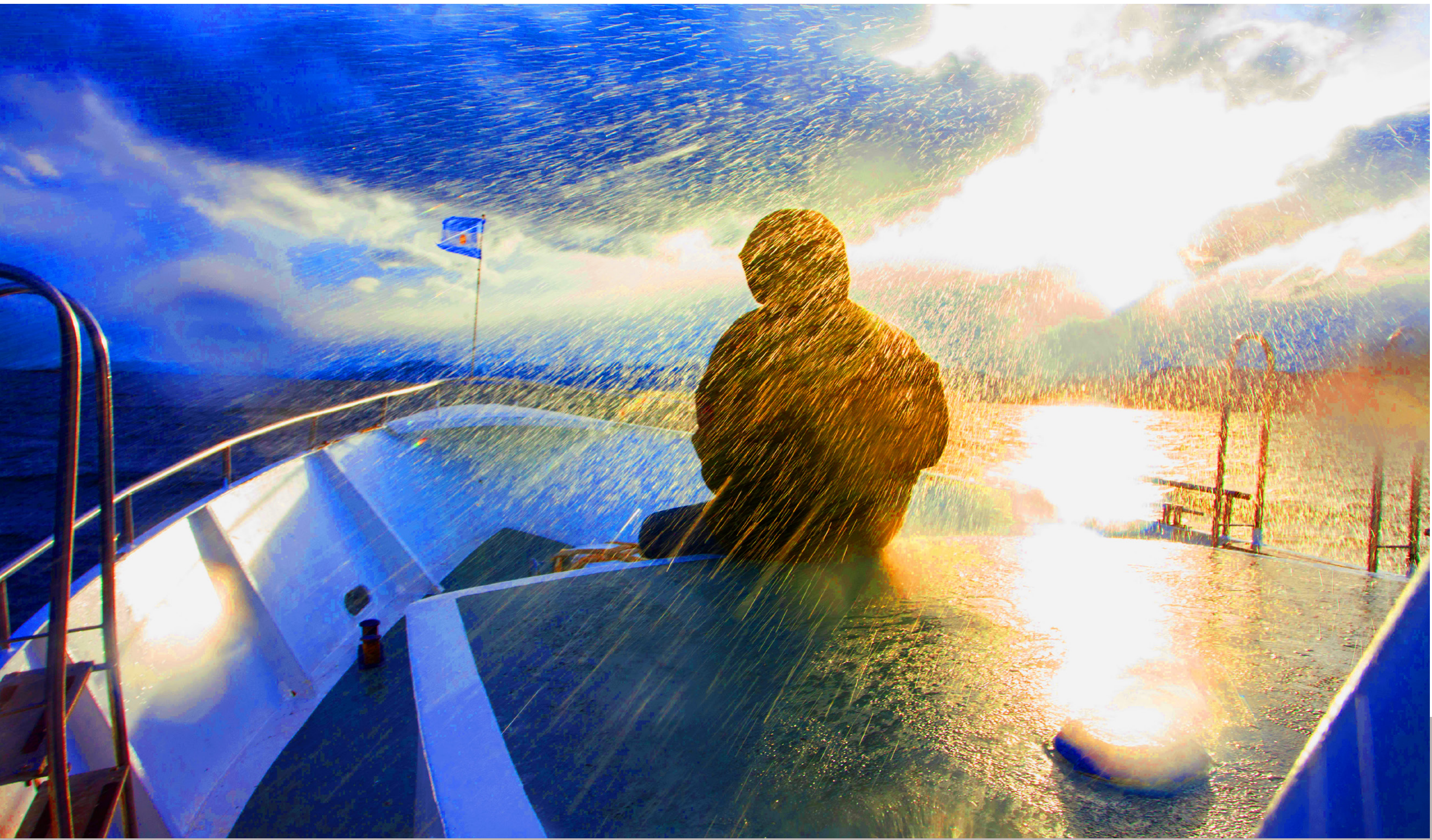
EYE ON THE MARKET • ENERGY OUTLOOK 2018

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

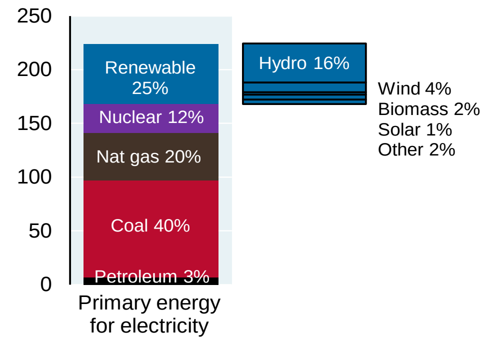
Impressive wind and solar power milestones have been reached in the last few years: ongoing declines in capital costs, power auction prices well below 10 cents per kWh, rising wind capacity factors and rising capacity additions which in 2016 exceeded non-renewable new capacity for the 4th year in a row. 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.

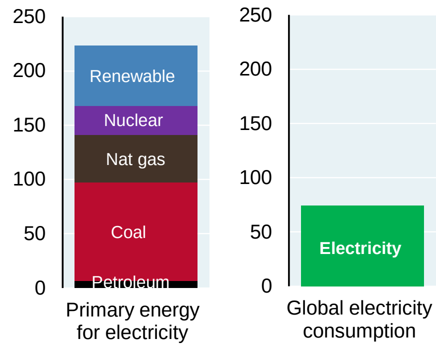
The second chart shows **how electricity gets generated**: 225 quads of primary energy are required to generate 75 quads of electricity. Where did the rest go? 150 quads are lost to thermal conversion[1], power plant consumption and transmission.

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



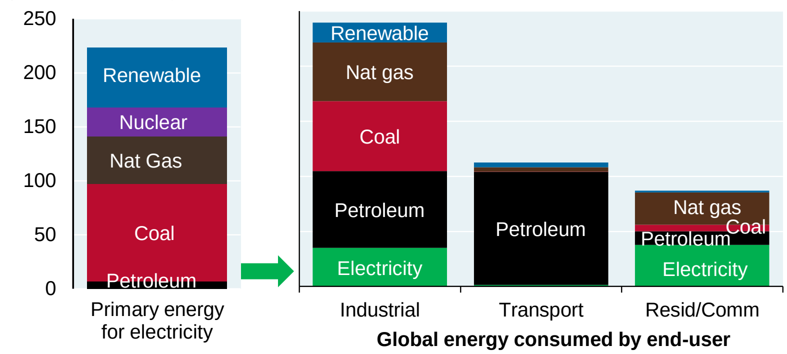
Source: Energy Information Administration, JPMAM. 2017.

[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:**

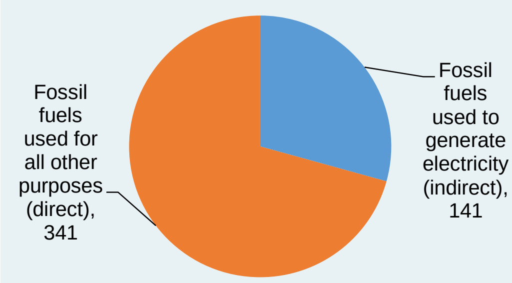
- Electricity is only 17% of global final energy consumption, and is consumed almost entirely by industrial and residential/commercial users (a very small amount is used by electrified rail)
- Electricity accounts for less than one third of global fossil fuel use
- While coal usage still exceeds natural 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.

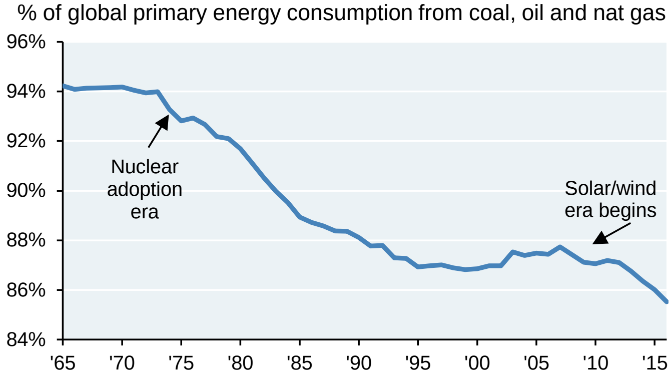
Electricity accounts for less than one third of global fossil fuel consumption
quadrillion BTU, global



Source: EIA, IEA, JPMAM. 2017.

