

Energy Econ Notes 2019

Prof Jacobson

This is as an informal discussion of the characteristics and the pros and cons of the various energy sources of greatest interest to us, from the perspective of what we know today and today's concerns. In it, I provide data from reliable sources as well as my perspective (which, as always, should be taken with a grain of salt). This document should not be used as a major or primary source, particularly for a paper on energy, but it will cite primary sources you may find useful; these source documents are generally really interesting and go into lots more detail than I include here.

Energy Choices

Economists generally believe that people and firms buy the cheapest inputs we can find. This applies to energy just as to everything else. The implication of this is that the pattern of energy use we observe should allow us to infer the relative explicit (i.e., market) prices of different kinds of energy. (I say "explicit" there because hidden prices, mostly externalities, are not considered; most the problems we are concerned with in energy stem from the fact that the private costs differ from the social costs.) In other words, the resources we use a lot be providing cheap energy; the resources we don't use much must be more expensive for the same amount of energy. So if you ask what kind of energy we use, the answer is generally, "cheap energy," and when we use different energy sources for different purposes that's because different things are more and less costly in different locations or contexts.

Because we think people are so driven to increase profits and/or decrease costs, it seems unlikely that miraculous alternative energy sources are hidden in plain view or are being suppressed by some corporate establishment. There are no miracle cures to provide limitless energy at low cost. If someone tells you there is an overlooked energy source that would solve all of our problems, ask yourself why no-one's bought up all the rights to it. Such a source would be very profitable, and while no-one is perfectly rational, I can't imagine firms leaving that much money on the table. If an energy source is overlooked, it's probably overlooked for a reason. There are certainly conspiracy theories that "big oil" and related interests are blocking these miracle energy solutions, but doesn't it seem more likely that they'd be buying them up and profiting from them? (Indeed, the big oil companies are all working to become "big energy" by diversifying their portfolios even now.)

What kind of energy will we use in the future? Let's recall that our most important energy sources, fossil fuels, are nonrenewable in the sense that they don't regenerate at a meaningful rate. Right now they are all still very plentiful, and we are continuing to explore and find more reserves. On the other hand, we may have found a lot of the easiest-to-exploit mines and wells already (we may have picked the "low-hanging fruit"). At some point these fuels will show increasing scarcity, and even now we're finding ourselves exploiting harder-to-get-at resources. Thus marginal extraction costs will probably continue to rise even in the face of technology improvements. So what will happen as a result?

First, price will increase. This is almost certain to happen eventually even though we go through periods where energy prices drop, sometimes dramatically. This increasing price will cause us to

use less energy and to develop technologies that more efficiently extract energy from a resource or that more efficiently turn that energy into the light, heat, power, etc. that we use.

This increasing energy efficiency may or may not cause us to lower our fossil fuel use; we'll use less resource per unit of energy but this reduced-resource-need-per-unit-of-energy feature tends to make energy cheaper (it embodies fewer resources), so people and firms buy more energy as a result. Thus, the net effect of increased energy efficiency on resource use is ambiguous. This is the "Jevons paradox," also known as the rebound effect.

In the end, however, we can't infinitely increase our efficiency. Thus, with a growing population and energy demand also still growing in some parts of the world (notably, developing countries), not all of the world's energy problems can be solved simply by conservation and efficiency gains.

Second, the increasing price will drive us to switch from fossil fuels to other energy sources. Other energy sources serve as a backstop technology: when energy from fossil fuels becomes too expensive, it will be cheaper to use something else to serve our energy needs. This is why some economists don't worry much about future energy. A free market's energy prices will transmit the signal "We need more energy, and we're willing to pay for it!" There will be money to be made in providing cheap energy, so profit-seeking firms will research and develop new energy sources. In other words, increasing prices because of increasing scarcity will inevitably cause us to switch from nonrenewable (fossil fuel) energy sources to other sources as we continue to seek the lowest-cost source at every moment in time. That's the fundamental picture, but there are details that matter. First, externalities distort this path so that with just market forces we'll switch later and slower than would be optimal. Also, the market for energy and related resources is not quite a free market: there are all kinds of subsidies and government controls in energy markets and resource extraction all over the world, and it's hard to assess the net impact of all of them. Plus, the transition from fossil fuels to other energy sources may be painful in the costs it imposes on people and firms; there may be a role for policy in easing that transition.

International Energy Use

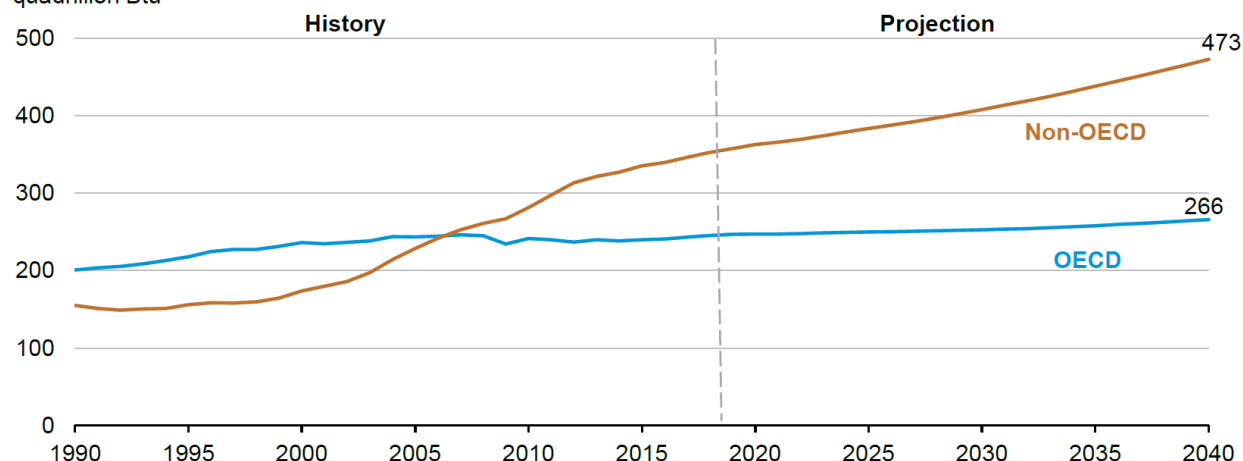
We measure energy in Btu (British thermal units), which allows us to compare energy use and energy supply and whatnot across different energy sources. Historically, energy use in developed (rich) countries was much greater than energy use in developing (poor) countries. However, now we see energy use growth slowing, or in some cases energy use starting to peak, in developed countries, with their mature economies and stable populations. At the same time, energy use is skyrocketing in developing countries where the economies and (usually) populations are growing and they are catching up with technologies that developed countries have already adopted (e.g., expanding access to electricity and cars, building up industry, etc.). But one thing to bear in mind is that energy use generally tracks with how strongly economies are performing; weak economies (e.g. economies in recession) are producing and consuming less, which means less energy use.

