cost | \$235 / kWh |
| Potential cost | \$100-\$160 / kWh |
| Current cycle life | 1000-5000 |
| R&D needs | High voltage cathode/electrolyte; Lower cost electrode processing technology; Extreme fast charging |

Next generation technology: lithium ion battery based on silicon composite/high voltage NMC

| | |
|--------------------|--|
| Current cost | \$256 / kWh |
| Potential cost | \$90-\$125 / kWh |
| Current cycle life | 500-700 |
| R&D needs | High voltage cathode/electrolyte; Lower cost electrode processing technology; Extreme fast charging; Durable silicon anode |

Longer term: lithium metal

| | |
|--------------------|---|
| Current cost | \$320 / kWh |
| Potential cost | \$70-\$120 / kWh |
| Current cycle life | 50-100 |
| R&D needs | High voltage cathode; Lithium protection; High conductive solid electrolyte |

Source: "Electrochemical Energy Storage R&D Overview", US Department of Energy, D. Howell, 2017.

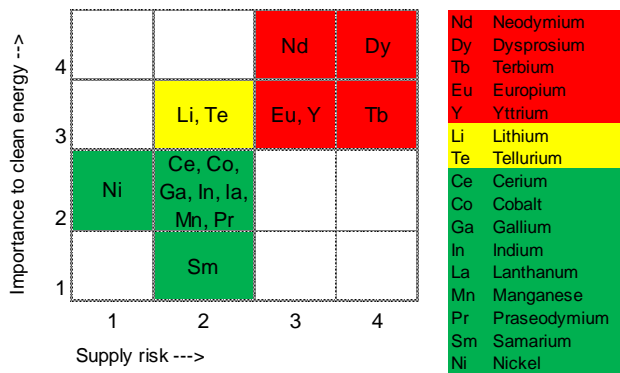
⁷ "Status and challenges in enabling the lithium metal electrode for high-energy and low-cost rechargeable batteries", Albertus et al (US Department of Energy Advanced Research Projects Agency), *Nature Energy*, Jan 2018.



What about **rare earth metals and other critical materials**? Most research we've seen projects that there will be enough lithium, graphite and other minerals to meet growing demand. It's a bit dated, but in 2011, the US Department of Energy published a report on critical materials supply and found that with the exception of dysprosium, neodymium and terbium, most did not present a medium term supply risk. In 2017, researchers from the University of Science and Technology in Beijing looked at the same question⁸, perhaps since China is the world's largest EV market. Here's what they found:

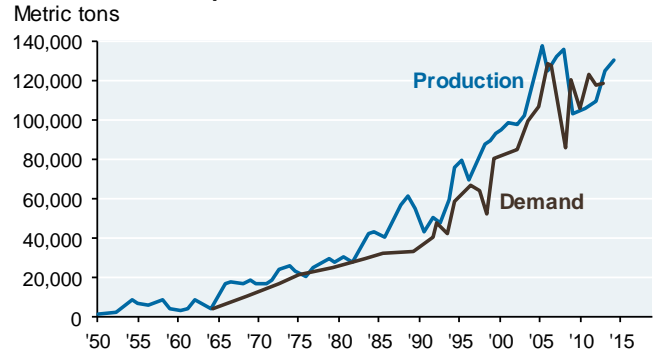
- Demand from electric vehicles is expected to reach 68% of all rare earth demand in 2030 (compared to 50% today)
- While current rare earth elements are mined primarily by China and Australia, there are 478 megatons of rare earth oxides widely distributed around the world which could sustain current global rare earth production for over 100 years
- However, the largest increases in demand are expected to be for **neodymium and dysprosium** (as in the 2011 DoE study), whose shortages could become an issue for supply chains

Medium Term Criticality Matrix



Source: US Department of Energy, 2011.

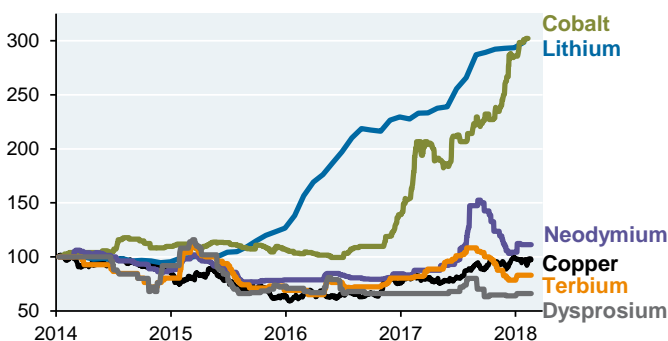
Global rare earth production and demand



Source: "Global Potential of Rare Earth Resources and Rare Earth Demand from Clean Technologies", Zhou, Li, Chen, October 2017.

EV battery metals prices

Index = January 2014



Source: Bloomberg. February 2018.

A brief comment on autonomous car energy use

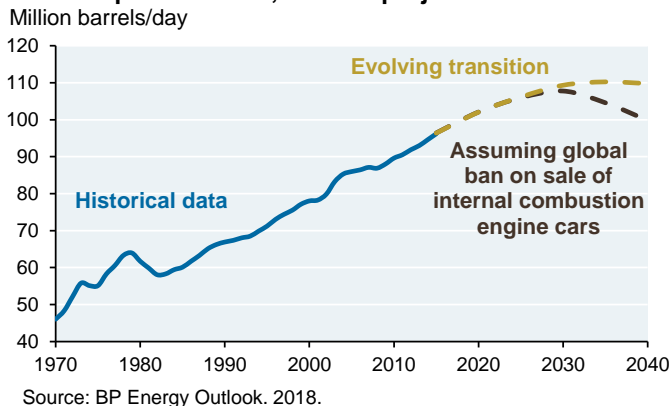
Researchers from the University of Michigan Center for Sustainable Systems looked at autonomous car energy use vs passenger-controlled EVs and ICE cars. For some vehicles, energy benefits from autonomous driving more than offset its incremental energy drag due to computing power needs, additional weight and vehicle drag. But for larger applications (e.g., Waymo installed in a minivan), autonomous car tests showed *higher* net energy use. We will keep an eye on this.

⁸ "Global Potential of Rare Earth Resources and Rare Earth Demand from Clean Technologies", Zhou, Li and Chen, University of Science and Technology in Beijing, *Minerals* magazine, October 2017.



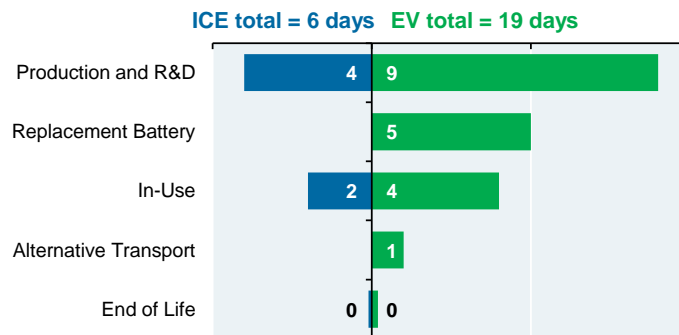
Bottom line: the EV revolution is here, and some manufacturers claim that break-even costs vs ICE vehicles are closing fast (see next page). But some EV forecasts seem too aggressive to us, given the challenges. As a result, we're inclined towards the lower half of the forecasts on page 10, and are dubious that EV demand will exert a material impact on oil prices in the next few years. The concept of **"peak oil extraction due to falling demand"** might exist, but (a) closer to 2030 rather than during this decade, and (b) be more likely if most of the world enacts an outright ban on the sale of ICE cars. As shown earlier, that's not happening, at least not yet. Changes in GDP growth, improvements in the efficiency of the internal combustion engine⁹ and the cost/regulation of hydraulic fracturing of shale oil are all likely to have a larger impact on oil prices than EVs for the foreseeable future.

Global liquid fuels use, with BP projections to 2040



"Days of life" impact for passenger ICE vs EV

Hypothetical days lost to death or disability due to toxicity



Source: "Battery Electric Vehicles vs. Internal Combustion Engine Vehicles", Arthur D Little, November 2016.

EV Appendix I: How green are electric cars?

Most lifecycle analyses agree that EVs reduce global warming risks. Electric motors using natural gas and renewable energy as indirect fuel are more carbon-efficient than ICE cars, reducing emissions by 25%-50%. [Note: in our 2016 energy paper, we showed [this chart](#) on the renewable percentage of the electricity grid by country and by US state].

However, environmental impacts are not limited to CO₂ emissions. The chart above from Arthur Little estimates the lifecycle environmental impact of ICEs vs EVs, measured as "days of life lost to toxicity". In this analysis, EV environmental impacts are 3x higher. The primary reason: freshwater and terrestrial exposure to copper, cobalt, nickel and graphite during the mining process. Even if the grid were fully renewable and EV "in-use" toxicity were zero, Arthur Little still estimates a higher environmental impact for EV cars. I doubt this will be a roadblock in the EV revolution, since such risks are borne mostly by countries which have shown less ability/interest to aggressively control them: the Philippines, Russia, the Congo, China, India, Brazil, Vietnam and Turkey. Arthur Little's analysis on EV toxicity draws from a widely cited 2013 paper in the *Journal of Industrial Ecology* from Anders Stromman at the Norwegian University of Science and Technology on EV supply chain eco-toxicity and eutrophication.

I'm not 100% sold on the relative aspect of Arthur Little's analysis, since it seems to underestimate toxicity risks from oil production and exploration, as well as from gasoline refining and distribution. One example: a 2016 paper from the Johns Hopkins School of Public Health measured hydrocarbon spills at gas stations, and found that regulations typically do not address subsurface contaminations from chronic gasoline spills, even though they could result in non-negligible exposure to toxic and carcinogenic compounds. Every lifecycle analysis has its own biases, and the Arthur Little version is no exception.

⁹ In its forecasts for 2040, BP estimates that oil displaced by ICE fuel efficiency gains will be **7x** larger than oil displaced by electric vehicles.



EV Appendix II: could Tesla produce an EV truck with a fast payback period?

Taxis, garbage trucks and semi trucks could be good candidates for conversion to electricity or natural gas if fuel savings offset higher upfront costs in a short period of time. Tesla claims that its new semi truck will do just this. However, our estimate of its payback period is longer than some recent forecasts.

The average short haul diesel truck costs \$120k, travels ~90,000 miles per year (~300 per working day and capable of traveling 1,000+), and lasts for around one million miles. Tesla announced two possible substitutes: an EV semi capable of travelling 500 miles per charge at a cost of \$180k, and a 300 mile version at \$150k. Tesla claims that its EV fuel efficiency will offset higher upfront costs in a short period of time. Some analysts agree, and we have seen estimates as low as a 2 year payback period.

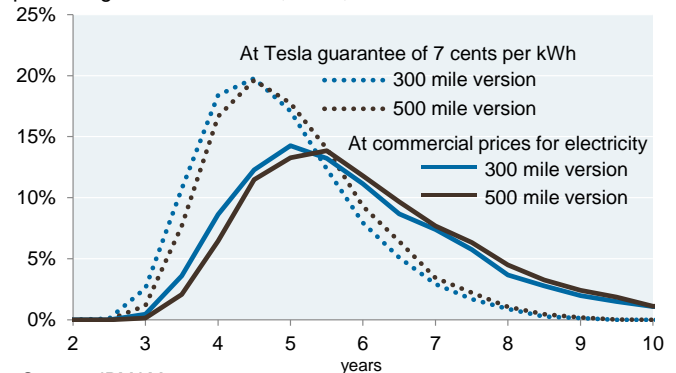
There's a lot that isn't known yet about Tesla's hypothetical truck; the table shows our estimates of factors that affect payback periods, and the chart shows our simulated results. **Our Tesla payback period estimates are higher than 2 years, and are similar for 300 mile and 500 mile versions.** One decision we had to make: what about Tesla's electricity price guarantee of 7 cents per kWh? This guarantee is available to drivers using Tesla's proprietary mega-charging stations (a network that doesn't exist yet), and relies on Tesla remaining a going concern. In any case, we modeled it both ways.

| Assumptions | Fixed | Min | Mean | Max | Units |
|---------------------------|--------|--------|--------|--------|-----------|
| Battery replacement | | \$115 | \$125 | \$135 | \$/kWh |
| Tesla fuel efficiency | | 1.80 | 2.00 | 2.40 | kWh/miles |
| Diesel fuel efficiency | | 6.00 | 7.50 | 8.50 | miles/gal |
| Annual miles driven | | 80,000 | 85,000 | 90,000 | miles |
| Battery cycles (lifetime) | | 1,500 | 1,750 | 2,000 | cycles |
| Diesel price | | \$2.50 | \$3.50 | \$4.25 | \$/gal |
| Electricity prices | | \$0.09 | \$0.10 | \$0.13 | \$/kWh |
| Electricity prices (guar) | \$0.07 | | | | \$/kWh |
| Increm. diesel repair | | \$0.06 | \$0.10 | \$0.12 | \$/mile |
| Depth of discharge | | 80% | | | % |
| Discount rate | | 3% | | | % |

Source: JPMAM, 2018. Normal distributions truncated at min/max values.