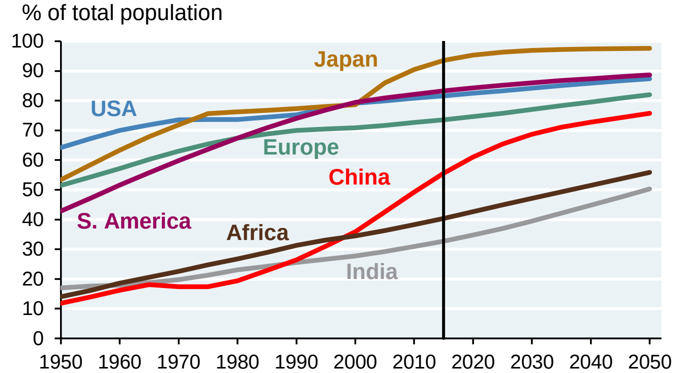
- Fossil fuels accounted for **~85%** of global primary energy consumed[3] in 2016**.** That figure is now gradually declining with the onset of the solar/wind era
- Energy solutions need to be designed for increasingly urbanized societies, rendering discussions about so-called "off-the-grid" approaches 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.

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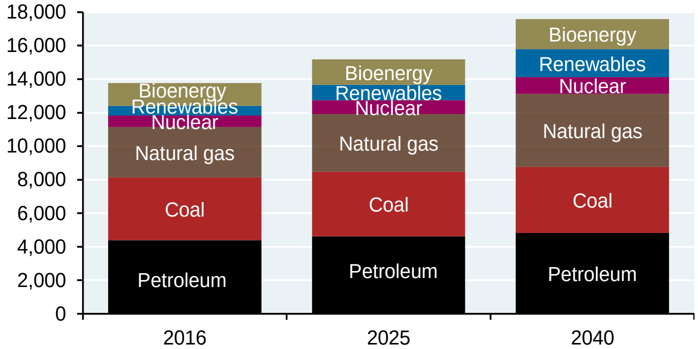
[2] "*The environmental case for natural gas*", International Energy Agency, November 2017

[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.

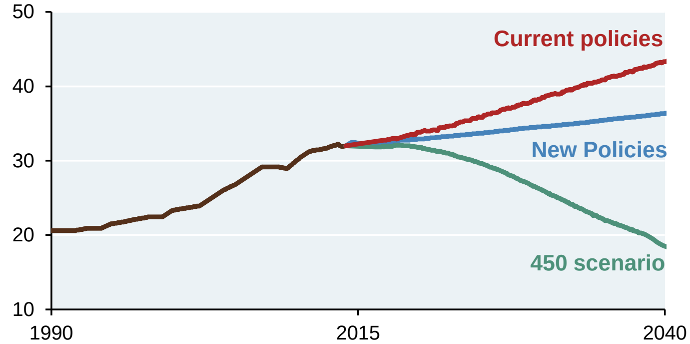
Where does that leave us? Even if renewable sources rose to 50% of electricity generation from 25%, fossil fuels could still represent ~70% of total energy use unless transport and industry decarbonize as well. On transportation, the International Energy Agency has one of the most optimistic electric 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 bioenergy[4], the renewable share expands from 14% in 2016 to just 20% by 2040. While CO_2 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 CO_2 emissions from primary energy demand
Gigatonnes per year



Source: International Energy Agency. 2016.

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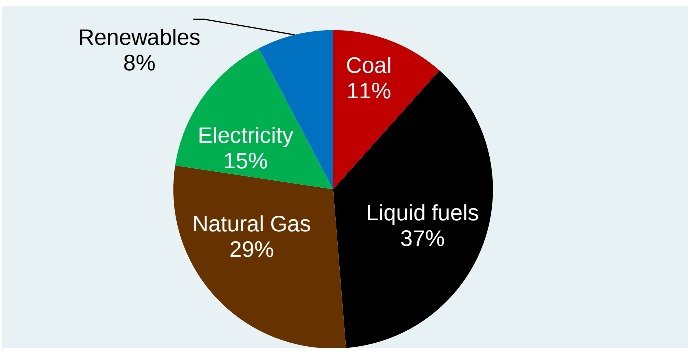
[4] **The bioenergy question.** Bioenergy currently provides 10% of the world's primary energy. It may sound "**green**", but around 2/3 of bioenergy is consumed in developing countries for cooking and heating, using open fires or cookstoves with considerable negative impact on health (smoke pollution) 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

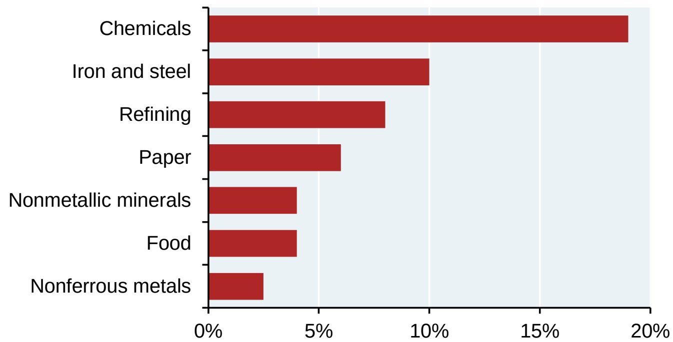
Only 15% of OECD industrial energy use is derived from electricity; the rest is mostly direct consumption of fossil fuels. What does the industrial sector do with all these fossil fuels? The bar chart and tables show examples: oil refining and the manufacture of chemicals, iron, steel, paper and food 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.

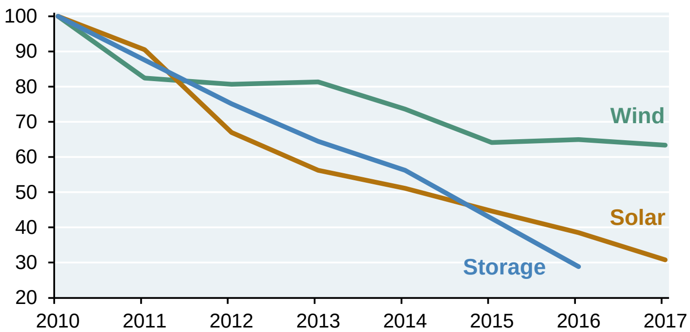
Table of Contents

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:

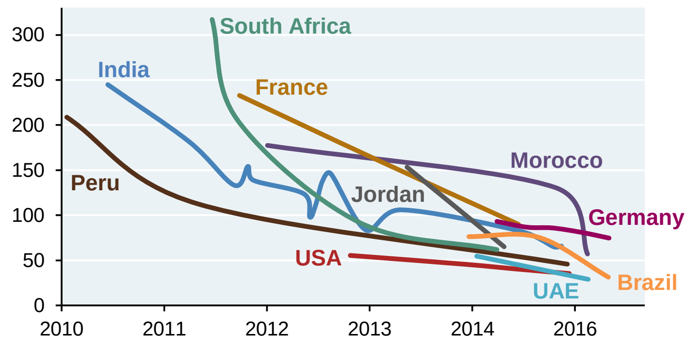
- wind and solar reaching 5% of global electricity generation in 2017 (up from 0.5% in 2004), alongside 16% from hydropower
- wind and solar power auction prices converging below $100 per MWh (10 cents per kWh); the latest US levelized wind power purchase agreements have reached 2 cents per kWh according 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



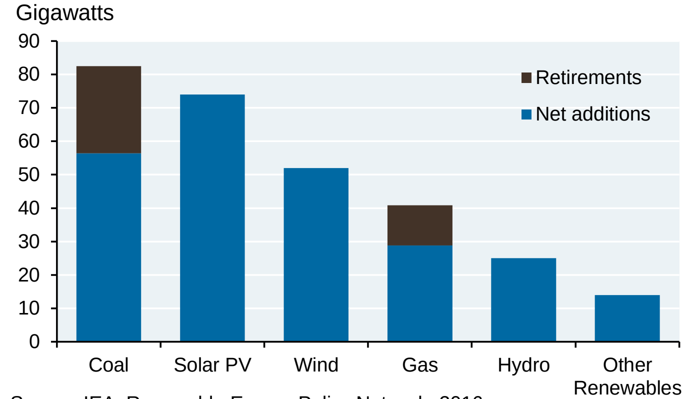
Source: EIA, NREL, Lazard, UBS, Nykvist, et. al. December 2017. Storage proxied by electric vehicle battery packs.