The figure below (which, like a lot of the figures in here, comes from Capuano, 2018), looks at energy consumption in OECD and Non-OECD countries. The OECD (Organization of Economic Cooperation and Development, a group including developed countries) includes 36 countries,

with 1.3 billion people, while the Non-OECD group includes the rest of the world—and remember that world population has passed 7.7 billion people. Notice that you can see a dimple in both curves for the 2008 Great Recession.

**IEO2018 Reference case
world energy consumption**

quadrillion Btu

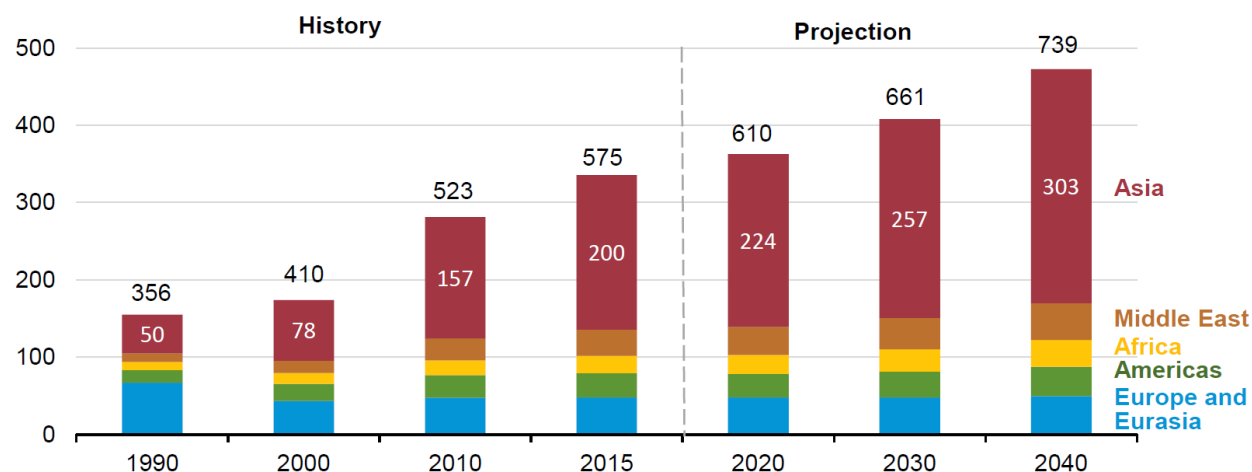


Source: EIA, International Energy Outlook 2018

A lot of that growth in Non-OECD countries is driven by Asia, and in particular, China. See the figure below. Indeed, a lot of the swings in global energy prices are driven by swings in the Chinese economy.

**IEO2018 Reference case
non-OECD energy consumption by region**

quadrillion Btu



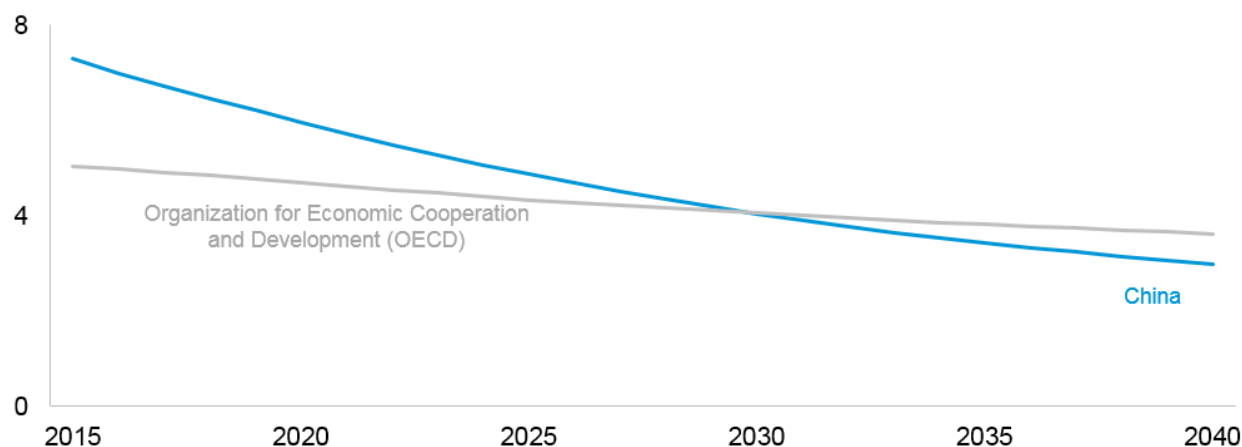
Source: EIA, International Energy Outlook 2018

The relationship between economic growth and energy is represented by the concept of energy intensity, which is the amount of energy needed to produce a given amount of GDP (economic output). Energy intensity has been declining for years, which reflects energy efficiency in a

broader definition of the sense: it includes doing things that take less energy (e.g., switching from manufacturing to service in the economy) and doing any given thing more efficiently. As the figure below shows, energy intensity in OECD countries is currently lower than it is in China, and while it's declining in both places, it's declining more quickly in China.

regional energy intensity

thousand Btu per 2010 dollar GDP



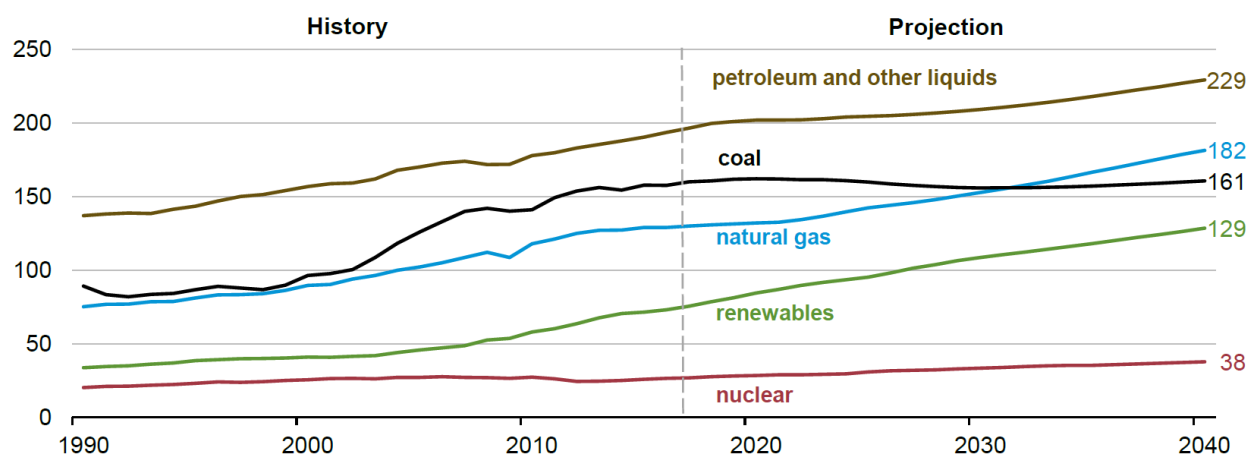
Source: EIA, *International Energy Outlook 2018*

We get energy from a number of different kinds of sources. Currently, most of it comes from fossil fuel sources: liquids (including oil), coal, and natural gas.¹ Non-fossil fuel sources (nuclear and renewables) make up a portion of the sources, but they are still dwarfed by the fossil fuels.