Payback periods for Tesla EV trucks vs diesel

percentage of observations, n=10,000



Source: JPMAM, 2018.

Important notes on our analysis

- Some analysts assume that Tesla's one million mile warranty **includes battery replacement**. There has been no clear messaging from Tesla on this issue. We assume the driver replaces the battery once its cycle lifetime has run its course. The driver could opt instead to relegate the truck to other uses at this point since it would still function, albeit with depleted battery capacity. However, in this case the EV truck is no longer an economic substitute for the diesel, and entails revenue losses that would have to be factored in. **Payback analyses that do not assume that the battery is replaced (either by Tesla or the driver) and do not account for utility loss make little sense to me.**
- We did not include possible losses associated with **reduced Tesla payloads**. Tesla battery packs have energy densities of 160-200 Wh/kg, which include the weight of housing, cooling systems, mechanical support structures, electronics and cell connectors. For the 500 mile version, the weight of the battery could result in a 15%-20% lower max payload than the comparable diesel truck. However, many trucks max out on volume rather than weight, in which case this would be less of an issue.
- Why are payback periods similar for 300 & 500 mile versions? While the former's upfront cost is lower, it requires 2 battery replacements over its million mile life rather than 1, as per our assumptions.
- Tesla's **electricity subsidy** for truck buyers appears substantial, since the company recently increased its Supercharger electricity prices for new model S/X/3 buyers to 24-26¢/kWh in Oregon, California and NY.

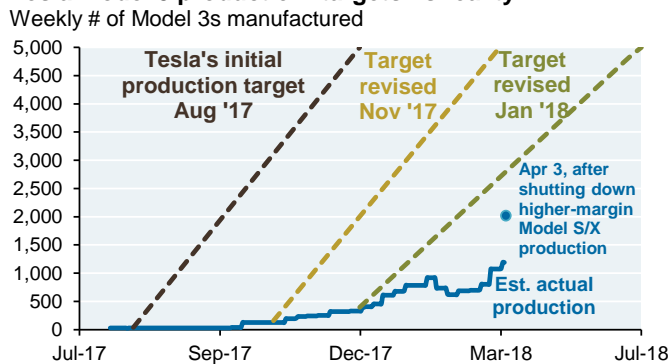


Let's keep some things in mind about **Tesla and its hypothetical truck**:

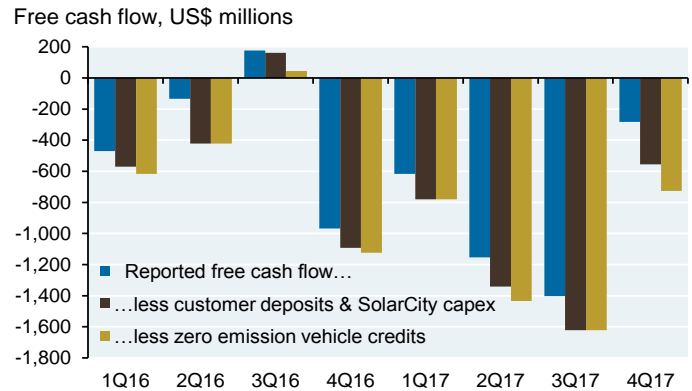
- Tesla's truck doesn't exist yet, and neither does its production facility
- Tesla truck prices are indicative and non-binding, and could change
- Our analysis doesn't incorporate possible impacts of constant driving and fast-charging on battery capacity, safety and useful life
- Payback periods do not incorporate how truck buyers might feel about a company that usually does not allow anyone else to work on their vehicles, and does not sell service manuals or parts either
- Tesla has a history of missing its production targets, just suffered the worst quarterly financial loss in its history as well as an outflow of senior executives, has a high level of junk debt and has a high level of CEO compensation for a loss-generating enterprise.

Consider us skeptical, at least until more details emerge. Here are some charts assessing Tesla as a going concern with long term warranty and electricity price guarantees. For the complete set of our Tesla charts on these and other related topics, please click [here](#).

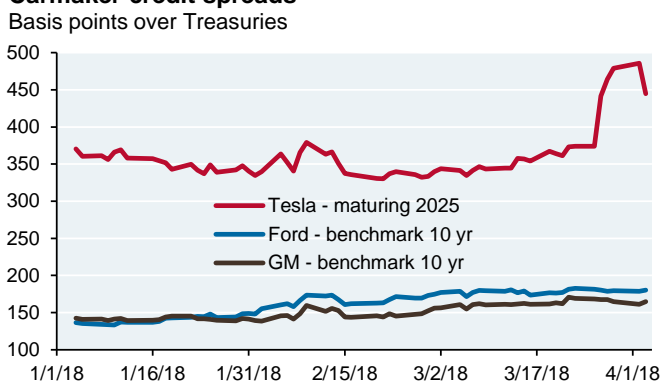
Tesla Model 3 production: targets vs reality



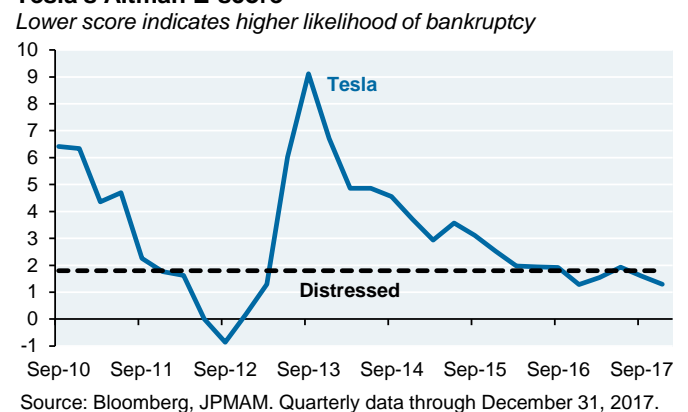
Tesla's cash burn



Carmaker credit spreads



Tesla's Altman Z-score

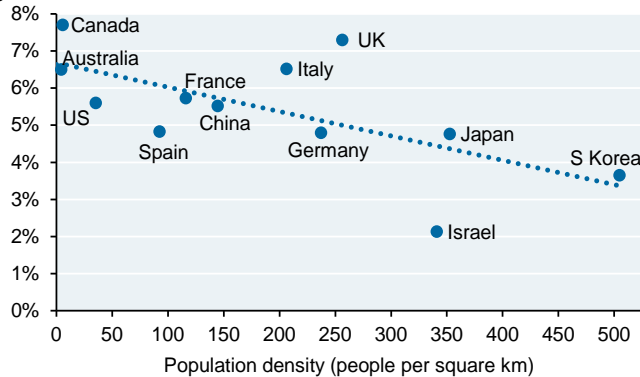




[2] High voltage direct current lines: China leads, US lags

In China, the US, Brazil, India and Australia, there are long distances between wind/solar/hydro facilities and major population centers. How this power is transmitted is an important part of grid efficiency and renewable energy integration. Using standard AC transmission lines, longer distances tend to result in larger transmission losses and also in greater involuntary curtailment of wind/solar power (i.e., power that could have been generated but which wasn't consumed).

Transmission and distribution losses as a % of total generation



Source: IEA Energy Technology Systems Analysis Programme, 2014.

Involuntary curtailment ratios

| Country | Obs Year | Wind/Solar Curtailment |
|----------|----------|------------------------|
| Denmark | 2014 | 0.0% |
| Germany | 2013 | 0.2% |
| Ireland | 2013 | 3.8% |
| Italy | 2014 | 0.3% |
| Portugal | 2014 | 0.0% |
| Spain | 2013 | 1.6% |
| US-ERCOT | 2014 | 0.5% |
| US-MISO | 2014 | 5.5% |
| China | 2012 | 17.1% |
| China | 2013 | 10.7% |
| China | 2016 | 17.0% |

Source: 2015 Wind Integration Workshop, Kansai University (Japan), NRDC.

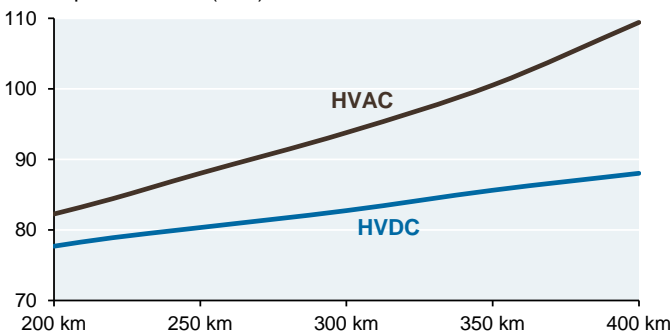
While AC lines are usually best for short and medium distances, **high voltage direct current lines (HVDC)** can be more economic for longer distances. The tradeoffs involve the following:

- higher upfront capital costs for DC terminals given the need for voltage conversion equipment
- lower per km line costs for DC due to fewer conductors, less metal for towers and lower land costs (a 3-conductor 500 kV AC tower is ~1.5 times larger than a 2-conductor 500 kV DC tower)
- fewer transmission losses for DC lines over the project's life as distances increase (see chart, left)

The chart on the right from the IEA puts all the pieces together: DC lines are usually cheaper once distances exceed 600-700 km¹⁰. Siemens and ABB report similar breakeven distances (both are working on the world's first 1,100 kV HVDC transformers for use in Guquan, China).

Transmission losses: HVAC vs HVDC

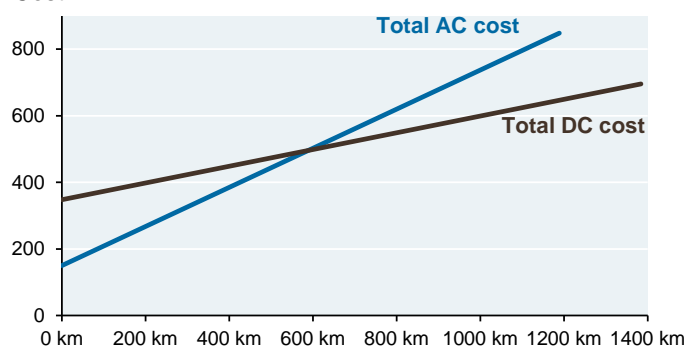
Active power losses (MW)



Source: "Power loss evaluations for long distance transmission lines", Nguyen and Saha (University of Queensland), 2009.