Global solar auction prices converging below $100/MWh
US$/MWh



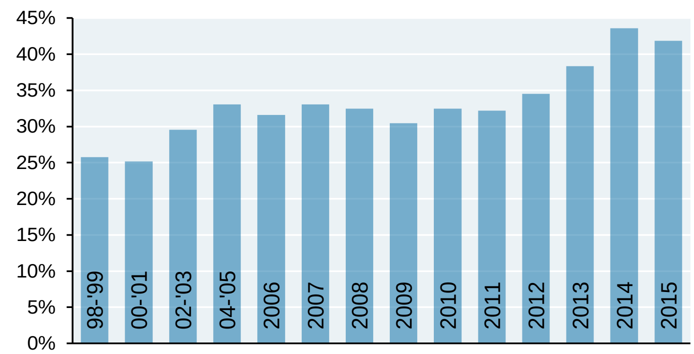
Source: International Renewable Energy Agency. 2017.

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 CO_2 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.

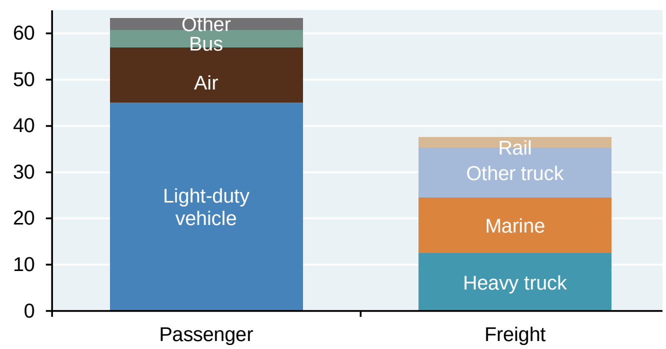
Select topics from prior *Eye on the Market* energy editions (hyperlinks)

- 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.

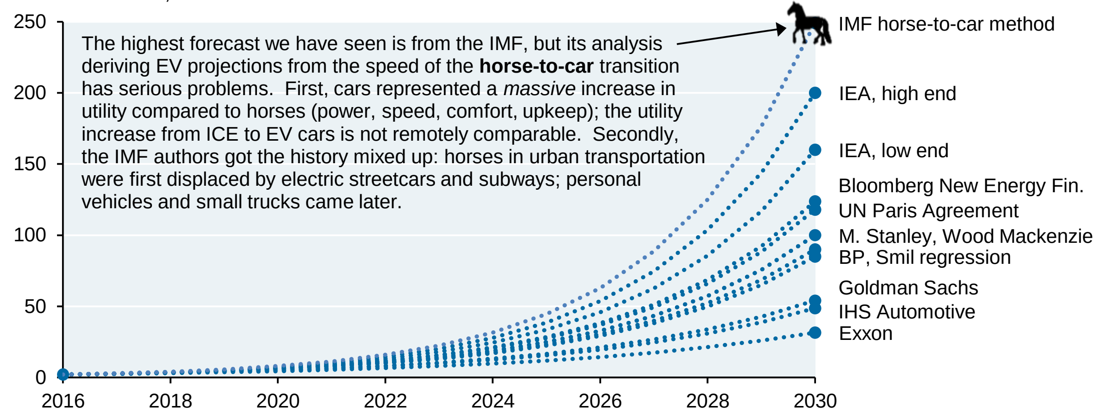
Company policy goals

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

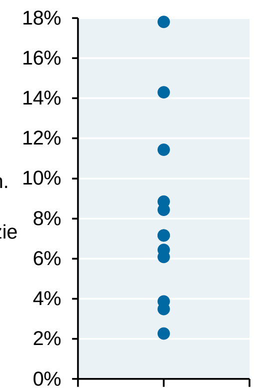
Source: IEA Global EV Outlook, OICA, Reuters, NYT, Bloomberg, listed companies. 2018.

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 2030[5]. 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 fleet[6]. 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



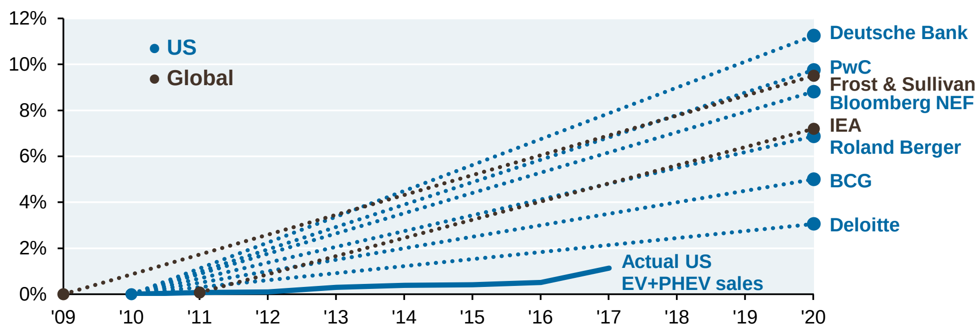
2030 EV penetration
% of global fleet size



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



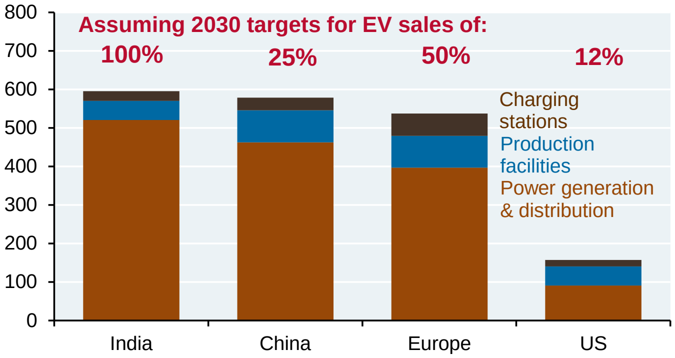
Source: DOE, BEA, hybridcars.com, and listed organizations. 2017. Note: global EV+PHEV sales in 2016 were also around 1.1%.

[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.