IEO2018 Reference case

world energy consumption by energy source

quadrillion Btu



Source: EIA, *International Energy Outlook 2018*

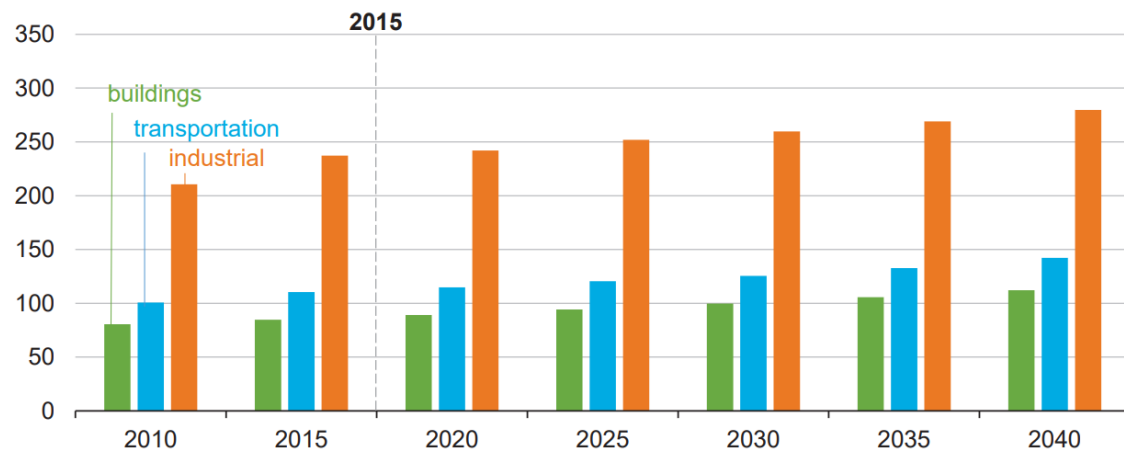
¹ Fossil fuels are formed by decomposition of organic matter over millions to hundreds of millions of years. They do not regenerate at an economically meaningful rate. They are dense sources of carbon, and energy locked in atomic bonds is released when the fuels are burned. Unfortunately, pollutants are also released at the same time—notably CO₂ and other greenhouse gases.

Now, we should note that the reference case (which you should think of as the most-expected projection) from the EIA has been dramatically under-predicting the rise of renewable energy over the last bunch of years. I don't know the reason for this, but perhaps this current projection is also excessively conservative. Still, we shouldn't expect miracles. So to me, it's pretty clear that it will take some time and some significant effort to switch off of fossil fuels. The idea that we can put our collective tree-hugger foot down and in a momentary flash of global insight see coal cease to be burned seems to me to be totally unrealistic.

I think it's wisest to think about our energy future in terms of an energy portfolio: our future energy needs can only be met by a mix of a variety of sources. Deliberate energy policy is a choice to encourage a rebalancing of that portfolio relative to what would happen without intervention. But such a rebalancing can't happen overnight.

Different energy sources go to different uses, so let's now look at energy uses for a moment. The figure below shows how energy use worldwide is divvied up across sectors in a very coarse way. You can see that industrial uses (which include mining, manufacturing, agriculture, and construction) far outstrip transportation and buildings, but the other sectors are increasing faster.

World energy consumption by end-use sector
quadrillion Btu



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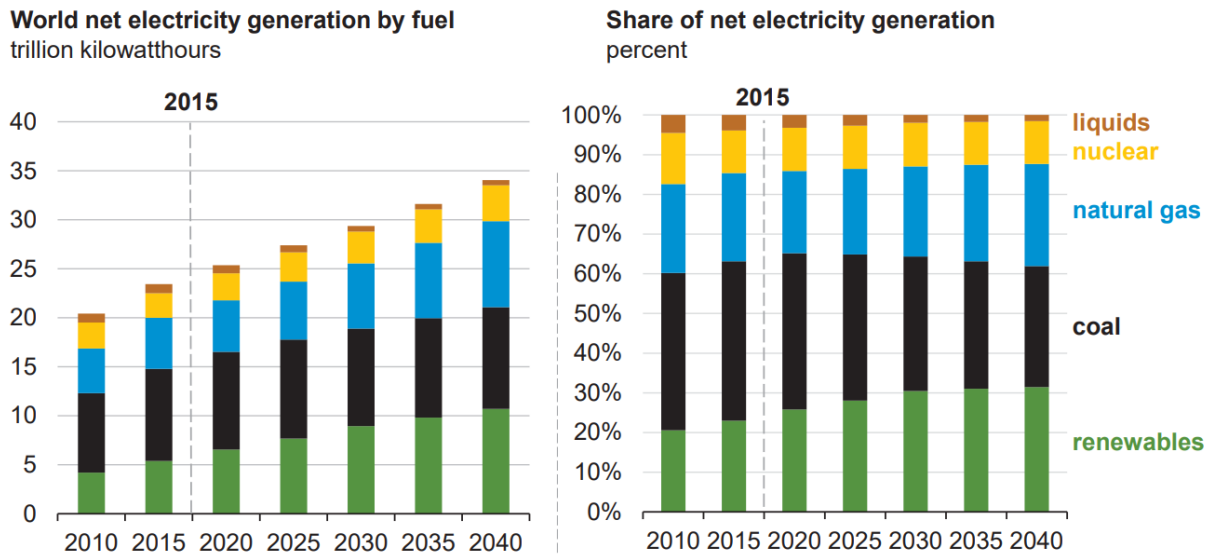
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Source: EIA, *International Energy Outlook 2017* (U.S. Energy Information Agency, 2017)

Note that there are funny things to think about in how to allocate energy use across sectors. I'm not actually sure whether this "buildings" measure includes the embodied energy in building – since concrete is very energy intensive, buildings represent energy use not just in their operation but in the energy that was used to make the materials they're made out of.

But, again, not all sources are well suited to all possible uses. Much, although certainly not all, of the liquid fuel produced in the world is used for transportation. Electricity, on the other hand,

largely uses coal and natural gas, with small but growing elements contributed by renewable and nuclear. The mix of electricity sources varies quite a bit from country to country and across recent time. That mix is expected to continue to change in coming years. Two major developments that have been changing the pattern of sources we currently use and project to use for electricity are cheap natural gas and improvements in renewable technologies, both of which I discuss below in detail. The figure below shows the mix of different energy sources used to produce electricity and how that's changed over time as well as projections. You can see the decline of coal and the rise of natural gas and renewables.