Comparison of HVAC and HVDC lifetime system costs

Cost



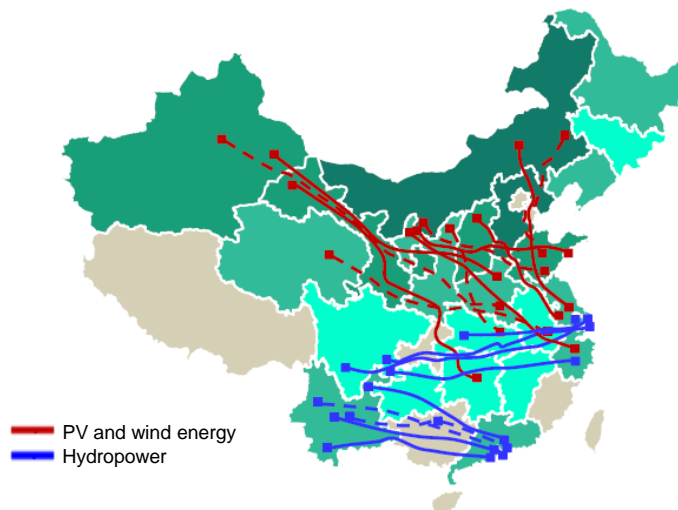
Source: IEA Energy Technology Systems Analysis Programme, 2014.

¹⁰ **For electricity aficionados only.** For underwater or underground systems, HVDC tends to be used at distances over 50-80 km. Above that level, high capacity AC transmission systems become less feasible for reasons related to electrical capacitance, reactive power losses and the cost/feasibility of shunt reactor substations. Since polymer- or paper-insulated conductors in underground/underwater cables are located much closer to ground than conductors in overhead lines, their electrical capacitance per km is generally much higher. This causes long AC cables to generate significant reactive power, degrading performance over longer distances to the point where eventually less and less real power can be transmitted without some kind of expensive reactive power compensation.



China leads the world in the installation of HVDC transmission lines. While China has installed 30% of the world’s wind and solar capacity, wind and solar power account for just 5% of Chinese electricity generation. China has a “mandatory goal” of reducing coal’s contribution to primary energy from 62% in 2016 to 58% by 2020, and plans to add more wind, solar and hydro as part of this transition. However, the distance between wind, solar and hydro facilities and China’s urban centers has created challenges, including the high levels of renewable curtailment shown on the prior page. As part of the solution, China is building plenty of HVDC lines, with 20 in operation or under construction.

HVDC transmission lines for transfer of renewable energy across China, Solid lines = in operation, dotted lines = to be completed by 2020



Source: "Renewable Energy Transmission by HVDC Across the Continent: System Challenges and Opportunities", RPI, State Grid Corporation of China, China Electric Power Research Institute. December 2017.

The table below shows announced HVDC projects of more than 400 kV for several countries. To put China’s HVDC development in context, we created a metric for each country that is equal to the kilometers of its HVDC projects per gigawatt of its total electricity generation capacity. **China’s HVDC ratio is more than double that of the US.** That’s worrisome enough, but as we discuss on the next page, some announced US projects might not even be completed.

Announced high voltage direct current line projects > 400 kV

In-country projects

| | Distance of domestic projects (km) | Total electricity generation capacity (GW) | Total distance of projects / el gen capacity |
|-----------|------------------------------------|--|--|
| Mexico | 2,740 | 67 | 40.6 |
| Brazil | 4,640 | 156 | 29.8 |
| China | 27,953 | 1,519 | 18.4 |
| Indonesia | 876 | 57 | 15.3 |
| UK | 1,187 | 95 | 12.5 |
| Germany | 2,495 | 204 | 12.2 |
| USA | 8,075 | 1,074 | 7.5 |
| India | 2,021 | 325 | 6.2 |

Source: Global Transmission Research, 2017. Projects shown are in-country only and exclude cross-border HVDC interconnection projects, of which there are 2,500 km in Asia and 5,200 km in Europe.



US HVDC lines: slower progress, more bottlenecks. A good way to understand challenges in the US is to track the experience of Clean Line LLC. This Houston-based company accounts for 50%-60% of all planned US HVDC development, according to data from Global Transmission Research¹¹. Clean Line projects are all subject to complex regulatory approvals in multiple states. While certain legal rulings have gone in its favor, the length and complexity of the approval process has delayed some of their projects for years, with one rejected outright. We wrote about Clean Line’s Plains & Eastern project last year as an example of belated success, the first HVDC transmission line to be built in the US in more than 20 years after 11 years of planning. **Now, that project is up in the air again since the Federal government has ended its partnership agreement with Clean Line.**

| Name of Clean Line Project | Voltage (kV) | Distance (km) | % of total US HVDC distance | Comments |
|----------------------------|--------------|---------------|-----------------------------|---|
| Centennial West | 600 | 1,449 | 17.9% | Environmental impact statement submitted, approval pending. States affected: New Mexico, Arizona, and California |
| Grain Belt Express | 600 | 1,256 | 15.6% | Approvals received in Kansas, Indiana and Illinois but waiting for approval in Missouri, where it has already been rejected twice since all affected Missouri counties must approve. Clean Line now appealing to Missouri Supreme Court |
| Plains & Eastern | 600 | 1,160 | 14.4% | Approvals received in Oklahoma and Tennessee, but not from Arkansas. Clean Line appealed to US Federal Govt for help in using Section 1222 of the Energy Policy Act of 2005 to override Arkansas objections. However, in March 2018, the Federal Government ended its partnership agreement with Clean Line, removing the possibility of Federal assistance with eminent domain. TVA recently withdrew as purchaser given lack of need and out of concern for costs of backup thermal generation. Clean Line then sold part of its ownership. |
| Rock Island | 600 | 805 | 10.0% | Illinois Supreme Court rejected Clean Line's application since as an out of state entity with no Illinois assets, it did not qualify as a public utility, which is needed to engage in transmission line development. States affected: Iowa and Illinois. |
| Western Spirit | 345 | 224 | 2.8% | Approvals received from FERC and Bureau of Indian Affairs, negotiating with potential power end-user customers. States affected: New Mexico |

Source: Global Transmission Research (2017), JPMAM.

Clean Line isn’t the only company experiencing delays. The 1 GW **Northern Pass** line connecting Hydro-Quebec to Southern New England was supported by Massachusetts regulators and its Department of Energy Resources. However, a New Hampshire siting committee rejected the proposal by 7-0, since it worried that the 192-mile system would disrupt streets and harm tourism, particularly in the northern portion of the state. Concessions by the Northern Pass group to bury 52 miles of the route and set aside 5,000 acres of preservation and recreation land have been insufficient to change the outcome so far; appeals are pending. There have also been delays on the New Mexico-based **Tres Amigas** project, which was supposed to link the three US regional grids with a 750 MW, 345 kV HVDC system costing \$1.5 billion. In 2017, Tres Amigas was scaled down to 200 MW and \$200 mm, and will no longer include the Texas grid.

US HVDC lines are often mentioned as an integral part of a renewable energy future, but it would take a sea change in regulation and local practices to realize it. Researchers at the National Oceanic and Atmospheric Administration explored the possibility of a national US grid of interconnected HVDC lines overcoming wind and solar intermittency, and also reducing the need for storage. They found that by 2030, HVDC lines meeting at 32 nodes could add allow for enough wind and solar power to cut power sector emissions by up to 80% from 1990 levels. But if recent experience is any indication, a national grid of US HVDC lines will remain part of the renewable energy wish list rather than a reality.

¹¹ The GTR database includes HVDC projects that are proposed, under development or under construction.



[3] Renewable Rap Battle: A scathing critique of Mark Jacobson's 100% renewable grid proposal

Some policy recommendations attain notoriety because they're simple, and because they appeal to the hopes of people who support them. The thankless work of a "critic", dating back to ancient Greece where the word was derived (κριτικός), is to judge if these policies make sense. Modern day energy critics separate innovations from illusions, and steer us towards actionable, achievable solutions.

In 2015, Stanford's Mark Jacobson and three other researchers published a paper on a low-cost solution to the US grid which would rely **100% on wind, hydro and solar power by 2050**. Their 2015 paper is an updated version of an article they first published in *Scientific American* in 2009¹². You may have read about their all-renewable US grid idea, or their recent work applying the same concept to 139 countries. Many media outlets and energy blogs cite Jacobson's proposal as a vision of a possible renewable energy future, if only we just would reach for it.

In 2017, the battle began. A large team of scientists and researchers from US universities, think tanks and research labs published a paper in the *Proceedings of the National Academy of Sciences*¹³ which (there is no other way to put this) **savaged** the Jacobson proposal. It's worth reviewing some of the arguments in their rebuttal, since they illustrate the challenges and complexity of designing real-world energy solutions. While 21 researchers participated in the PNAS paper, for simplicity, we refer to it here as the "Clack rebuttal". Here's their overarching **conclusion** on Jacobson's proposal:

"The authors claim to have shown that their proposed system would be low cost and that there are no economic barriers to the implementation of their vision. However, the modeling errors described, the speculative nature of the terawatt-scale storage technologies envisioned, the theoretical nature of the solutions proposed to handle critical stability aspects of the system, and a number of unsupported assumptions, including a cost of capital that is one-third to one-half lower than that used in practice in the real world, undermine that claim."

Affiliations of the 21 authors participating in the Clack rebuttal

- Carnegie Institution for Science (Department of Global Ecology)
- Carnegie Mellon University (Department of Engineering and Public Policy; Tepper School of Business)
- Columbia University (Center for Global Energy Policy)
- Lawrence Livermore National Laboratory
- NOAA Earth System Research Laboratory
- Stanford University (Department of Energy Resources Engineering; Management Science and Engineering Department; Precourt Energy Efficiency Center)
- UC Berkeley (Energy and Resources Group; Goldman School of Public Policy; Renewable Energy Laboratory)
- UC Irvine (Department of Earth System Science)
- UC San Diego (Department of Mechanical and Aerospace Engineering; School of Global Policy and Strategy)
- Univ. of Colorado (Inst. for Research in Environmental Sciences; Renewable and Sustainable Energy Institute)
- University of Vermont (Electrical Engineering and Complex Systems Center)
- Uppsala University (Department of Physics and Astronomy)
- Brookings Institution and the Council on Foreign Relations

¹² **Even in 2009, Jacobson's thesis came under fire.** Physicist Michael Briggs at the University of New Hampshire wrote the following in response to Jacobson's article: "As a physicist focused on energy research, I find this paper so absurdly and poorly done that it is borderline irresponsible. There are so many mistakes, it would take hours of typing to point out all of the problems." [Source: M. Briggs, Letter to the editor, *Scientific American*, 2009].

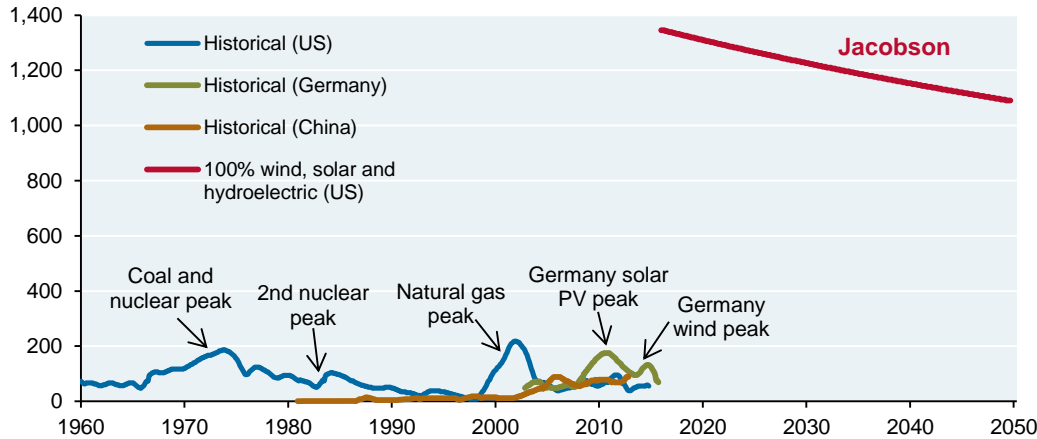
¹³ "Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar", Clack et al, *Proceedings of the National Academy of Sciences*, February 2017. Sources for Jacobson's original piece, the Clack rebuttal, the Jacobson response and another Clack rebuttal are found on p.33. In 2017, Jacobson sued Clack for intellectual defamation, but withdrew the lawsuit in 2018.