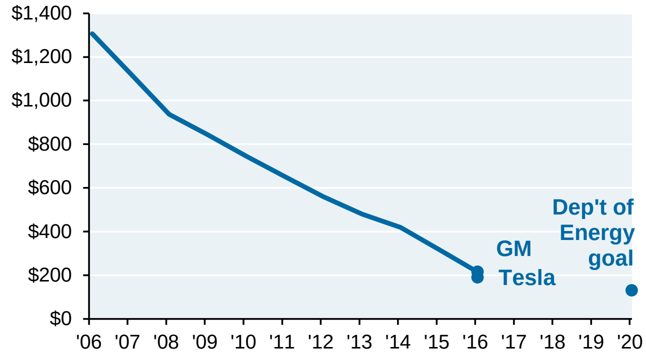
Why might the EV revolution occur at slower speeds rather than faster ones? First, related infrastructure needs are not just charging stations and production factories. Large power generation and transmission investments would be needed as well. According to one analysis we have seen, India, China and 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 design[7]. 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

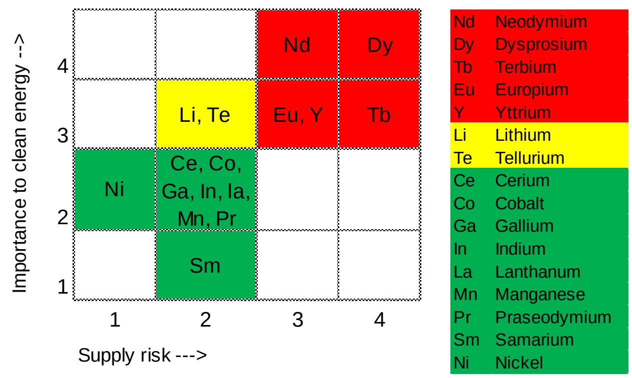
Source: "*Electrochemical Energy Storage R&D Overview*", US Department of Energy, D. Howell, 2017.

[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 question[8], perhaps since China is the world's largest EV market. Here's what they found:

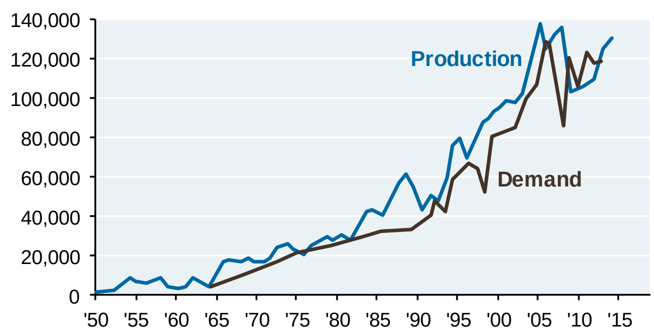
- Demand from electric vehicles is expected to reach 68% of all rare earth demand in 2030 (compared to 50% today)
- While current rare earth elements are mined primarily by China and Australia, there are 478 megatons of rare earth oxides widely distributed around the world which could sustain current 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



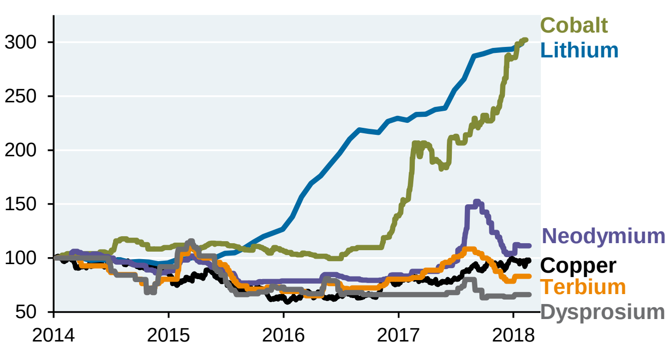
Source: US Department of Energy, 2011.

Global rare earth production and demand
Metric tons



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.

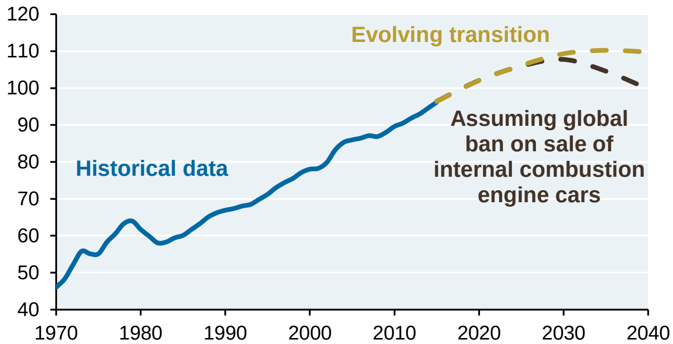
A brief comment on autonomous car energy use

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.

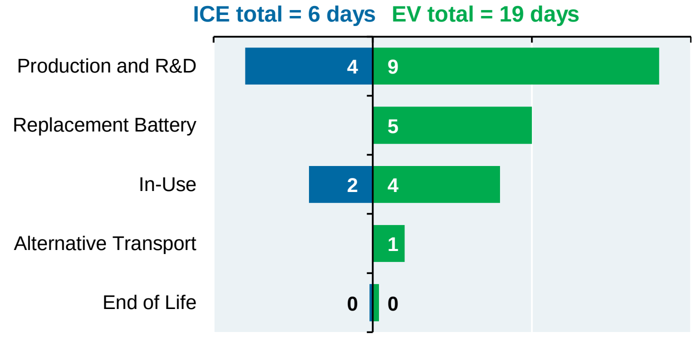
Bottom line: the EV revolution is here, and some manufacturers claim that break-even costs vs ICE vehicles are closing fast (see next page). But some EV forecasts seem too aggressive to us, given the challenges. As a result, we're inclined towards the lower half of the forecasts on page 10, and are dubious 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 engine[9] 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
Million barrels/day



Source: BP Energy Outlook. 2018.

"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 CO_2 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.

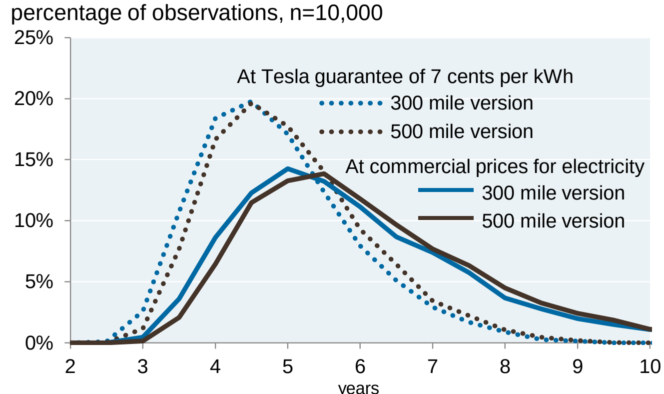
The average short haul diesel truck costs $120k, travels ~90,000 miles per year (~300 per working day and capable of traveling 1,000+), and lasts for around one million miles. Tesla announced two possible substitutes: an EV semi capable of travelling 500 miles per charge at a cost of $180k, and a 300 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

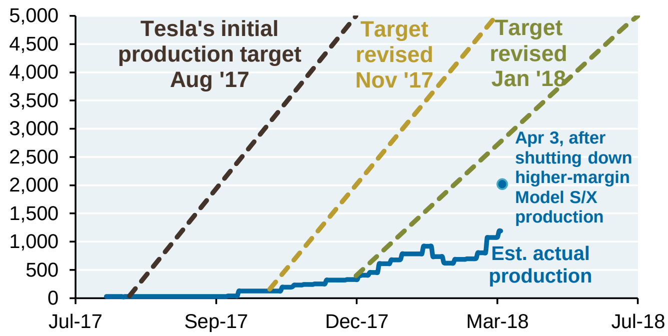
- Some analysts assume that Tesla's one million mile warranty **includes battery replacement**. There has been no clear messaging from Tesla on this issue. We assume the driver replaces the battery once its cycle lifetime has run its course. The driver could opt instead to relegate the truck to other 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.

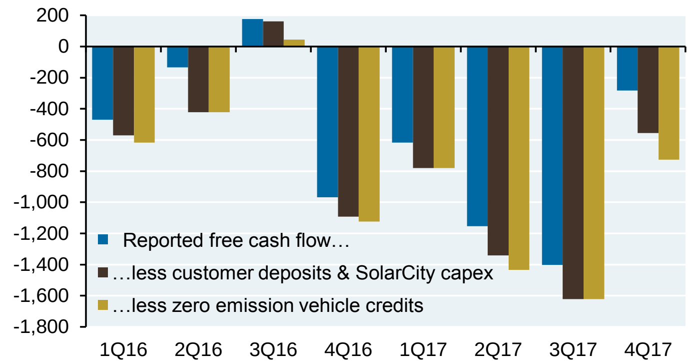
Consider us skeptical, at least until more details emerge. Here are some charts assessing Tesla as a going concern with long term warranty and electricity price guarantees. For the complete set of our Tesla charts on these and other related topics, please click **here**.