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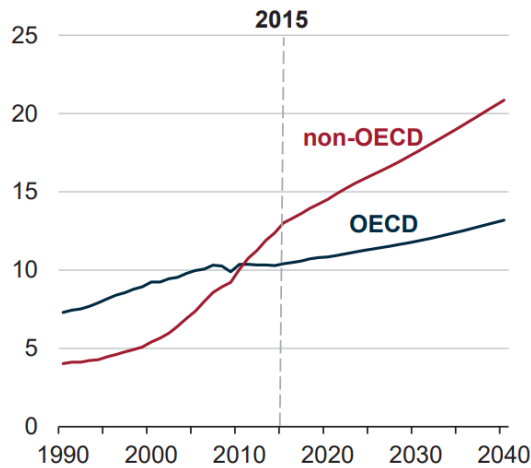
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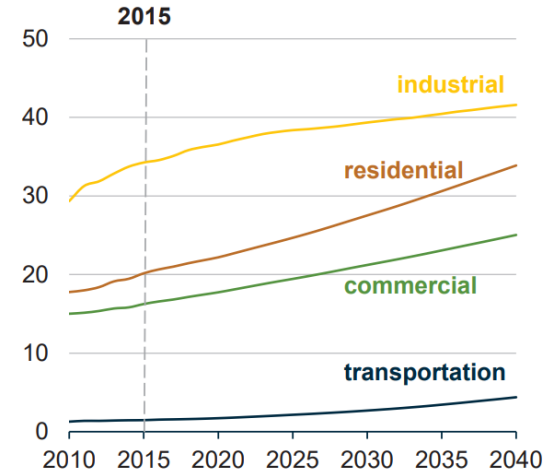
Source: EIA, *International Energy Outlook 2017* (U.S. Energy Information Agency, 2017)

One reason this is important is that the renewable energy sources typically generate electricity, and thus to switch over to renewable energy sources, there are a lot of uses we need to switch over to electricity. For example, houses in the northeast are typically heated with heating oil or natural gas; to transition from fossil fuels to renewables, we need to get them on electric heating. Similarly, the most likely way to get cars off fossil fuels is to go electric. But this will only help once the electric grid is on renewables: with the current grid, there is evidence that electric cars are worse for the environment if driven in most places in the United States because of the large amount of coal still used for electricity in many places (Holland et al., 2016). Global uses of electricity by sector are in the figure below, along side electricity use projections.

OECD and non-OECD net electricity generation
trillion kilowatthours



World electricity use by sector
quadrillion Btu



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Source: EIA, *International Energy Outlook 2017* (U.S. Energy Information Agency, 2017)

To summarize a few important points about international energy use:

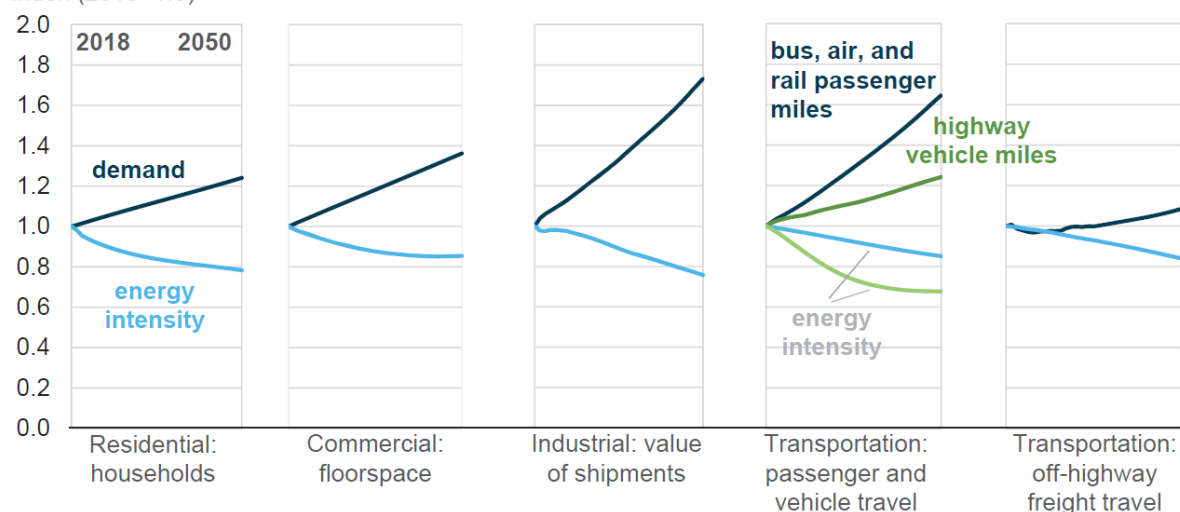
- It's growing slowly in rich (OECD) countries, but quite fast in low-income countries, and we expect these trends to continue
- We're becoming better at producing more stuff with less energy (energy intensity is decreasing), especially in developing countries
- Fossil fuels make up a large part of our current energy portfolio, and in absolute numbers they are still growing
- Renewables are a growing share of energy sources, but still below 15% of the total
- Going from direct fossil fuel use to electric power will probably be necessary to complete the switch to non-greenhouse gas generating energy sources

US Energy Use

Most of the information I give here come from U.S. Energy Information Agency (2019), though the latest report is not fully released so that some of the figures come from the 2017 version. The US uses a lot of energy, but energy consumption has lately been flat, as energy needs increase at about the same rate as increases in energy efficiency. Energy intensity is projected to continue improving at different rates in different sectors, as shown in the figure below.

Indexed end-use demand drivers and energy intensities by sector (2018–50) (Reference case)

index (2018=1.0)



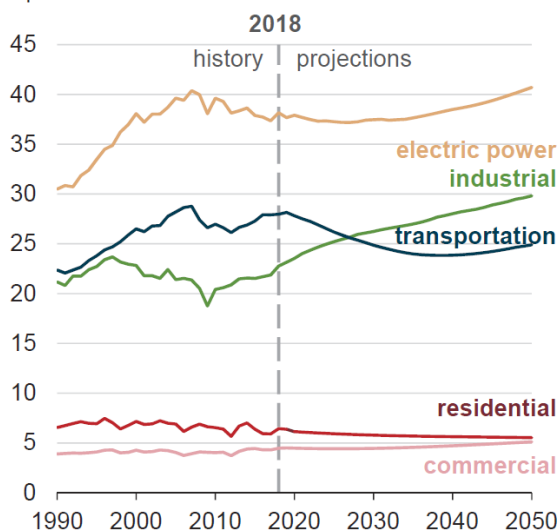
Note: Energy intensities are a lighter shade of the same color as the respective demand, and they are calculated as energy used per unit of respective demand.