The simplest way to illustrate the scope of Jacobson’s proposal is to compare it to the pace of prior capacity additions. The first chart shows annual electricity generation capacity additions from 1960 to 2015 for the US, Germany and China, measured per capita. Peak additions were associated with US nuclear and natural gas build-outs, Germany’s solar and wind era and China’s 21st century grid upgrade. Look at the red line: as per the Clack rebuttal, Jacobson proposed capacity additions are 14x larger than what took place over the prior 50 years, a staggering amount and pace of new generation.

Historical rates of installed electric-generating capacity per capita

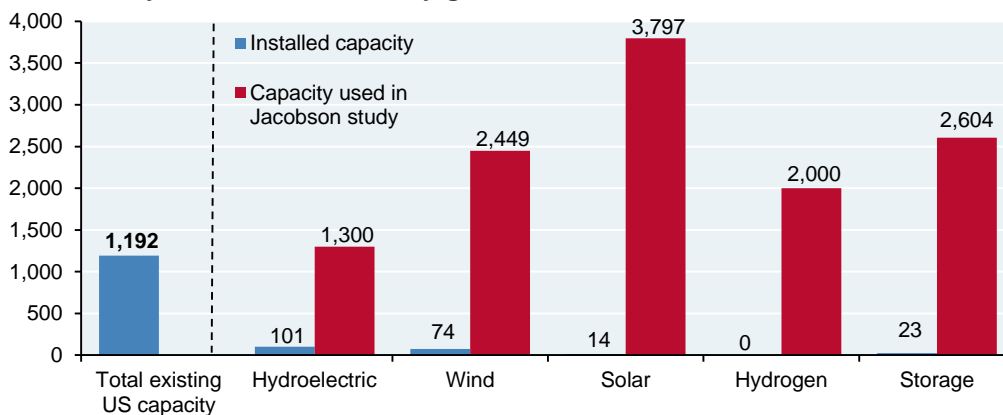
Capacity additions, watts per year per capita



Source: "Evaluation of a proposal for reliable low-cost grid power with 100% wind, water and solar," Clack et al. 2017.

Another look: according to the Clack rebuttal, Jacobson assumes that new US solar, wind, hydro, hydrogen and storage capacity (red bars) will each be built out on a scale that **exceeds the entire US electricity generation system** as it exists today (blue bar).

Jacobson proposal: each of 5 renewable technologies are built-out to be larger than today's entire US electricity grid, GW



Source: "Evaluation of a proposal for reliable low-cost grid power with 100% wind, water and solar", Clack et al. February 2017.



If the scope/cost of Jacobson's proposal were its only issues, I wouldn't write about it. The **implausible assumptions** cited in Clack's rebuttal are more concerning, and why such proposals should be evaluated based on substance rather than "vision". If you're interested, the next 2 pages get into the details.

On Jacobson's hydropower assumptions:

- The Clack rebuttal claims that Jacobson assumes a huge **13x hydropower capacity build-out**. However, this is not based on new projects: instead, Jacobson proposes that existing dams be retrofitted with additional turbines to increase potential instantaneous generation.
- According to the Clack rebuttal, this is highly implausible. US hydropower facilities are **generally already built over capacity**, and already have priority on the grid over thermal power as well as wind and solar: "the primary factor limiting hydroelectric capacity factor is water supply and environmental constraints" rather than under-optimized dams. Clack's rebuttal also states that Jacobson's paper is undermined by a hydro modeling error¹⁴, and does not adequately incorporate the infrastructure cost of its assumed hydropower expansion.

Understanding the bizarre implications of Jacobson hydropower assumptions: The Grand Coulee Dam

If the Grand Coulee Dam in Washington state expanded by the same relative amount as Jacobson's overall hydro expansion, it would have a new peak power rating of 101 GW: more than all hydropower in the US combined today, and 4.5x larger than the largest power plant of any kind ever constructed (the Three Gorges Dam in Hubei Province, China). The required flow rate through this upgraded Grand Coulee Dam at full power would regularly need to be 5.5x higher than the largest flow rate of its part of the river ever recorded in history, which occurred on June 12, 1948 during an historic Columbia River flood. This flow rate corresponds to 13x the average discharge rate of the entire Columbia river system, and 3.5x the maximum spillway capacity of the Grand Coulee dam itself. [Source: June 2017 Clack et al response to Jacobson]

On Jacobson's assumed expansion of the hydrogen economy:

- As per the Clack rebuttal, in Jacobson's model, "hydrogen is produced at a peak rate consuming nearly 2,000 GW of electricity, nearly twice the current US electricity-generating capacity". To understand how large this is: "Total worldwide production of hydrogen from electrolysis is approx. 2.6m tons/year, corresponding to an average electrolysis power consumption of ~16 MW. The US electrolysis build-out envisioned by Jacobson is thus at least a **factor 100,000x increase** over total world electrolysis capacity today"
- And the price tag? "The costs for electrolyzers necessary to produce hydrogen at a rate of 2,000 GW are at least 10-25 times higher than those reported, with the capital cost for these components totaling approximately \$2 trillion"; this is "not appropriately accounted for in the cost estimates".
- Jacobson's proposal "includes a wide range of currently un-costed innovations that would have to be deployed at large scale (e.g., replacement of our current aviation system with yet to-be-developed **hydrogen-powered planes**)".

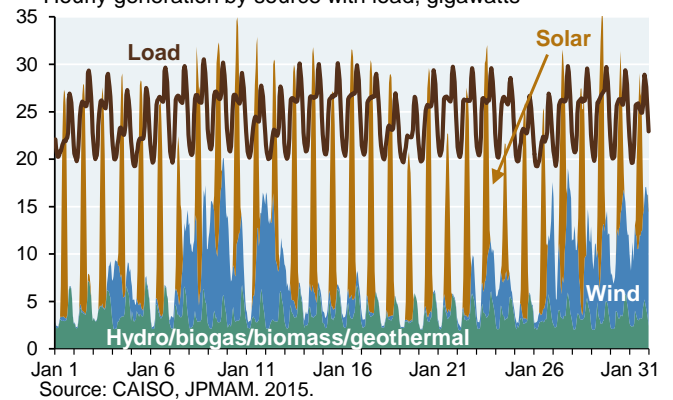
¹⁴ Clack's rebuttal cites a hydro **modeling error** in Jacobson's paper that is "so large (and so obvious) that it by itself invalidates the entire effort". In a rebuttal of his own, Jacobson refutes assertions of this error, and stands by the notion that hydroelectricity capacity that is larger than the current US electricity grid can be retrofitted on existing hydro plants. In our 2016 review of hydroelectric power, we cited research from Oak Ridge National Labs showing that US hydropower could increase from 6% to 9% of total electricity generation through development of existing non-powered dams and new stream development.



One challenge for a grid with a lot of renewable energy is the mismatch between renewable generation and electricity demand. In this chart from our 2015 energy paper, we plot load and renewable generation for California in January, broken down by hour. We assumed a large build-out of wind and solar, enough to provide 70%-80% of annual generation. As you can see, there would still be long periods in January during which there is insufficient renewable generation to meet demand. Jacobson proposes that gaps like these be addressed through both **energy storage and load-shifting** (requiring businesses to adjust to when electricity is available rather than when they need it). But...

California: January load vs. renewable generation

Hourly generation by source with load, gigawatts



...On Jacobson's assumed massive increase in underground thermal energy storage:

- Current electricity storage systems store energy for a few hours at a time, and are not built to store excess wind or solar power for weeks or months. Jacobson assumes this problem is primarily solved through underground thermal energy storage (UTES), which utilizes geothermal boreholes to store heat in the ground. As per the Clack rebuttal, Jacobson assumes that UTES would be "deployed in nearly every community to provide services for every home, business, office building, hospital, school, and factory in the United States. However, the analysis does not include an accounting of the costs of the physical infrastructure (pipes and distribution lines) to support these systems."
- And this: "Jacobson assumes a total of 2,604 GW of storage charging capacity, more than double the entire current generation capacity of all power plants in the United States. The energy storage capacity consists almost entirely of two technologies that remain unproven at any scale: 515 TWh of UTES (the largest UTES facility today is 0.004 TWh), and 13 TWh of phase-change materials. Although both UTES and phase-change materials are promising resources, **neither has reached the level of technological maturity to be confidently used as the main underpinning in a study aiming to show the technical reliability and feasibility of an energy system**. Solar district heating with UTES on large scales and at high rates of deployment is rare outside of Denmark".

...On Jacobson's assumption of flexible load-shifting:

Jacobson's models assume "free time-shifting of loads at large scale in response to variable energy provision", and assume that "**somewhere between 65% and 80% of Jacobson's daily loads are assumed to be flexible**". This includes 60% of industrial demand, which is assumed to be able to freely reschedule all energy inputs within an 8-hour window. "The authors do not provide evidence to justify this **implausible scale of load flexibility**. The idling of capital-intensive industrial facilities when intermittent energy sources are unable to meet demand represents a large cost that is not included".

And finally, on the underestimation of transmission investment

According to the Clack rebuttal, Jacobson assumes that 45% of wind, hydro and solar generation will be sent through a new national long-distance grid. However, they found no explicit modeling, reference or cost information on transmission in Jacobson's proposal, and believe that "their analysis **ignores transmission capacity expansion**, power flow, and the logistics of transmission constraints". While there are estimates of transmission costs in Jacobson's proposal, Clack et al believe they are way too low.

The mic has been dropped.

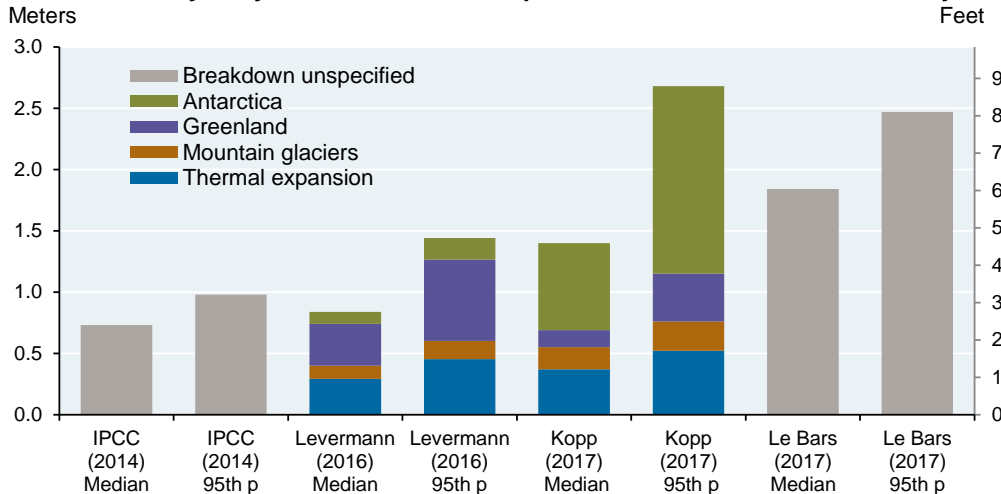


[4] Better safe than sorry: sea level rise, coastal exposure and flood mitigation projects

What if the earlier sections of this paper are correct about the *gradual* pace of grid and industrial sector decarbonization, electric vehicle penetration and HVDC transmission line adoption? Possible outcomes argue for flood mitigation projects in major coastal cities.

Let's begin with sea levels. In 2014, the Intergovernmental Panel on Climate Change estimated that sea levels could rise by 0.6 to 1.0 meters by the year 2100¹⁵. Some newer estimates show higher levels, ranging from 2.0 to 2.5 meters of sea level rise instead¹⁶. In most of these models, sea levels keep rising after the year 2100, reaching 5 meters by the year 2200.

Sea level rise by the year 2100 based on Representative Concentration Pathway 8.5



Source: IPCC, Levermann et al, Kopp et al, Le Bars et al.

Why are new sea level rise estimates higher than the 2014 IPCC estimates?