Tesla Model 3 production: targets vs reality
Weekly # of Model 3s manufactured



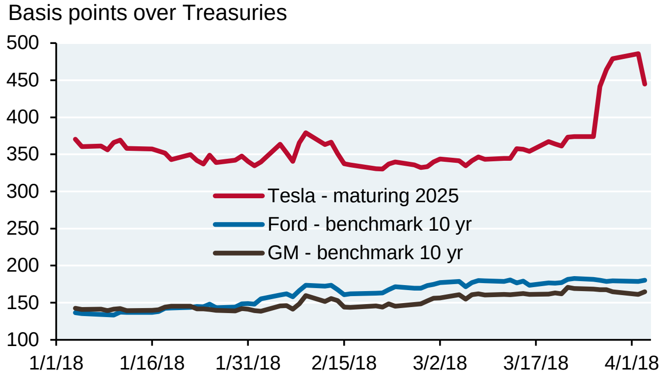
Source: Bloomberg. April 3, 2018. Actual production estimated based on manufacturer vehicle registrations.

Tesla's cash burn
Free cash flow, US$ millions



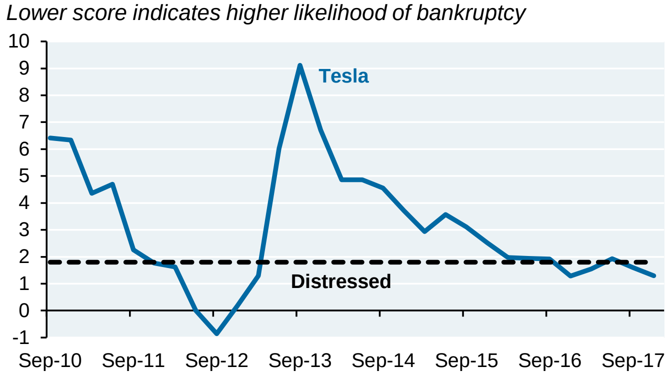
Source: Bloomberg. 4Q 2017.

Carmaker credit spreads
Basis points over Treasuries



Source: Bloomberg, April 3, 2018.

Tesla's Altman Z-score
Lower score indicates higher likelihood of bankruptcy

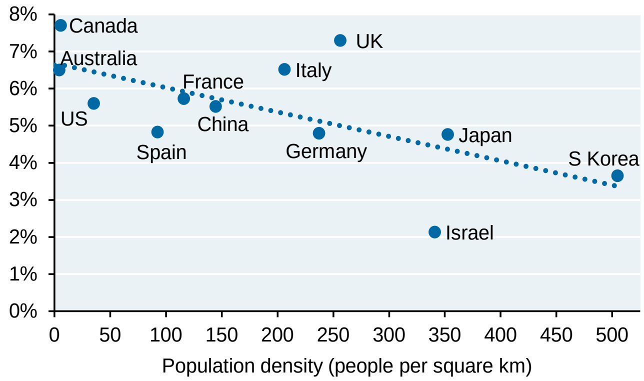


Source: Bloomberg, JPMAM. Quarterly data through December 31, 2017.

[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%

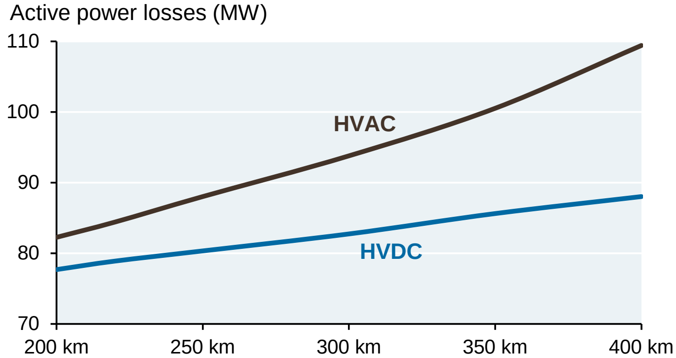
Source: 2015 Wind Integration Workshop, Kansai University (Japan), NRDC.

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)

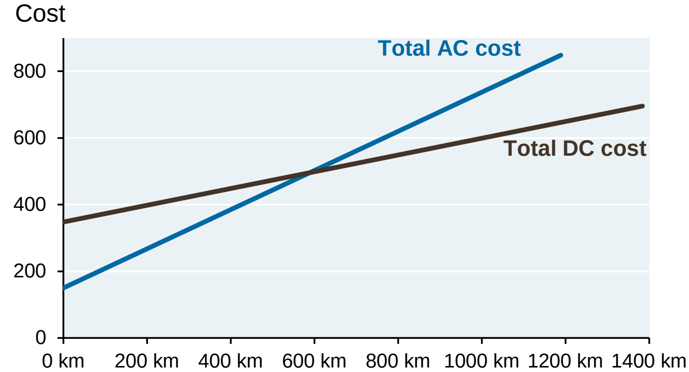
The chart on the right from the IEA puts all the pieces together: DC lines are usually cheaper once distances exceed 600-700 km[10]. Siemens and ABB report similar breakeven distances (both are working on the world's first 1,100 kV HVDC transformers for use in Guquan, China).

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

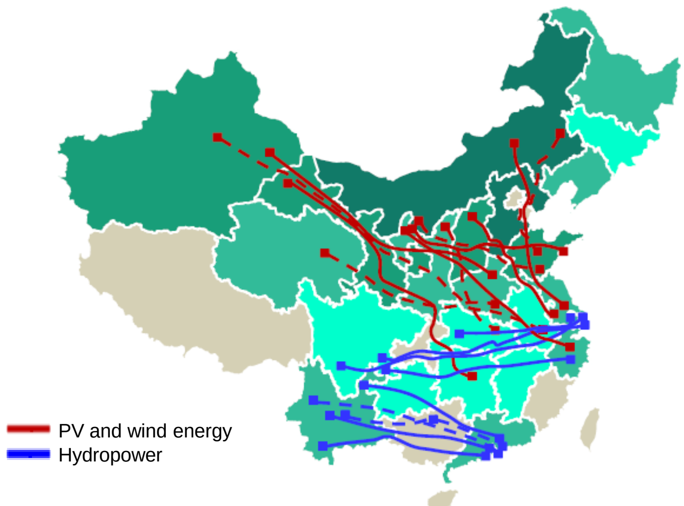


Source: IEA Energy Technology Systems Analysis Programme, 2014.

[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, Sold 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 Research[11]. 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 Gov't 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 quality 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 2009[12]. 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

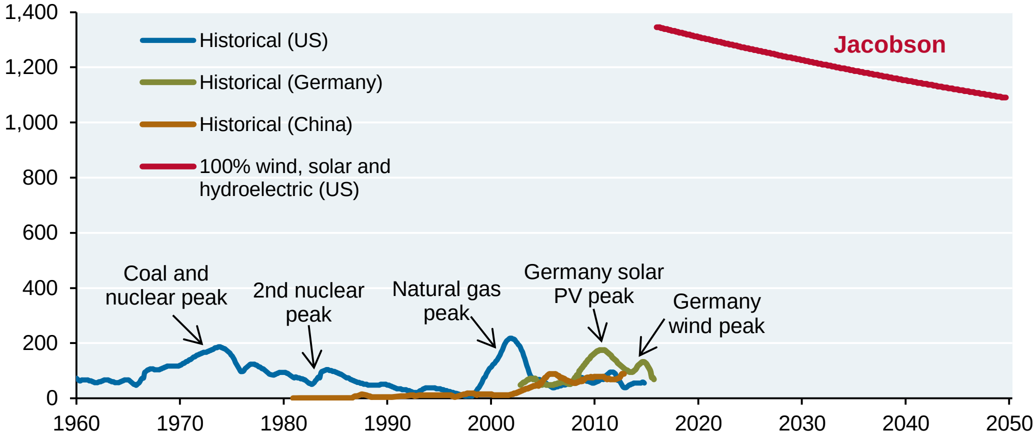
- Carnegie Institution for Science (Department of Global Ecology)
- Carnegie Mellon University (Department of Engineering and Public Policy; Tepper School of Business)
- Columbia University (Center for Global Energy Policy)
- Lawrence Livermore National Laboratory
- NOAA Earth System Research Laboratory
- 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.