Source: US Energy Information Administration Annual Energy Outlook 2019

Let's look at what we use energy for and what fuels we use, and how that's varied over time and is projected in to the future; see the figure below. Electric power is our largest use, and then transportation and industrial are next; residential and commercial are at the bottom. This is one reason I'm skeptical of pushes for residential energy conservation; it's just not going to get us there. Looking at the fuels, you can again see that fossil fuels are king here as worldwide, though renewables are increasing. That drop in nuclear is occurring as old plants are decommissioned.

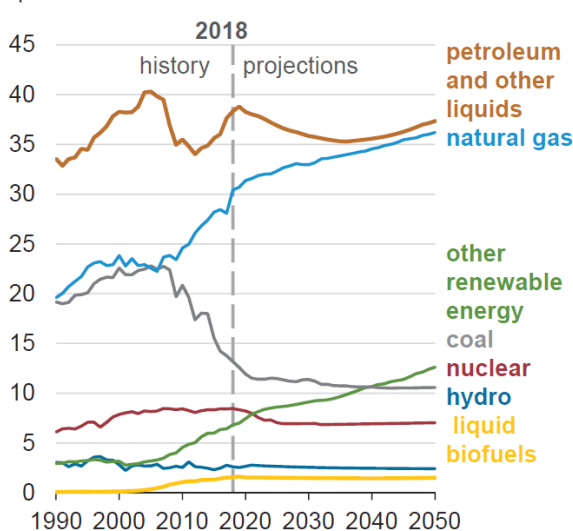
Energy consumption by sector (Reference case)

quadrillion British thermal units



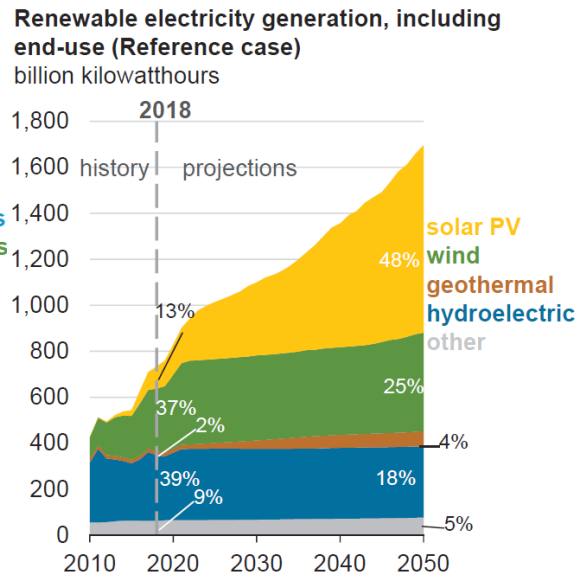
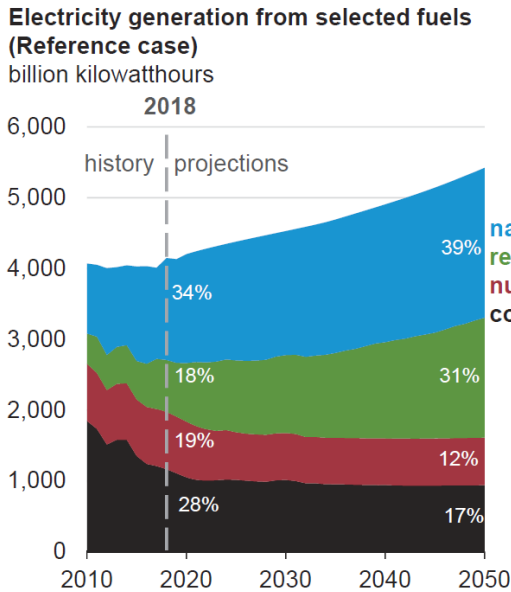
Energy consumption by fuel (Reference case)

quadrillion British thermal units



Source: US Energy Information Administration Annual Energy Outlook 2019

The picture in terms of just electricity is important, recall, because that's the way we translate renewable energy into use most easily. You can see in the figure below that right now renewables make up 18% of the electricity grid right now and that's expected to expand to 31% by 2050. But again, bear in mind the historical underestimation of renewables' growth I noted above. In terms of renewable projections, they expect solar to expand most aggressively, but wind to also make a strong showing. You'll also see that coal is clearly in decline; this projection says that will flatten out at a certain point; I wonder about that.



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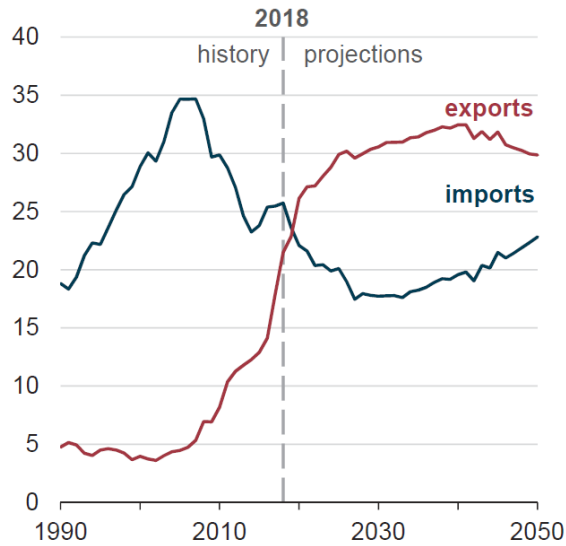
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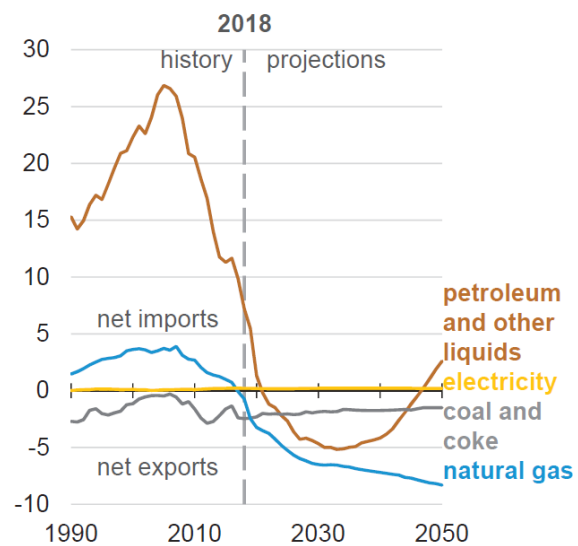
Source: US Energy Information Administration Annual Energy Outlook 2019

The US has been a net energy importer since 1953 (U.S. Energy Information Agency, 2019), but as you can see from the figure below, that's been changing dramatically over the last decade, and we're just on the cusp of becoming a net energy exporter. This is because of increased petroleum and natural gas exports and reduced petroleum imports.

Gross energy trade (Reference case)
quadrillion British thermal units



Net energy imports (Reference case)
quadrillion British thermal units



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Source: US Energy Information Administration Annual Energy Outlook 2019

Oil (Petroleum)

Oil is one of our favorite sources of energy, particularly for transportation. Oil is a fossil fuel source, which means that it is energy-dense and nonrenewable. But with use of oil, as with use of other fossil fuels, we also release an array of pollutants, including greenhouse gases such as CO₂ and a nasty things that hang around in the local area to make smog and cause health problems.