In scientific terms: "Underappreciated processes linking atmospheric warming with hydro-fracturing of buttressing ice shelves and structural collapse of marine-terminating ice cliffs"¹⁷.

In layperson's terms: Large areas of ice that are currently attached to the ocean floor and protruding above sea level (i.e., not floating) could cleave into the ocean as large blocks of ice fall from cliffs at the ice edge, thereby raising sea levels regardless of when/if they melt. The authors of this paper reminded me that their work is highly theoretical, but also based on observed processes now taking place in Antarctica and Greenland.

¹⁵ A January 2018 paper from researchers at the University of Colorado and the National Center for Atmospheric Research used a different approach and estimated future sea levels solely based on observed changes over the last 25 years. Their results were similar to the IPCC 8.5 scenario.

¹⁶ The chart shows projected sea level rise under the **RCP 8.5 scenario**, which is the most bearish assessment of future greenhouse gas emissions. Supplementary materials on page 28 illustrate how sea level rise estimates differ under **RCP 4.5**, and also include a chart on estimated sea level changes from the year 500 BC to today.

¹⁷ "Contribution of Antarctica to past and future sea-level rise", DeConto (UMass) and Pollard (Penn State), Nature Magazine, March 2016.

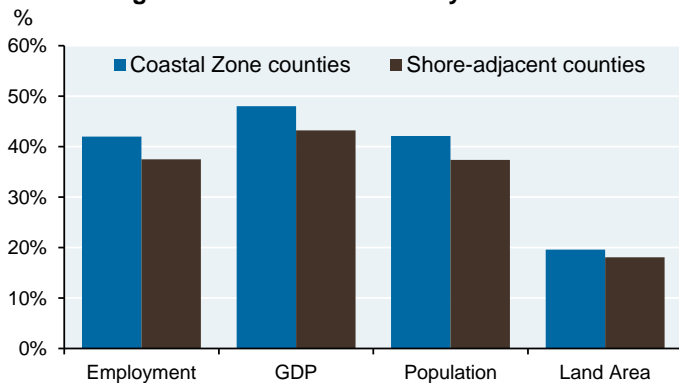


How much damage could be caused by 2 meters (~6.5 feet) of sea level rise in the US, incorporating additional heights associated with storm surges? The US Global Change Research Program¹⁸ estimated that this amount of sea level rise could put at least 6,000 square miles and \$1 trillion (in 2014\$) of property and structures at risk. Its Climate Assessment report also included the following stats which further illustrate the risks if sea level rise projections are accurate:

- Each year, more than 1.2 mm people (the equivalent of nearly one San Diego) move to the coast, the Great Lakes or open-ocean coastal watershed counties and parishes of the US
- 164 mm Americans (more than 50% of the population) now live in these densely populated areas and help generate 58% of US GDP. Economic activity in shoreline counties accounted for 66 million jobs and \$3.4 trillion in wages
- Low-lying water-dependent infrastructure such as onshore gas and oil facilities, ports, thermal power plants and wastewater management/drainage systems are difficult and expensive to relocate

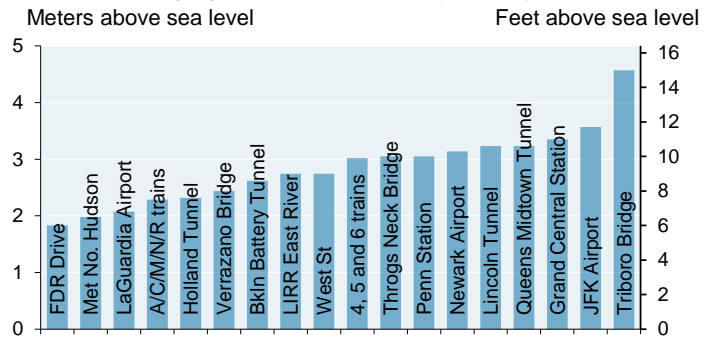
Here are some charts that make the point as well: the large contribution to the US economy from coastal and shore-adjacent counties; storm surge heights that render major NYC infrastructure inoperable; and the increasing number of tidal flood days per year in coastal states.

Coastal regions' share of US economy



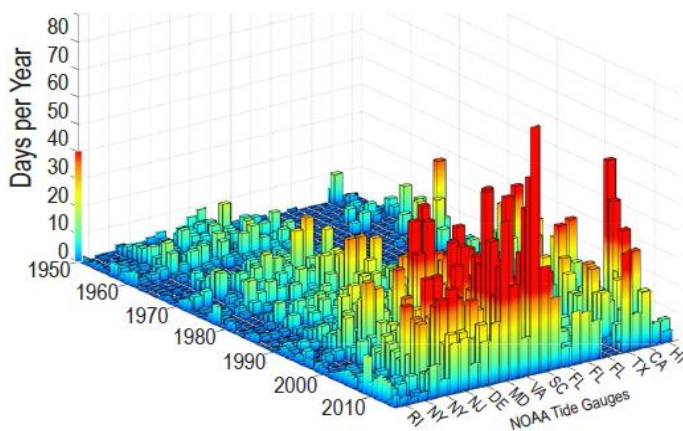
Source: Middlebury, Nat'l Ocean Econ Program. 2016. Data as of 2014.

Critical storm surge elevations by location (at which New York City systems become inoperable)



Source: US Army Corps of Engineers, FEMA, Nat'l Weather Service. 2000.

Tidal Flood Days per year, 1950-2015



Source: USGCRP Fourth Climate Assessment, Chapter 12. 2014.

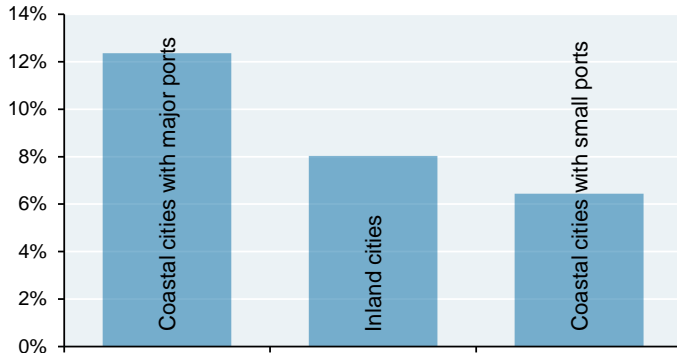
¹⁸ The **United States Global Change Research Program** coordinates and integrates research from 13 different Federal agencies on changes in the global environment and their implications for the US. The program was launched by President George H.W. Bush in 1989.



Similar coastal exposures exist outside the US. A common feature of population exposure models is the assumption that more people will move from inland regions to the coasts, where the opportunities are. In recent years, coastal cities with major ports have seen faster growth rates.

Coastal port cities boast stronger growth vs inland cities

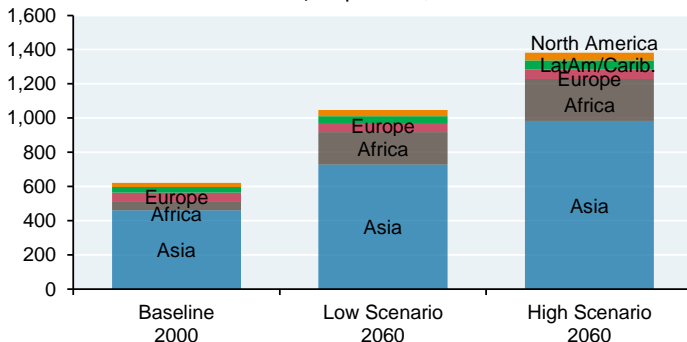
Aggregate real GDP growth, 2008-2013, %



Source: Euromonitor. 2014.

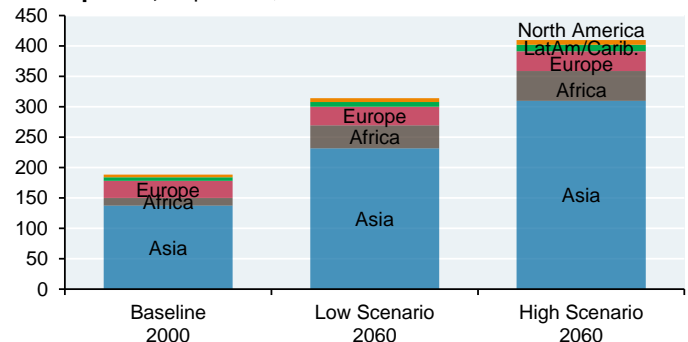
One assessment of exposed populations comes from the Coastal Risks and Sea-Level Rise Research Group at Kiel University in Germany. Their analysis takes two approaches: how many people will live in “low coastal elevation zones”, and how many will live in the “100-year flood plain”¹⁹. The former is larger than the latter, but in either case, (a) their 2060 projections of exposed populations are at least 2x the year 2000 baseline, and (b) the largest affected populations live in Asia (mostly in China, India, Vietnam and Bangladesh).

Flood exposure population by region based on Low Elevation Coastal Zones, Population, millions



Source: "Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment", Neumann et al. 2015.

Flood exposure population by region based on 100-year flood plains, Population, millions









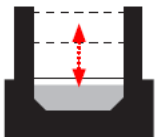
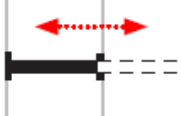

Source: "Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment", Neumann et al. 2015.

¹⁹ The “low-elevation coastal zone” describes all coastal land adjacent to the sea (and hydrologically connected to the sea), and not more than 10 meters above mean sea level. The “flood plain” refers to land inundated in storm surge events that occur statistically every 100 years.



While modeling sea level rise is complicated, building flood mitigation infrastructure is not.

The simplest projects involve land-based sea walls, dikes or sand dunes. The more advanced versions are sea-based, and involve a series of hydraulic locks, dams, gates, etc, and have been proven to work during severe storm and flooding events. Here’s a sampling of different kinds of sea-based barriers, including their existing locations and common maximum dimensions (in meters):

| Hydraulic sea barrier types | | | | | |
|---|---|---|---|---|---|
| |  |  |  |  |  |
| Type | Rotary segment | Inflatable | Flap | Barge gate | Vertical rising |
| Max W,H,WD | 40 / 8 / 2 | 120 / 10 / 6 | 6 / 8 / 2 | 80 / 20 / 6 | 50 / 5 / 2 |
| Location | Thames, Gandersum | Ranspol | Stamford, Venice | New Orleans | St Petersburg |
| View shown | Cross section | Cross section | Cross section | Top view | Cross section |
| Comments | In recess, gate lies in a concrete sill on ocean floor | Synthetic rubber or laminated plastic, inflated with air or water | Pivoted on fixed axis | Pivoted on vertical axis | Positioned largely under water in open and closed positions |
| |  |  |  |  | |
| Type | Segment | Vertical lift gate | Rolling | Segment gates | |
| Max W,H,WD | 100 / 8 / 6 | 60 / 12 / 4 | 60 / 20 / 6 | 360 / 20 / 2 | |
| Location | Eider, Thames, St Petersburg | Utrecht, Zeeland, Hull(UK), Gandersum, N. Orleans | Panama, Hamburg | New Bedford, St Petersburg, New Orleans, Maeslant, Seabrook | |
| View shown | Cross section | Cross section | Top view | Top view | |
| Comments | Rotates around horizontal axis | Tower-supported lift gates with overhead cables or hydraulic cylinders | Sliding panels stored adjacent to the waterway | Double gates swinging on vertical axis; stored in docks | |
| Sources: "Multifunctional Flood Gates", Dijk and van Ziel, Royal Haskoning DHV; and "Overview and Design of Storm Surge Barriers", Mooyart and Jonkman, Delft University of Technology, Civil Engineering and Geosciences Dept. | | | | | |
| "Max W,H,WD" refers to the estimated maximum width, height and water differential for each barrier, measured in meters, and based on current materials limitations. | | | | | |

How are these projects paid for? When there’s a will, there’s a way:

| | |
|------------------|--|
| Taxes | A state-wide surcharge (tax) on property & casualty insurance premiums A “local option sales tax” levied by a local municipality to fund infrastructure Earmarked revenue streams connected to properties that benefit |
| Government funds | EPA federal funding through the Water Infrastructure Finance and Innovation Act Hybrid approach enlisting federal, state and local dollars Local municipal asset sales to fund construction |
| Bonds | Issuance of “green bonds”, traditional private activity bonds or general obligation debt |
| Privatization | Requires stream of revenues or an operating business to incentivize private capital, whether through outright privatization or via public private partnerships |



The bigger challenge for policymakers: the cost. While recent estimates put the cost of simple coastal barriers (e.g., piles of sand or simple sea walls) at 15,000 to 20,000 Euros per meter, water-based storm surge infrastructure can be up to 100x more expensive. The table below is from a paper published in the New York Academy of Sciences in 2013; estimated costs range from \$0.5 to \$3.5 million per meter. A more recent paper from 2017 cites costs of 2.2 million Euros per meter, which is at the higher end of the figures shown in the table.