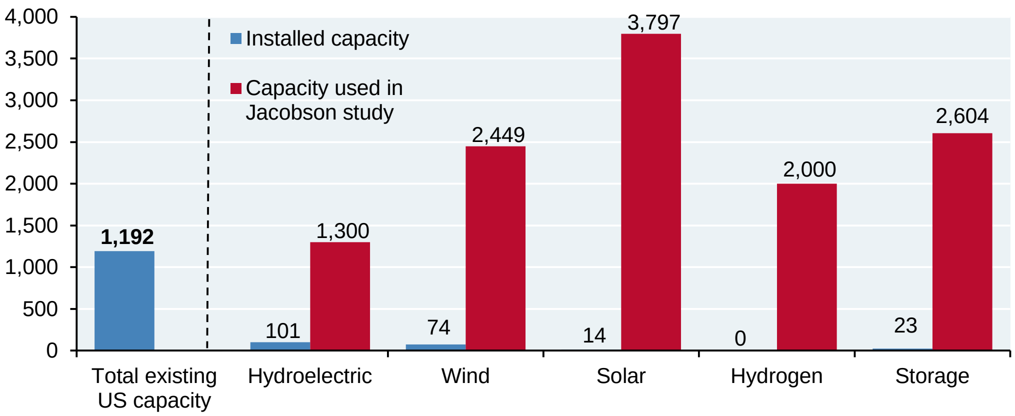
Historical rates of installed electric-generating capacity per capita
Capacity additions, watts per year per capita



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 error[14], 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*]

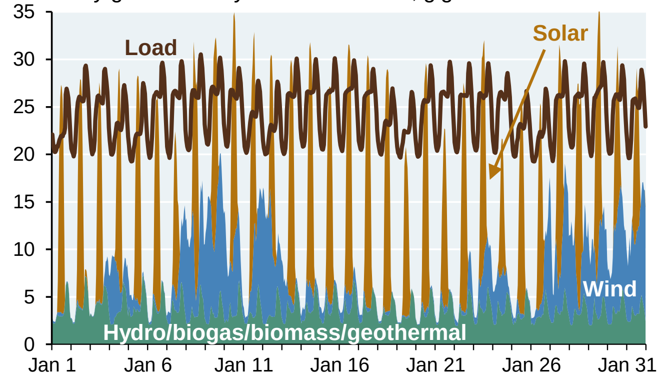
On Jacobson's assumed expansion of the hydrogen economy:

- 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



Source: CAISO, JPMAM. 2015.

…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.

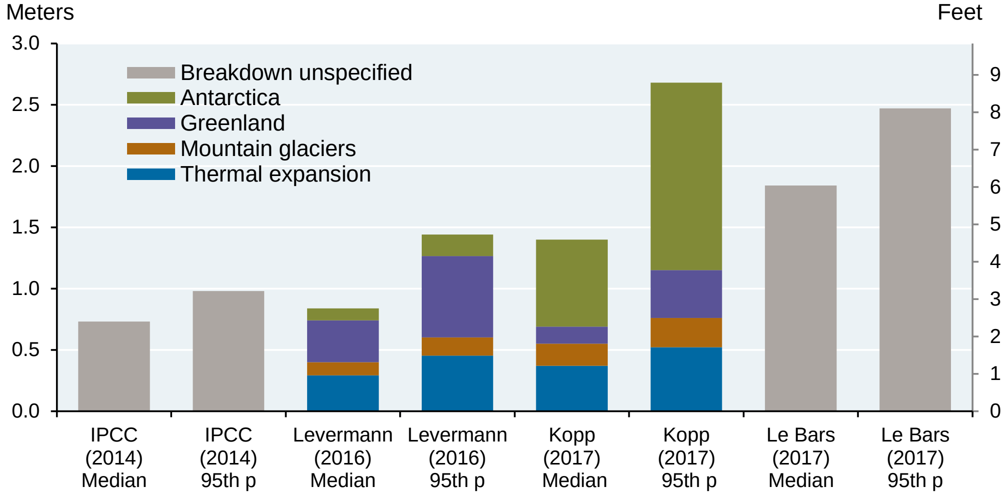
The mic has been dropped.

[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 2100[15]. Some newer estimates show higher levels, ranging from 2.0 to 2.5 meters of sea level rise instead[16]. 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.

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[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.

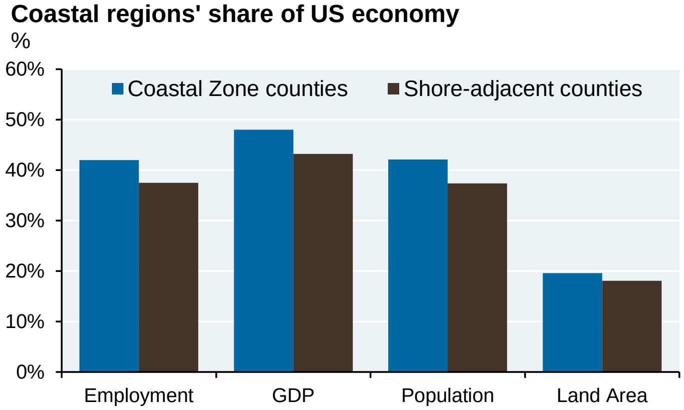
[17] "*Contribution of Antarctica to past and future sea-level rise*", DeConto (UMass) and Pollard (Penn State), Nature Magazine, March 2016.

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 Program[18] 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

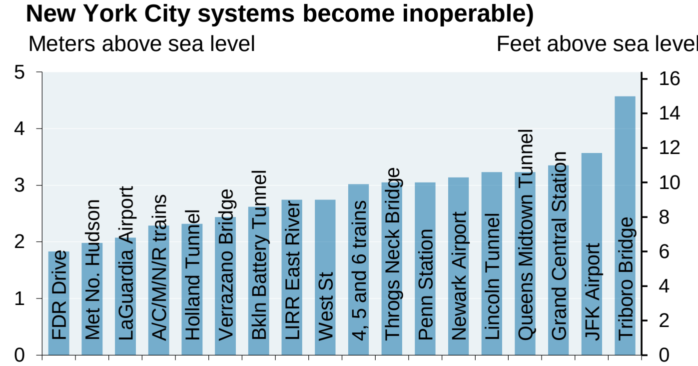
Here are some charts that make the point as well: the large contribution to the US economy from coastal and shore-adjacent counties; storm surge heights that render major NYC infrastructure inoperable; and the increasing number of tidal flood days per year in coastal states.