There are many kinds and qualities of oil. Oil as it is pulled out of a well is crude; it must then be refined so it can be turned into a usable fuel source. In the US, many refineries are in the Gulf Coast region, but there are others scattered across the country, particularly in the Midwest. US oil exports have been picking up for the last bunch of years which has meant refineries have been operating close to capacity after going through a rough period because of low demand.

Also, there are different kinds of crude. “Light” crude is low density and yields more fuel than does “heavy” oil; “sweet” crude has less sulfur and other nasty things in it than does “sour.” Geopolitical events that affect the supply of the nicest oil, light sweet crude, have outside impacts because of how important light sweet crude is. And lots of geopolitical events happen in places with oil.

Finally, there’s a distinction between conventional and unconventional oil. Conventional oil is extracted from an oil well. This includes offshore drilling, which is costlier and has more externality risks than onshore wells. Unconventional oil uses other methods. One example is the “oil sands” or “tar sands” (the technical name is “bituminous sands”). These oil sands contain heavy oil mixed with various chemicals in deposits that are very hard (costly) to extract from. The chemicals in the oil make it “dirtier” when the refined oil is eventually burned. There are big

deposits of unconventional oil in Canada and Venezuela, among other places. Since the price of oil has risen and technology has progressed, it's become economically viable to use these resources. Environmentalists are concerned about both the impact on habitats of extracting the oil and the impact on air quality of burning fuel thus derived. The hullabaloo about the Keystone XL pipeline is about whether we will extend a pipeline that currently runs from Canada into the US, where this extension would go all the way to the Gulf Coast so that tar sands oil can be transported there to be refined.

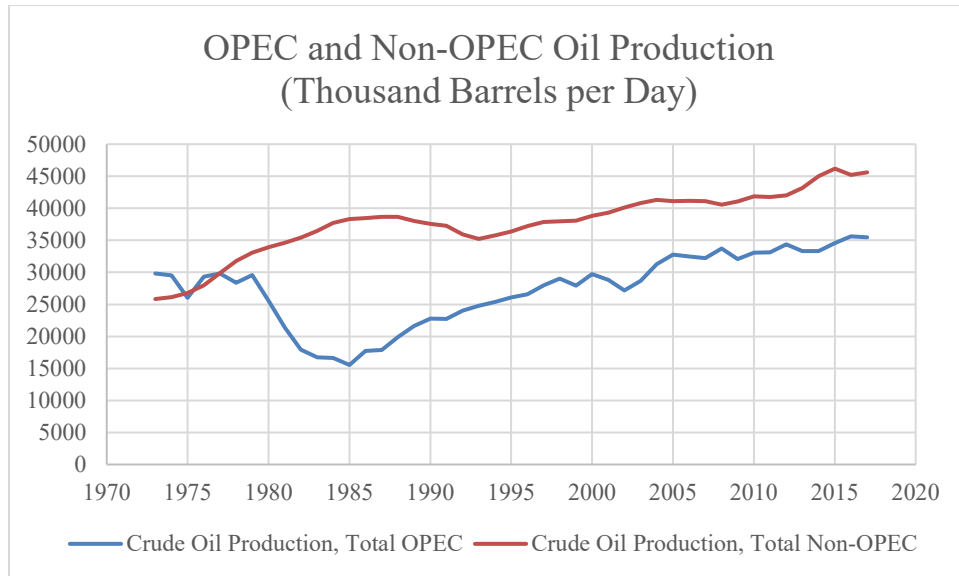
Another source of unconventional oil is "tight oil," also known as "shale oil." This is "fracking" (hydraulic fracturing), which you've probably heard of in the context of natural gas, but actually natural gas and oil are both found in underground formations of shale or other rock and can be extracted this way. I'll discuss fracking in more detail below.

Where does oil come from? The biggest single(ish) player is the cartel OPEC (the Organization of Petroleum Exporting Countries). A cartel is a group of firms (or, in this case, countries) that agrees to manage their interaction with the market for their mutual benefit. In this case, it's a quantity-fixing cartel: they meet regularly to decide how much each member state will produce. In this way, they limit the supply of oil, which pushes up the price and thus their profits. They say that their goal is to stabilize global oil markets, but let's be real.

OPEC has 14 member countries,² after Qatar left the cartel in January 2019 to focus on natural gas production. Saudi Arabia produces over twice as much oil as the next largest producer (Iran). Together, OPEC countries produce around 40% of the world's oil, though they used to produce a larger share; however, they do produce about 60% of the oil that's traded globally, so they can still be influential. However, it's not really clear how big of an influence their cartel can have on the market; or, indeed, how well Saudi Arabia can control the rest of OPEC to try to do this quantity coordination.

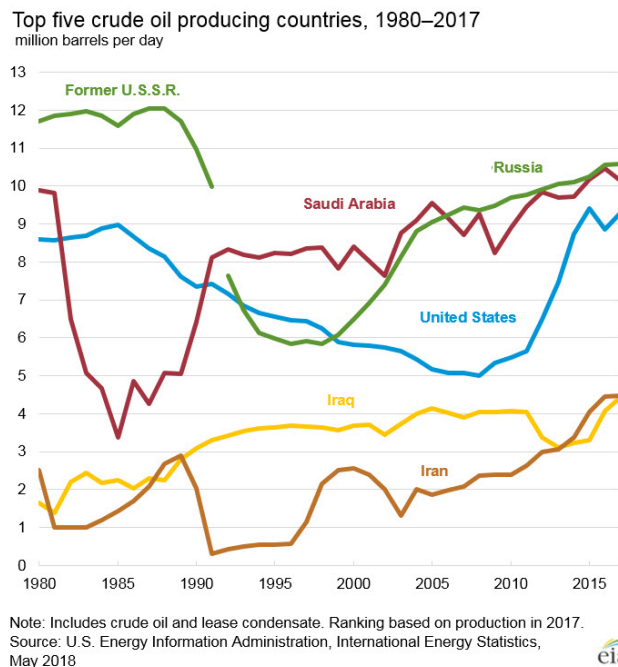
As I said, total non-OPEC production is actually greater than OPEC production, although non-OPEC countries do not coordinate at all while OPEC tries to. Oil production overall, from both OPEC and non-OPEC countries, has continued to increase over recent years.

² Algeria, Angola, Ecuador, Equatorial Guinea, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, Republic of the Congo, Saudi Arabia, United Arab Emirates, and Venezuela



Source: Data comes from US Energy Information Administration website:
<https://www.eia.gov/totalenergy/data/browser/>

Major non-OPEC players include Russia and the US. In 2017, Russia made 10.6 thousand barrels a day and the US made 9.4. Canada and China each produces over 3 thousand barrels a day. Norway and the UK used to be major producers but their output is on the decline as their reserves dwindle. Overall, across OPEC and non-OPEC countries, the positions of top oil producers have varied a lot over time; see the figure below.