One last observation: **a storm surge barrier system protecting New York City and parts of New Jersey could cost \$2.7 million per meter**, assuming (i) a barrier across the 8 km gap between the northern tip of Sandy Hook, NJ and western tip of Breezy Point, NY combined with (ii) a smaller barrier across a 1 km area near the Throgs Neck Bridge. The larger barrier would consist of levees, rotating sector gates and vertical lifting gates, while the smaller barrier would incorporate flap gates. These proposed barriers are expected to be complemented by 2 meter seawalls along parts of Staten Island, Manhattan and Brooklyn to protect against potential surges from the Hudson River.

Examples of sea-borne infrastructure barriers, with costs in 2012\$

| Location | Gate type | Country | Construction Years | Width (m) | Gate height (m) | Head (m) | Constr. costs (\$ mm) | Constr. costs per meter (\$mm/m) | Operation & Maint. costs (\$mm/yr) |
|-------------------|----------------------------------|---------|--------------------|-----------|-----------------|----------|-----------------------|----------------------------------|------------------------------------|
| Thames | Rotating sector | UK | 1974-1982 | 530 | 17 | 7.2 | 1,883 | 3.55 | 13 |
| Maeslant | Floating sector | NL | 1989-1997 | 360 | 22 | 5.0 | 852 | 2.37 | 15 |
| Eastern Scheldt | Vertical lifting | NL | 1974-1986 | 2,400 | 14 | 5.0 | 5,227 | 2.18 | 20 |
| Venice MOSE | Inflatable flap | Italy | 2003-today | 3,200 | 15 | 3.0 | 6,125 | 1.91 | 12.8 |
| Seabrook | Vertical lifting/sector | USA | 2005-2011 | 130 | 8 | 4.0 | 165 | 1.26 | 2.1 |
| Hollandse IJssel | Vertical lifting | NL | 1954-1958 | 110 | 12 | 3.5 | 127 | 1.15 | 2 |
| Hartel | Vertical lifting | NL | 1993-1996 | 170 | 9 | 5.5 | 185 | 1.09 | 2.4 |
| Ems | Rotating sector | Germany | 1998-2002 | 476 | 11 | 3.8 | 376 | 0.79 | 6.3 |
| Ramspol | Inflatable rubber dam | NL | 1996-2002 | 240 | 8 | 4.4 | 171 | 0.71 | 1.1 |
| IHNC, New Orleans | Sector/vertical lifting | USA | 2005-2011 | 2,800 | 8 | 4.0 | 1,100 | 0.45 | 2.5 |
| Cardiff Bay | Sluice/lifting | UK | 1994-2000 | 1,100 | 8 | 3.5 | 340 | 0.31 | 15 |
| Fox Point | Vertical rotating | USA | 1961-1966 | 300 | 12 | 6.0 | 88 | 0.29 | 0.5 |
| St Petersburg | Floating sector/vertical lifting | Russia | 1984-2011 | 25,400 | 24 | 5.0 | 6,953 | 0.27 | N/A |
| Stamford | Flap | USA | 1965-1969 | 866 | 11 | 5.0 | 82 | 0.09 | N/A |
| New Bedford | Horizontally moving sector | USA | 1961-1966 | 2,774 | 18 | 6.0 | 111 | 0.04 | N/A |

Source: "Cost estimates for flood resilience and protection strategies in New York City," Aerts et al. 2013.

It might take more catastrophic storms to convince the public that cost-benefit ratios for flood mitigation projects make sense. Some studies already point in this direction, including an analysis of global coastal exposures by researchers at Berlin's Global Climate Forum. They found that by protecting only 13% of the world's coastline, positive benefit-to-cost ratios could be achieved on 90% of the global floodplain population and 96% of the assets²⁰. While some of their benefit-to-cost ratios were 2:1 or 3:1, many were on the order of 100:1 and 300:1, reinforcing that the cost of inaction can be much greater than spending on infrastructure today²¹. These studies analyze simple sea walls rather than the hydraulic structures described above; there are fewer comprehensive cost-benefit analyses of the latter. In any case, competition for dollars is intense; flood mitigation project proponents will have plenty of convincing to do.

²⁰ "Economically robust protection against 21 st century sea-level rise", Jochen Hinkel and Daniel Lincke, Global Climate Forum, Pending.

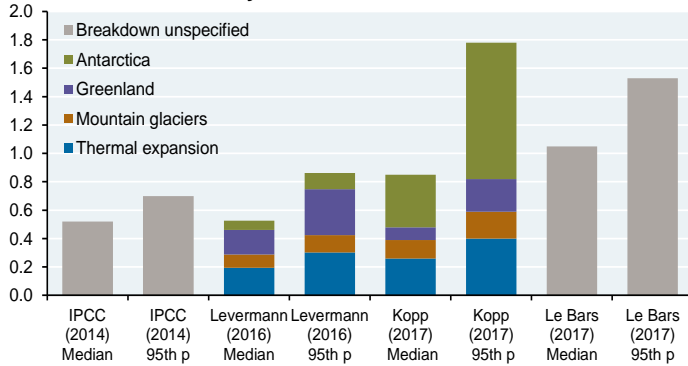
²¹ Flood mitigation can also include **nature-based engineering solutions** to restore wetlands between rivers and human settlements. This could provide extra water storage, slow down flood propagation and reduce flood risks in populated parts of a delta. One example: a plan to divert sediment-laden rivers back onto the Mississippi delta plain. Natural wetland-building processes with sediment delivered through river diversions are estimated to cost about 10x less than projects with conventional sediment delivery by barge or pipeline.



Flood Mitigation supplementary materials: carbon pathways, sea levels and storm surges

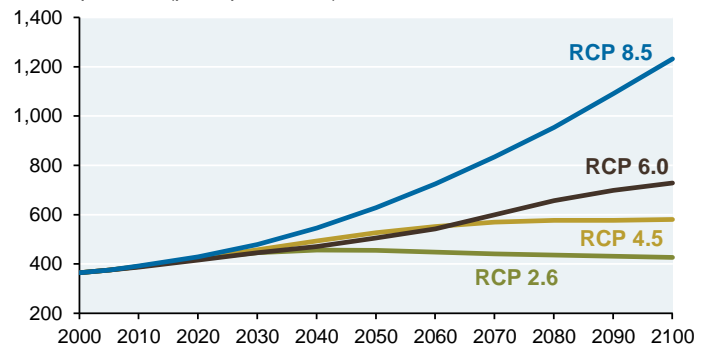
Most sea level rise analyses incorporate an assumed pace of global greenhouse gas emissions, referred to as “Representative Concentration Pathways”. The associated number refers to its GHG concentration relative to preindustrial values. Under RCP 8.5, sea levels are expected to rise by 2.0 to 2.5 meters by the year 2100. Under RCP 4.5, sea levels are expected to rise by 1.0 to 2.0 meters, as shown below. To be clear, RCP 4.5 assumes substantial progress in slowing the rate of GHG emissions over the next century.

Sea level rise by the year 2100 based on Representative Concentration Pathway 4.5, Meters



Source: IPCC, Levermann et al, Kopp et al, Le Bars et al.

Representative concentration pathways of GHGs CO₂ equivalent (parts per million)

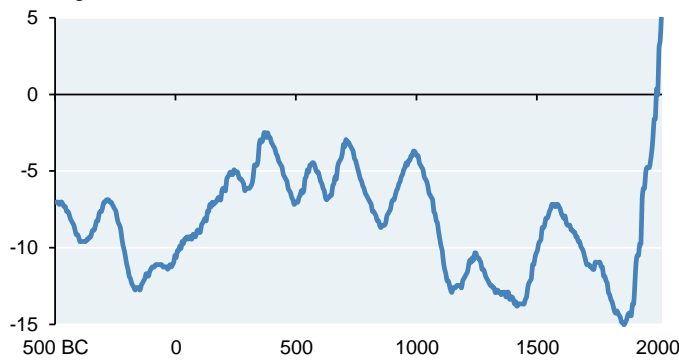


Source: "Fifth Assessment Report", IPCC. 2014.

The third chart shows a reconstructed estimate of sea levels since the year 500 BC. This chart appeared in the USGCRP Fourth National Climate Assessment, released in 2017. The last chart shows how the timing of storm surges can affect their severity, and the need to plan for surges which could happen at the worst times of the day.

Global mean sea level rising

Change relative to 2000, centimeters

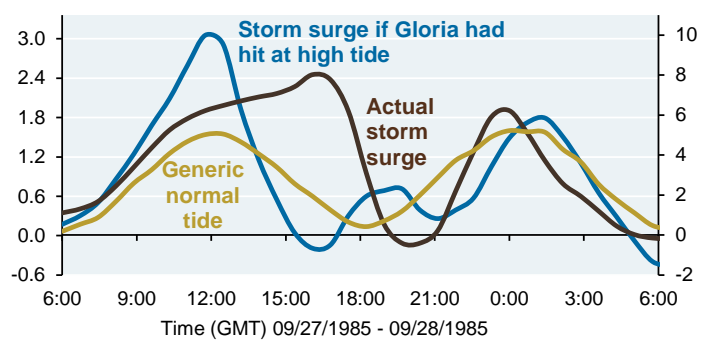


Source: US Global Change Research Program. 2017.

Hurricane Gloria (1985): the luck of the tides

Water level in meters

Water level in feet



Source: "Storm Surge Modeling and Climatology for the New York City Metropolitan Region", Brian A. Colle, Stony Brook University. 2009.



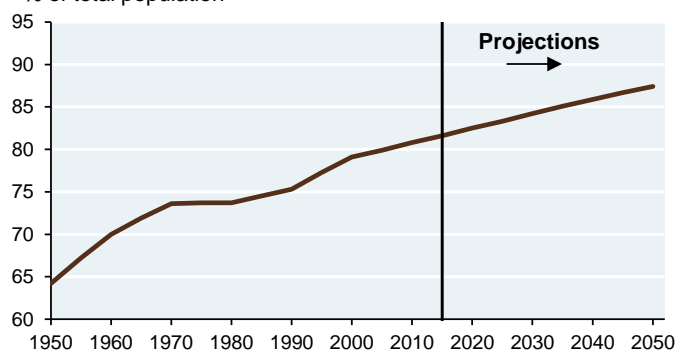
[5] Maybe the Constitutional framers were right about the Electoral College: who feeds and powers an increasingly urbanized world?

After the 2016 Presidential election, California Senator Boxer proposed a bill to abolish the Electoral College. In February 2018, a group led by litigator David Boies filed lawsuits in four states alleging that the way electors are allocated violates First Amendment rights. They're far from the first; over 700 proposals have been introduced in Congress to reform or eliminate the Electoral College over the last 200 years. In fact, there have been more proposals for Constitutional amendments on changing the Electoral College than on any other subject. As an alternative, opponents of the current approach often prefer a system that awards the Presidency to the candidate winning the popular vote, or a system that allocates electors proportionally within all states²². Everyone is entitled to their views, but I think the system works well as it is, partly due to the interconnection between **food, energy, national security and urbanization**. In this final section of our annual energy paper, I explain why.