Coastal regions' share of US economy



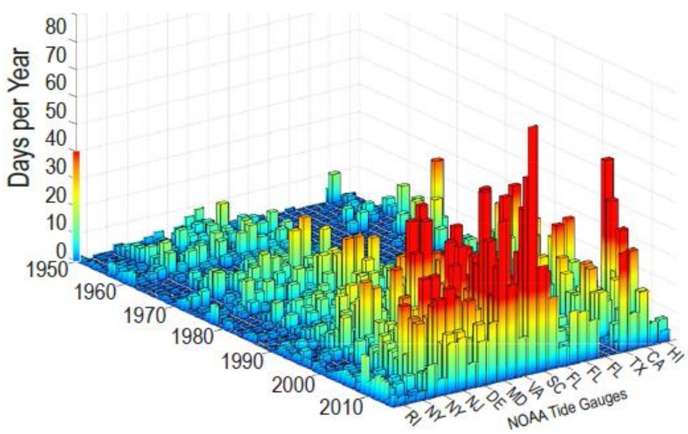
Source: Middlebury, Nat'l Ocean Econ Program. 2016. Data as of 2014.

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

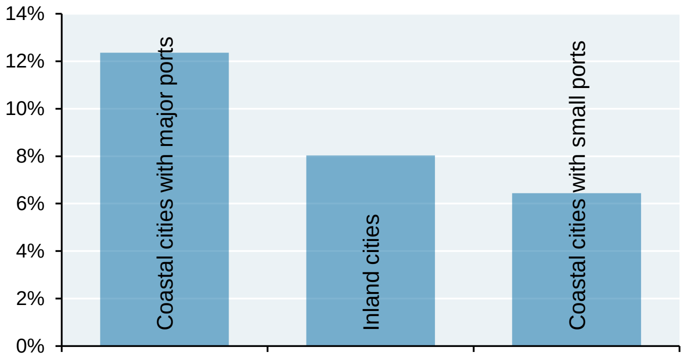


Source: USGCRP Fourth Climate Assessment, Chapter 12. 2014.

[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.

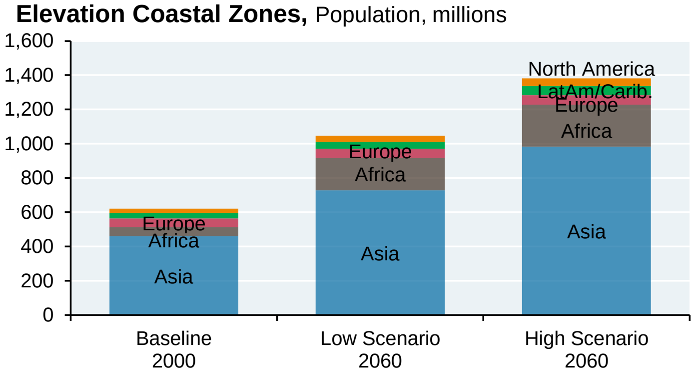
Coastal port cities boast stronger growth vs inland cities
Aggregate real GDP growth, 2008-2013, %



Source: Euromonitor. 2014.

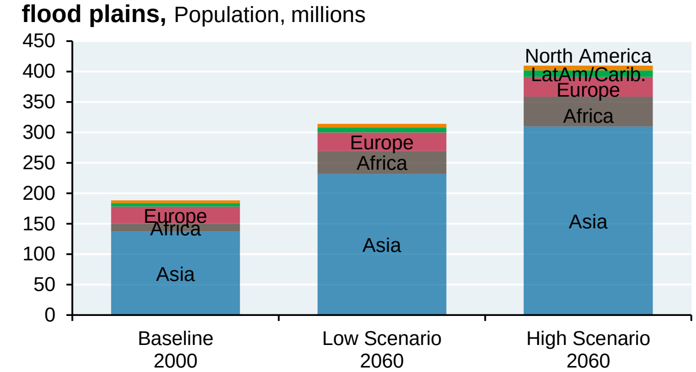
One assessment of exposed populations comes from the Coastal Risks and Sea-Level Rise Research Group at Kiel University in Germany. Their analysis takes two approaches: how many people will live in "low coastal elevation zones", and how many will live in the "100-year flood plain"[19]. The former is 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

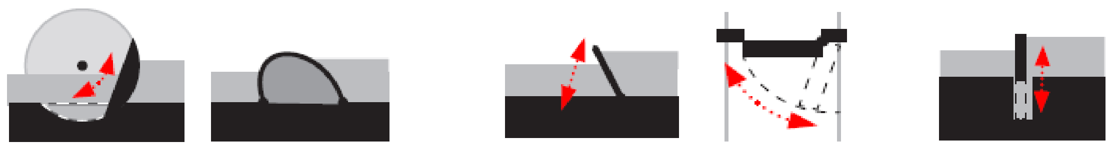


Source: *"Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment",* Neumann et al. 2015.

[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 Dep't.

"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 assets[20]. 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 today[21]. 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.

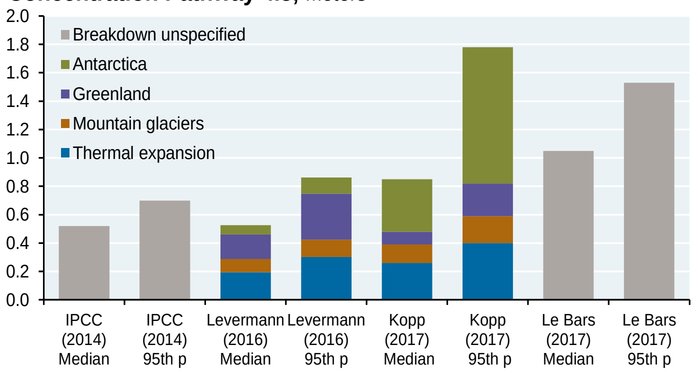
[20] "*Economically robust protection against 21 st century sea-level rise*", Jochen Hinkel and Daniel Lincke, Global Climate Forum, Pending.

[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

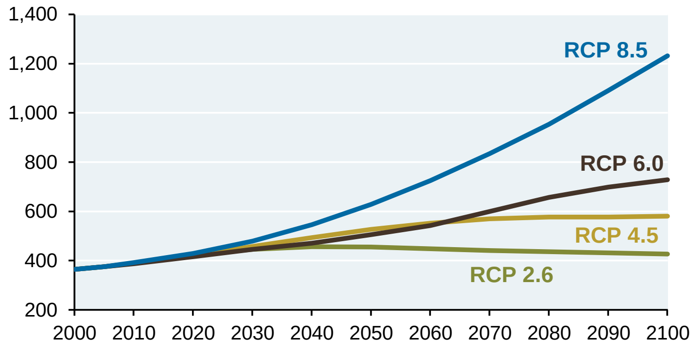
Most sea level rise analyses incorporate an assumed pace of global greenhouse gas emissions, referred to as "Representative Concentration Pathways". The associated number refers to its GHG concentration relative to preindustrial values. Under RCP 8.5, sea levels are expected to rise by 2.0 to 2.5 meters 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.

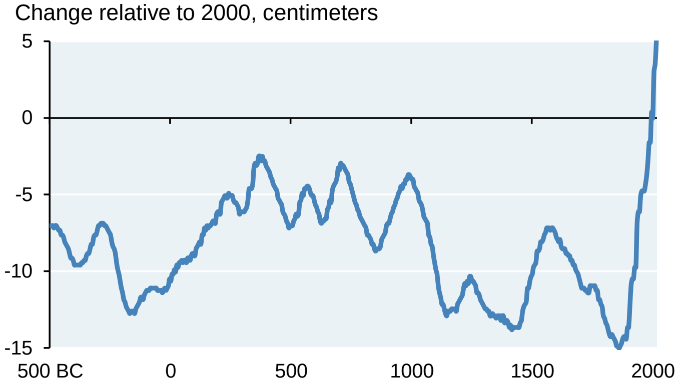
Representative concentration pathways of GHGs
CO_2 equivalent (parts per million)