Source: US Energy Information Agency website, https://www.eia.gov/energyexplained/index.php?page=oil_where

Oil production is very important to countries' economies. In fact, in many countries, particularly in OPEC, oil production is done by a government-owned and operated entity. Many non-OPEC countries do have oil production by private companies, though. Oil production companies

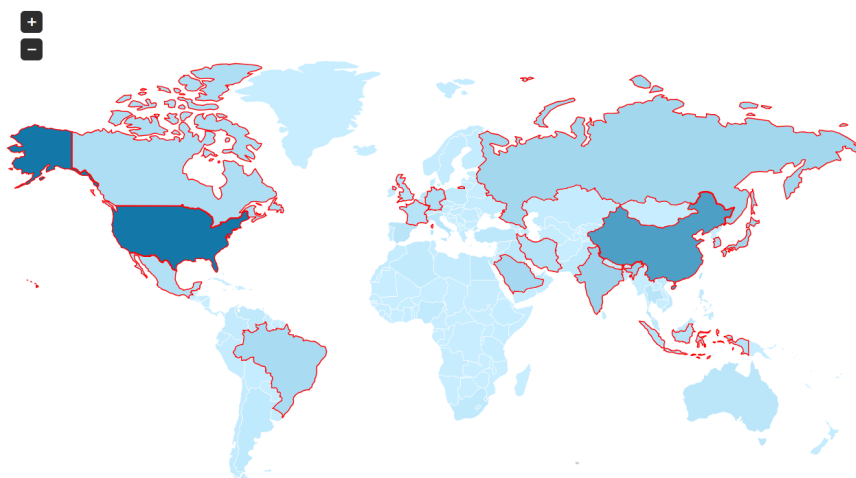
receive explicit and implicit subsidies in a variety of ways. (Here's an example of an implicit subsidy: if oil is drilled from an area that the government owns, the government is entitled to some kind of "royalty" payment. Those payments are far lower than the value that firms get from the right to this extraction, so this is an implicit subsidy.) Oil-producing countries often also subsidize purchase of oil by their citizens quite heavily; some argue that oil states are able to buy citizen complacency in the face of a relatively authoritarian regime through subsidies like this. Any talk about reducing the subsidization of oil is politically challenging, to say the least, not just in countries like Saudi Arabia but also here in the US.

What about oil consumption? As you might expect, US is the top consumer of oil by far, at nearly 20,000 thousand barrels per day; next is China at about 12,500 thousand barrels per day; no other country comes close, as all the rest are below 5,000 thousand barrels per day.

Total Petroleum Consumption - 2016* > (*most recent year with sufficient data for ranking)

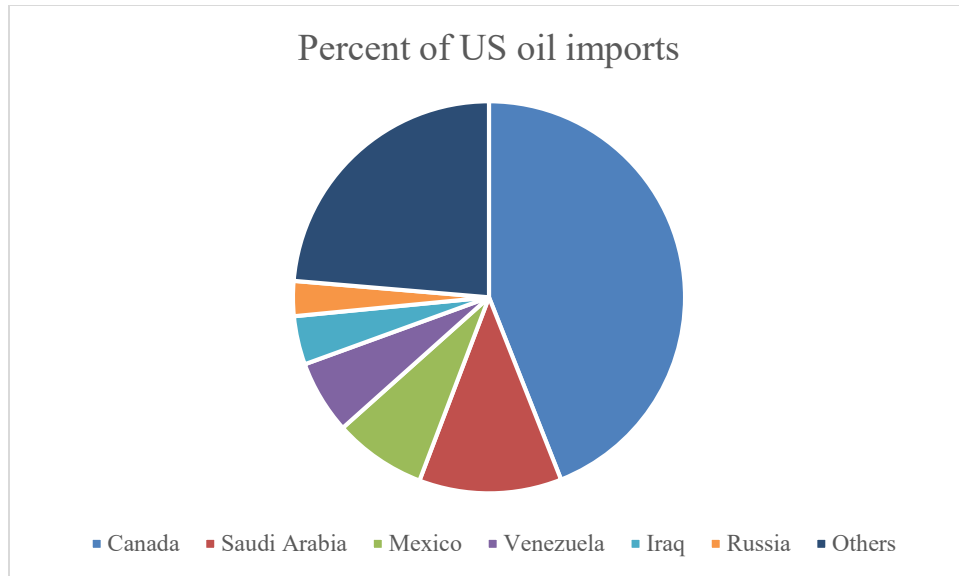
Thousand Barrels Per Day

1. United States
2. China
3. India
4. Japan
5. Russia
6. Saudi Arabia
7. Brazil
8. Korea, South
9. Canada
10. Germany
11. Mexico
12. Iran
13. France
14. Indonesia
15. United Kingdom



Source: US Energy Information Agency website <https://www.eia.gov/beta/international/>

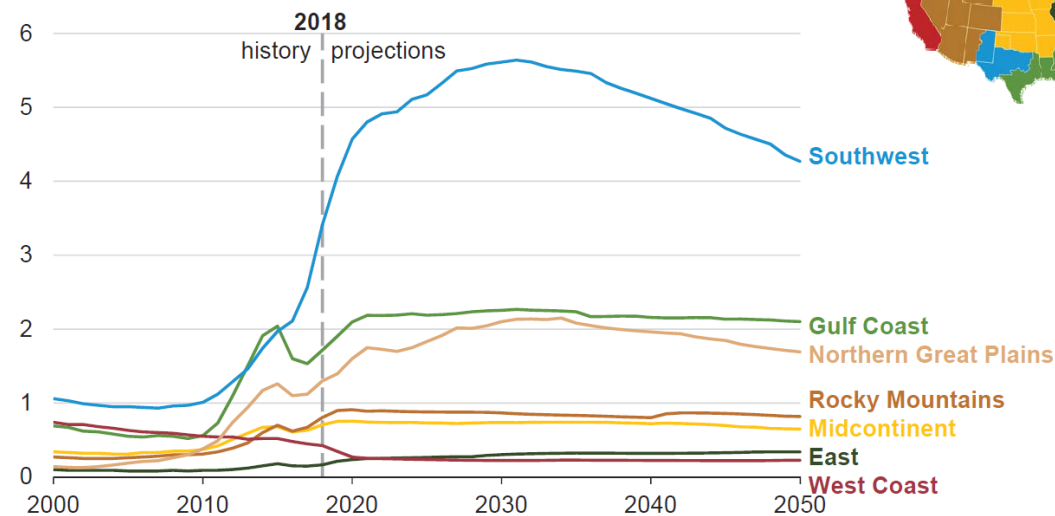
Where does imported US oil come from? Taking the data from October 2018, we imported 292 million barrels of oil, with 207 million (or 71%) of that from non-OPEC countries. Fully 44% of the oil we import comes from Canada. You can see in the graph below that we also get some significant amounts of oil from some countries we have complicated relationships with. (The "Others" category (24% of imports) includes 51 countries that each provide no more than 2% of our imports.) Anyway, these complicated relationships with oil producers are why we have concern about "oil security." You can think of some of these geopolitical concerns as an additional social external cost of the fuel source.