Despite the mobility that modern telecommunications allow, US citizens continue to flock to the nation's cities. As shown below, US urbanization rates have been climbing steadily since the 1960's and are projected to keep rising. **Unsurprisingly, 21st century cities are massive consumers of food and energy.** A 2016 paper on urban food consumption puts in plain terms what the consequences are: "Modern cities neither supply their bulk resource needs, nor have the capacity to assimilate their wastes within their borders, which given the predominance of urban economies characterized by linear flows (material needs imported, waste produced exported), has left them physically reliant on their hinterlands and beyond"²³. When comparing across countries, **US cities rank near the top in terms of their ecological footprints per person from food and energy consumption.**

Living for the city: US urbanization trends

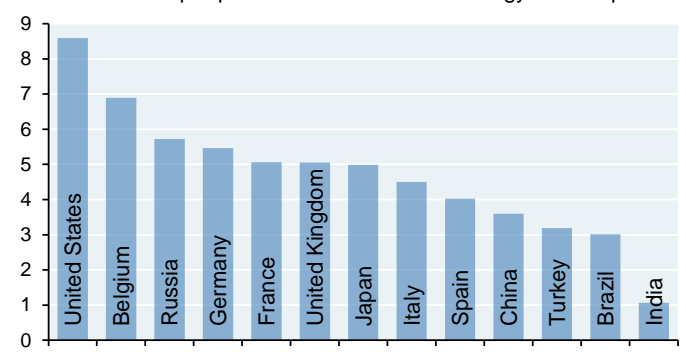
% of total population



Source: World Bank World Development Indicators. 2015, forecast to 2050.

Ecological footprint by country

Hectares of land per person based on food & energy consumption



Source: Global Footprint Network, 2013.

²² Constitutional rules allocate electors to states based on the number of their Representatives and Senators. The Constitution does *not* mandate the winner-take-all approach used by most states when allocating these electors to political parties; that decision is up to the states themselves.

Presidential candidates that **won the popular vote and lost the election**: Andrew Jackson (1824, to John Quincy Adams); Samuel Tilden (1876, to Rutherford B. Hayes); Grover Cleveland (1888, to Benjamin Harrison); Al Gore (2000, to George W. Bush); Hillary Clinton (2016, to Donald J. Trump). Some scholars believe this list should also include Richard Nixon in 1960 (who lost to John F. Kennedy), due to errant estimates of votes in Alabama.

²³ "Surveying the Environmental Footprint of Urban Food Consumption", B. Goldstein et al, Technical University of Denmark, Journal of Industrial Ecology, 2016.

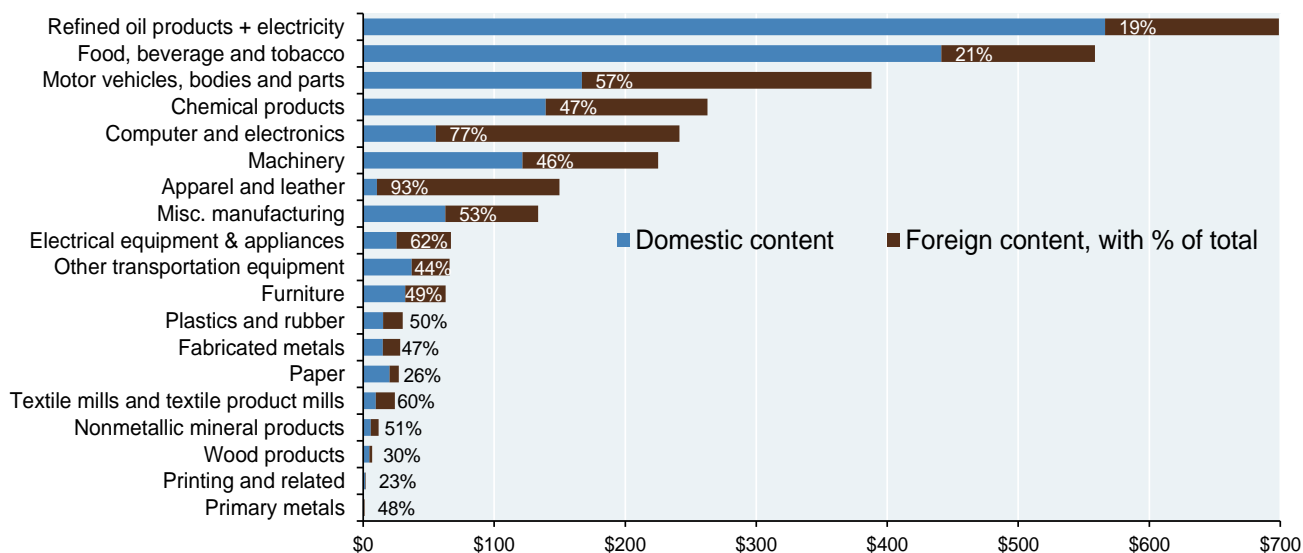


Next step: how reliant is the US on imported vs domestically produced food and energy? Using data from the Department of Commerce, the US Energy Information Administration and BP’s Annual Statistical Review of World Energy, we were able to determine three things, illustrated in the chart:

- Food products and oil products are the **two largest** sectors of manufactured goods in the US
- ~80% of US food and oil products are sourced **domestically**, with the rest being imported
- The percentage of food and oil products sourced domestically is much higher than for all other sectors, whose domestic content is generally below 50%

So, **in plain language**, the US relies extensively on its non-urban regions to provide massive amounts of food and energy to sustain its growing urban centers, and to a degree that sets food and energy apart from other sectors of the economy.

Food and oil products: the largest sectors of the US economy, and the ones most reliant on domestic production
Domestic demand for manufactured goods and electricity, billions of dollars



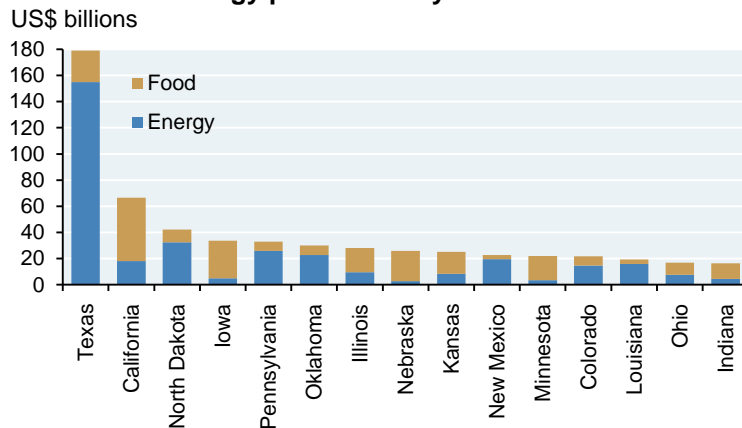
Source: Dept of Commerce, BEA, BP, EIA, JPMAM. Calendar years 2012-2016. Refined oil products = \$536 bn, electricity = \$163 bn. Refined oil product values based on \$74.6 per barrel (WTI crude plus Gulf Coast PADD 3 refining margin as of Feb 27, 2018) and 7.1 bn barrels per year of refined oil products consumption. Electricity value based on \$35 per MWh of wholesale electricity prices.



If that's the case, where does all the domestically produced US food and energy come from?

Mostly from Texas, California, the Midwest and the Rockies.

US food and energy production by state



Source: BP, EIA, USDA, JPMAM. 2017.

- Food based on farm receipts for meats, crops, seeds and related products
- Energy based on coal, natural gas and oil production; electricity generation from nuclear, hydroelectric, wind, solar, geothermal and biomass; and biofuels production

If you're interested...some details on US food and energy production by state

Food: In 2017, the US ranked #2 out of 113 countries in the Economist's Global Food Security Index. This high ranking reflects bountiful food production in seven states that account for almost 50% of total US food production: California, Iowa, Texas, Nebraska, Illinois, Minnesota and Kansas.

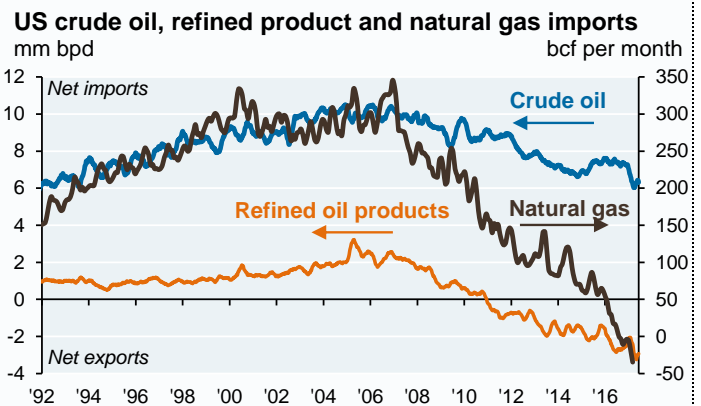
Energy

Natural gas. While the US is still a net importer of crude oil, it is a natural gas net exporter. As discussed in the Executive Summary, energy agencies project that natural gas will supply the greatest amount of energy in the decades ahead to meet growing demand (including any new electricity demand resulting from electric cars). Proven US natural gas reserves are concentrated in six states: Texas, Pennsylvania, West Virginia, Oklahoma, Ohio and Louisiana.

Oil. Texas accounts for half of US production; the largest 6 other oil production states are North Dakota, New Mexico, Oklahoma, California, Alaska and Louisiana.

Coal production is concentrated in Wyoming, West Virginia, Pennsylvania and Kentucky. Wyoming's production in value terms is diminished by the lower energy content of its subbituminous coal.

Other. Illinois and Pennsylvania generate the most nuclear power, with 12 other states not far behind; Washington and Oregon are notable producers and exporters of hydroelectric power; Texas, Iowa, Oklahoma and Kansas are the four largest wind-generation states; Iowa, Nebraska and Illinois lead in terms of ethanol production; and California generates roughly half the nation's solar and geothermal power. In value terms, natural gas, oil and coal accounted for 85% of US energy production in 2016.



Source: Energy Information Administration, JPMAM. February 2018.



Now to the crux of the issue: what political power should be vested in these food and energy centers? While their population densities are lower than in the cities, they provide the life blood to cities for their survival. Without them, cities would not be able to grow as they have, and/or the US would be highly reliant on geopolitically insecure and costlier imports of food and energy, and be exposed to volatile weather, environmental and exchange rate conditions out of its control.

Let's put the current Electoral College approach aside for a moment, and instead allocate the 538 electors to US states based on their **food & energy production** and based on their **population**, equally weighting both factors. The table shows the change in each state's electors using this revised approach. Texas, the Midwest and the Rockies gain electors, while East Coast states and Michigan lose them.

Reimagining the Electoral College: allocation of electors based on both food and energy production and population

| Largest increases in electors | | | |
|--------------------------------------|---------|---------|----------|
| State | Current | Revised | Increase |
| 1 Texas | 38 | 81 | 43 |
| 2 North Dakota | 3 | 14 | 11 |
| 3 Iowa | 6 | 13 | 7 |
| 4 Oklahoma | 7 | 13 | 6 |
| 5 Nebraska | 5 | 10 | 5 |
| 6 Kansas | 6 | 10 | 4 |
| 7 New Mexico | 5 | 9 | 4 |
| 8 Wyoming | 3 | 6 | 3 |
| 9 Colorado | 9 | 12 | 3 |
| 10 Alaska | 3 | 5 | 2 |
| 11 Louisiana | 8 | 10 | 2 |
| 12 South Dakota | 3 | 5 | 2 |

| Largest declines in electors | | | |
|-------------------------------------|---------|---------|---------|
| State | Current | Revised | Decline |
| 1 New York | 29 | 19 | (10) |
| 2 Florida | 29 | 20 | (9) |
| 3 New Jersey | 14 | 8 | (6) |
| 4 Massachusetts | 11 | 6 | (5) |
| 5 Michigan | 16 | 12 | (4) |
| 6 Virginia | 13 | 9 | (4) |
| 7 Maryland | 10 | 6 | (4) |
| 8 Georgia | 16 | 12 | (4) |
| 9 Tennessee | 11 | 7 | (4) |
| 10 Connecticut | 7 | 3 | (4) |
| 11 South Carolina | 9 | 6 | (3) |
| 12 Nevada | 6 | 3 | (3) |

Sources: USDA, EIA, BP, JPMAM. 2017.