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

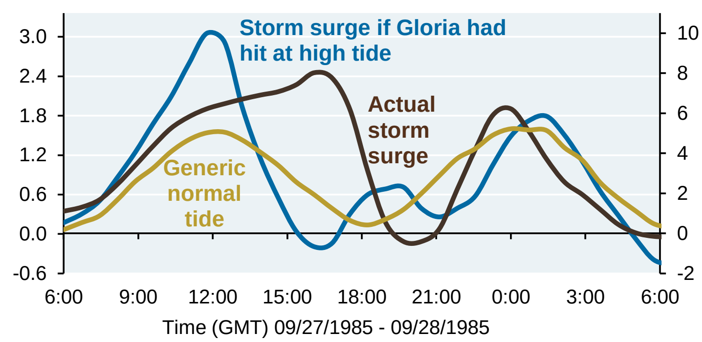
The third chart shows a reconstructed estimate of sea levels since the year 500 BC. This chart appeared in the USGCRP Fourth National Climate Assessment, released in 2017. The last chart shows how the timing of storm surges can affect their severity, and the need to plan for surges which could happen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



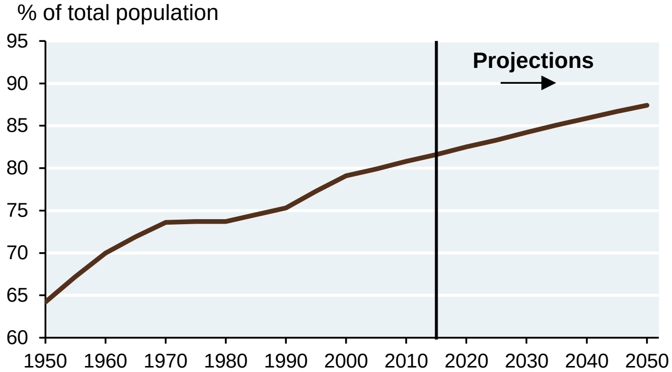
Source: "*Storm Surge Modeling and Climatology for the New York City Metropolitan Region*", Brian A. Colle, Stony Brook University. 2009.

[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 states[22]. 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.

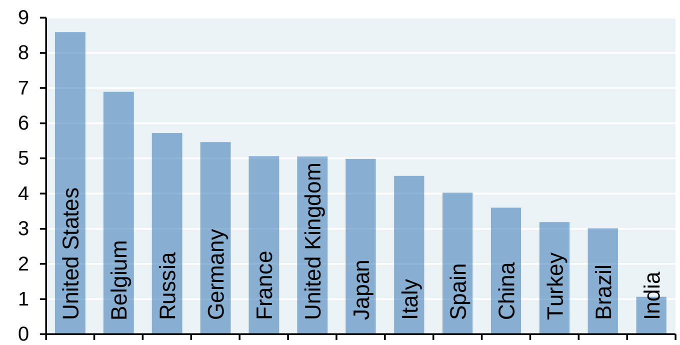
Despite the mobility that modern telecommunications allow, US citizens continue to flock to the nation's cities. As shown below, US urbanization rates have been climbing steadily since the 1960's and are projected to keep rising. **Unsurprisingly, 21st century cities are massive consumers of food and 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.

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[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.

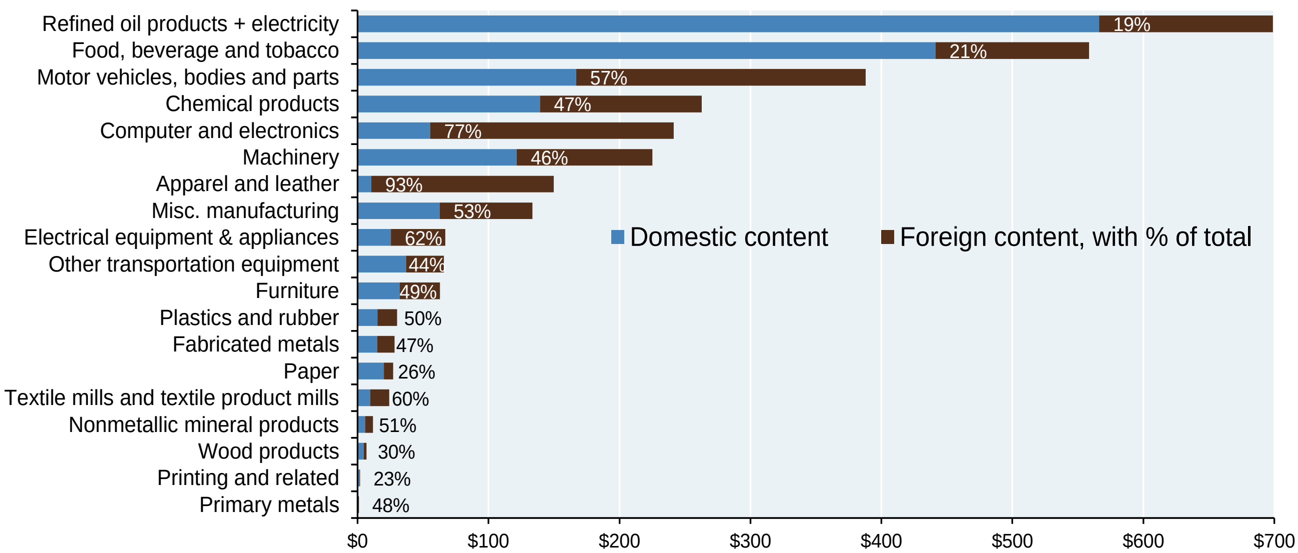
[23] "*Surveying the Environmental Footprint of Urban Food Consumption*", B. Goldstein et al, Technical University of Denmark, Journal of Industrial Ecology, 2016.

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

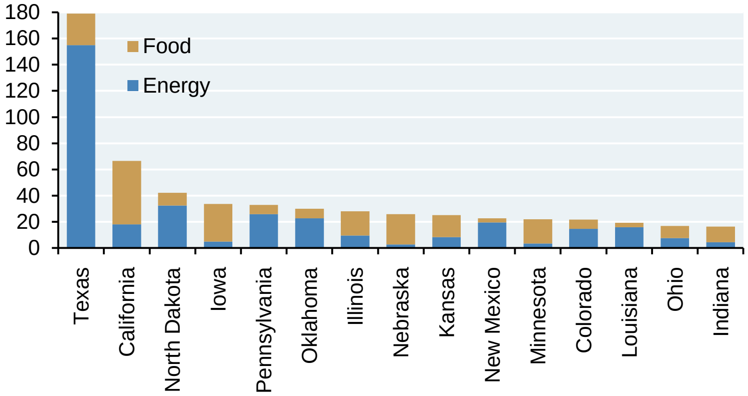


Source: Dept of Commerce, BEA, BP, EIA, JPMAM. Calendar years 2012-2016. Refined oil products = $536 bn, electricity = $163 bn. Refined oil product values based on $74.6 per barrel (WTI crude plus Gulf Coast PADD 3 refining margin as of Feb 27, 2018) and 7.1 bn barrels per year of refined oil products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



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

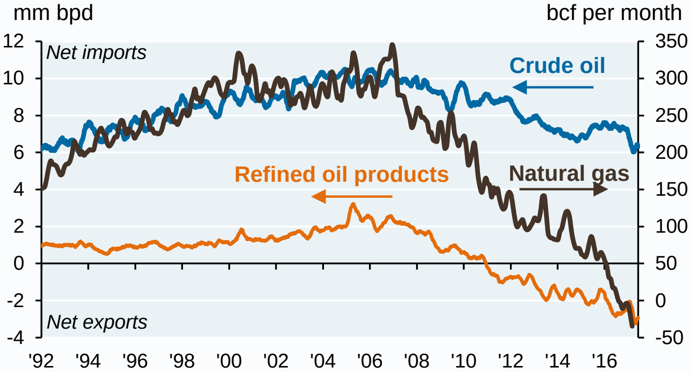
If you're interested…some details on US food and energy production by state

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.

US crude oil, refined product and natural gas imports
mm bpd / bcf per month



Source: Energy Information Administration, JPMAM. February 2018.

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.

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 country[24]. 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).

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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

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