Allocation of electors based 50% on food & energy production, and 50% on population. Food and energy based on production of crude oil, coal and natural gas; electricity generation from wind, solar, nuclear, hydropower, geothermal and biomass; biofuels production; and agricultural output from meats, crops, seeds and related products.

This approach might seem extreme, and that's because it is. However, it highlights something about the Electoral College that maybe the framers of the Constitution anticipated: a country's whose political system stands the test of time might need to distribute political power mostly based on population, but also based on each state's contribution to growth, security and geopolitical independence, and based on the environmental burden that it bears to support the rest of the country²⁴. With that in mind, the current Electoral College is already achieving that delicate balance, and is best left alone, just the way it is.²⁵

²⁴ While New York has banned hydraulic fracturing, **New York has no problem relying on the hydraulically-fractured natural gas that it imports from Ohio and Pennsylvania.** New York generated 40% of its electricity from natural gas in 2015, a figure that will almost certainly rise if the Indian Point nuclear plant is shut down.

²⁵ **And in all likelihood, that's the way it will stay.** A constitutional amendment to abolish the Electoral College would require a two thirds vote in the House and the Senate, **and** ratification by at least 38 state legislatures.

While there is **opposition** to the Electoral College among political science and law professors, there are also scholars that **defend** it. Examples include Constitutional Scholar Allen Guelzo who wrote on the subject after the 2016 election, and Richard A. Posner, identified by *The Journal of Legal Studies* as the most cited legal scholar of the 20th century (see source citations on page 34).



Sources (excluding materials mentioned in note and chart references earlier in the document)

Executive Summary

BP Statistical Review of World Energy, BP, June 2017.

International Energy Outlook 2016, Energy Information Administration, May 2016.

International Energy Outlook 2017, Energy Information Administration, September 2017.

Lazard's Levelized Cost of Energy Analysis – Version 10.0, Lazard, December 2016.

"Rapidly falling costs of battery packs for electric vehicles", Nykvist and Nilsson, Nature Climate Change, March 2015.

Renewable Energy Generating Capacity and Generation, Levelized Cost of Energy & Assumptions sections of Annual Energy Outlook 2017, Energy Information Administration, January 2017.

Rethinking Energy 2017, International Renewable Energy Agency, 2017.

Renewables 2017, International Energy Agency, 2017.

U.S. Solar Photovoltaic System Cost Benchmark, National Renewable Energy Laboratory, 2016.

World Energy Outlook 2017, International Energy Agency, 2017.

[#1] Electric vehicles

2018 BP Energy Outlook, BP, February 2018.

Critical Materials Strategy, U.S. Department of Energy, December 2011.

Energy Balances of Non-OECD Countries, International Energy Agency Statistics, 2015.

"Infiltration and evaporation of small hydrocarbon spills at gas stations", Hilpert and Breysse (Johns Hopkins), September 2014.

"The Macro Implications of the Push Toward Electric Vehicles," Bridgewater, August 31 2017.

"Performance metrics required of next-generation batteries to make a practical electric semi truck", Viswanathan, ACS, 2017.

[#2] High voltage direct current lines

"Understanding China's New Mandatory 58% Coal Cap Target", Alvin Lin, Natural Resources Defense Council, March 2017.

"Better power lines would help U.S. supercharge renewable energy, study suggests", Puneet Kollipara, Science Magazine, January 2016.

[#3] Jacobson rebuttal (in order of publication)

"Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes", Jacobson et al., Proceedings of the National Academy of Sciences, November 2015.

"Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar", Clack et al., Proceedings of the National Academy of Sciences, February 2017.

"The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims", Jacobson et al., Proceedings of the National Academy of Sciences, June 2017.

"Response to Jacobson et al.", Clack et al., June 2017.



[#4] Sea level rise and flood mitigation infrastructure

"A high-end sea level rise probabilistic projection including rapid Antarctic ice sheet mass loss", Le Bars et al., Institute of Physics Publishing, March 2017.

Climate Change 2014 Synthesis Report, Intergovernmental Panel on Climate Change, 2014.

"Climate-change-driven accelerated sea-level rise detected in the altimeter era", Nerem et al., Proceedings of the National Academy of Sciences, January 2018.

"Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections", Kopp et al., Earth's Future, November 2017.

"Future sea level rise constrained by observations and long-term commitment", Levermann, Proceedings of the National Academy of Sciences, January 2016.

"Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites", Kopp et al., Earth's Future, June 2014.

State of the U.S. Ocean and Coastal Economies: 2016 Update, Middlebury Institute of International Studies, 2016.

"Building land with a rising sea", Temmerman and Kirwan, Science Magazine, August 2015.

[#5] Food, energy and the US Electoral College

US National Archives and Records Administration: the Electoral College

"The Electoral College Has Been Divisive Since Day One", Smithsonian.com, November 21, 2016

"In defense of the electoral college", Allen Guelzo and James Hulme, Wash Post, November 15, 2016.

"In defense of the electoral college: Five reasons to keep our despised method of choosing the president", Richard A. Posner, Slate Magazine, November 12, 2012.

"What is made in America", US Department of Commerce, Economics and Statistics Administration, ESA Issue Brief #04-14, October 2014.

"Group of law firms file complaint challenging winner-take-all approach to electoral college", Jurist.org, February 23, 2018

Acronyms

AC Alternating current; **BTU** British thermal unit; **CNG** Compressed Natural Gas; **DoE** Department of Energy; **EIA** Energy Information Administration; **EV** electric vehicle; **GHG** greenhouse gas; **HVDC** high voltage direct current; **ICE** Internal combustion engine; **IEA** International Energy Agency; **IPCC** Intergovernmental Panel on Climate Change; **kV** kilovolt; **kWh** kilowatt-hour; **MWh** megawatt-hour; **NMC** Nickel Manganese Cobalt; **OECD** Organization for Economic Co-operation and Development; **PHEV** Plug in hybrid vehicle; **PV** Photovoltaic; **RCP** Representative Concentration Pathways



IMPORTANT INFORMATION

Purpose of This Material: This material is for information purposes only. The views, opinions, estimates and strategies expressed herein constitutes Michael Cembalest's judgment based on current market conditions and are subject to change without notice, and may differ from those expressed by other areas of J.P. Morgan. **This information in no way constitutes J.P. Morgan Research and should not be treated as such.**

Non-Reliance: We believe the information contained in this material to be reliable and have sought to take reasonable care in its preparation; however, we do not represent or warrant its accuracy, reliability or completeness, or accept any liability for any loss or damage (whether direct or indirect) arising out of the use of all or any part of this material. We do not make any representation or warranty with regard to any computations, graphs, tables, diagrams or commentary in this material which are provided for illustration/reference purposes only. We assume no duty to update any information in this material in the event that such information changes. Any projected results and risks are based solely on hypothetical examples cited, and actual results and risks will vary depending on specific circumstances. Forward looking statements should not be considered as guarantees or predictions of future events. **Investors may get back less than they invested, and past performance is not a reliable indicator of future results.**

Risks, Considerations and Additional information: There may be different or additional factors which are not reflected in this material, but which may impact on a client's portfolio or investment decision. The information contained in this material is intended as general market commentary and should not be relied upon in isolation for the purpose of making an investment decision. Nothing in this document shall be construed as giving rise to any duty of care owed to, or advisory relationship with, you or any third party. Nothing in this document is intended to constitute a representation that any investment strategy or product is suitable for you. You should consider carefully whether any products and strategies discussed are suitable for your needs, and to obtain additional information prior to making an investment decision. Nothing in this document shall be regarded as an offer, solicitation, recommendation or advice (whether financial, accounting, legal, tax or other) given by J.P. Morgan and/or its officers or employees, irrespective of whether or not such communication was given at your request. J.P. Morgan and its affiliates and employees do not provide tax, legal or accounting advice. You should consult your own tax, legal and accounting advisors before engaging in any financial transactions.

Contact your J.P. Morgan representative for additional information concerning your personal investment goals. You should be aware of the general and specific risks relevant to the matters discussed in the material. You will independently, without any reliance on J.P. Morgan, make your own judgment and decision with respect to any investment referenced in this material.

J.P. Morgan may hold a position for itself or our other clients which may not be consistent with the information, opinions, estimates, investment strategies or views expressed in this document. JPMorgan Chase & Co. or its affiliates may hold a position or act as market maker in the financial instruments of any issuer discussed herein or act as an underwriter, placement agent, advisor or lender to such issuer. References in this report to "J.P. Morgan" are to JPMorgan Chase & Co., its subsidiaries and affiliates worldwide.

Legal Entities and Regulatory Information: In the **United States**, Bank deposit accounts, such as checking, savings and bank lending, may be subject to approval. Deposit products and related services are offered by **JPMorgan Chase Bank, N.A.** Member FDIC.

JPMorgan Chase Bank, N.A. and its affiliates (collectively "**JPMCB**") offer investment products, which may include bank managed accounts and custody, as part of its trust and fiduciary services. Other investment products and services, such as brokerage and advisory accounts, are offered through **J.P. Morgan Securities LLC ("JPMS")**, a member of [FINRA](#) and [SIPC](#). **JPMCB and JPMS** are affiliated companies under the common control of JPMorgan Chase & Co. Products not available in all states.

In the **United Kingdom**, this material is issued by **J.P. Morgan International Bank Limited (JPMIB)** with the registered office located at 25 Bank Street, Canary Wharf, London E14 5JP, registered in England No. 03838766. **JPMIB** is authorised by the Prudential Regulation Authority and regulated by the Financial Conduct Authority and the Prudential Regulation Authority. In addition, this material may be distributed by **JPMorgan Chase Bank, N.A. ("JPMCB"), Paris branch**, which is regulated by the French banking authorities Autorité de Contrôle Prudentiel et de Résolution and Autorité des Marchés Financiers or by **J.P. Morgan (Suisse) SA**, which is regulated in Switzerland by the Swiss Financial Market Supervisory Authority (FINMA).

In **Hong Kong**, this material is distributed by **JPMCB, Hong Kong branch**. JPMCB, Hong Kong branch is regulated by the Hong Kong Monetary Authority and the Securities and Futures Commission of Hong Kong. In Hong Kong, we will cease to use your personal data for our marketing purposes without charge if you so request. In **Singapore**, this material is distributed by **JPMCB, Singapore branch**. JPMCB, Singapore branch is regulated by the Monetary Authority of Singapore. Dealing and advisory services and discretionary investment management services are provided to you by JPMCB, Hong Kong/Singapore branch (as notified to you). Banking and custody services are provided to you by JPMIB and/or JPMCB Singapore Branch. The contents of this document have not been reviewed by any regulatory authority in Hong Kong, Singapore or any other jurisdictions. You are advised to exercise caution in relation to this document. If you are in any doubt about any of the contents of this document, you should obtain independent professional advice.

With respect to countries in **Latin America**, the distribution of this material may be restricted in certain jurisdictions. Receipt of this material does not constitute an offer or solicitation to any person in any jurisdiction in which such offer or solicitation is not authorized or to any person to whom it would be unlawful to make such offer or solicitation. To the extent this content makes reference to a fund, the Fund may not be publicly offered in any Latin American country, without previous registration of such fund's securities in compliance with the laws of the corresponding jurisdiction. Public Offering of any security, including the shares of the Fund, without previous registration at Brazilian Securities and Exchange Commission – CVM is completely prohibited. Some products or services contained in the materials might not be currently provided by the Brazilian and Mexican platforms. This material should not be duplicated or redistributed without our permission.

© 2018 JPMorgan Chase & Co. All rights reserved.