Source: Data comes from US Energy Information Administration website:
https://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_ep00_im0_mbb1_m.htm

How about oil produced in the US? The figure below shows the geographic distribution of onshore crude oil production across the US. The Southwest, Gulf Coast, and Northern Great Plains have been the largest producers, and the Southwest is expected to grow even more

Lower 48 onshore crude oil production by region (Reference case)
million barrels per day



U.S. Energy Information Administration

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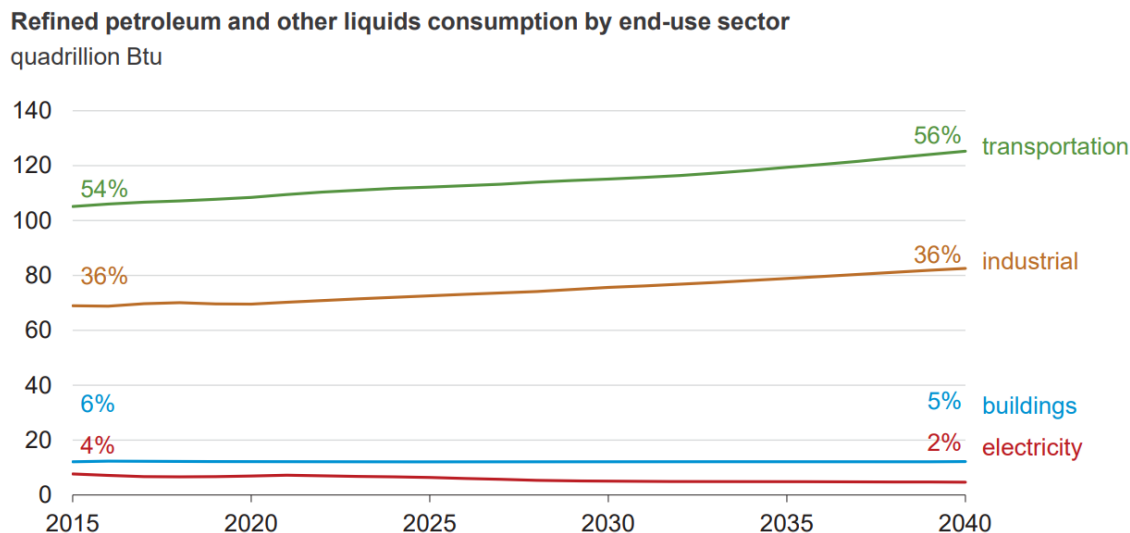
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Source: US Energy Information Administration Annual Energy Outlook 2019

How is oil used? Much of it goes into transportation, but some is used in industry. Remember, too, that transportation is used directly by consumers but production and retail of goods also

require transportation, so when oil prices rise that feeds into the cost of consumption directly and by increasing the costs of industrial use and business transportation.



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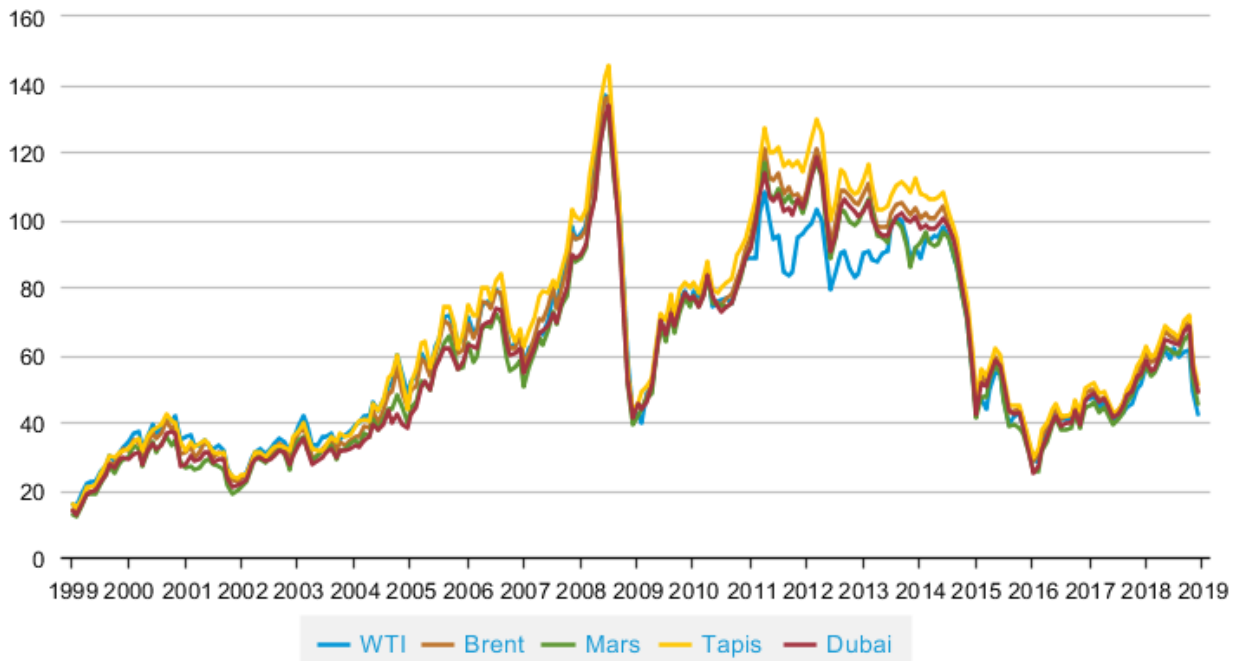
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Source: EIA, *International Energy Outlook 2017* (U.S. Energy Information Agency, 2017)

The oil market pretty important in global matters. See the figure below for the last 20 years of oil prices. Oil prices are driven by two or three factors: supply, demand, and possibly speculation. There are short term shocks to supply, like political stuff going on where oil is produced, that can drive down supply and thus drive up the price. High demand can also drive up prices, and weak demand can drive it down; this is why oil prices usually move in tandem with the global economy. It's before the time scale of this graph, but oil prices started to rise sharply in 1974 when OPEC and some of its allies levied an oil embargo against the United States. Oil prices shot up even further in the 1979 oil crisis. You can see in the graph that prices spiked in 2007-2008 (other commodity prices were spiking then), and then the recession hit, depressing prices again. The low oil prices of the last bunch of years were probably largely due to slow economic growth in China combined with increased supply from the US (though some argue that the cartel was in part responsible).

World crude oil prices

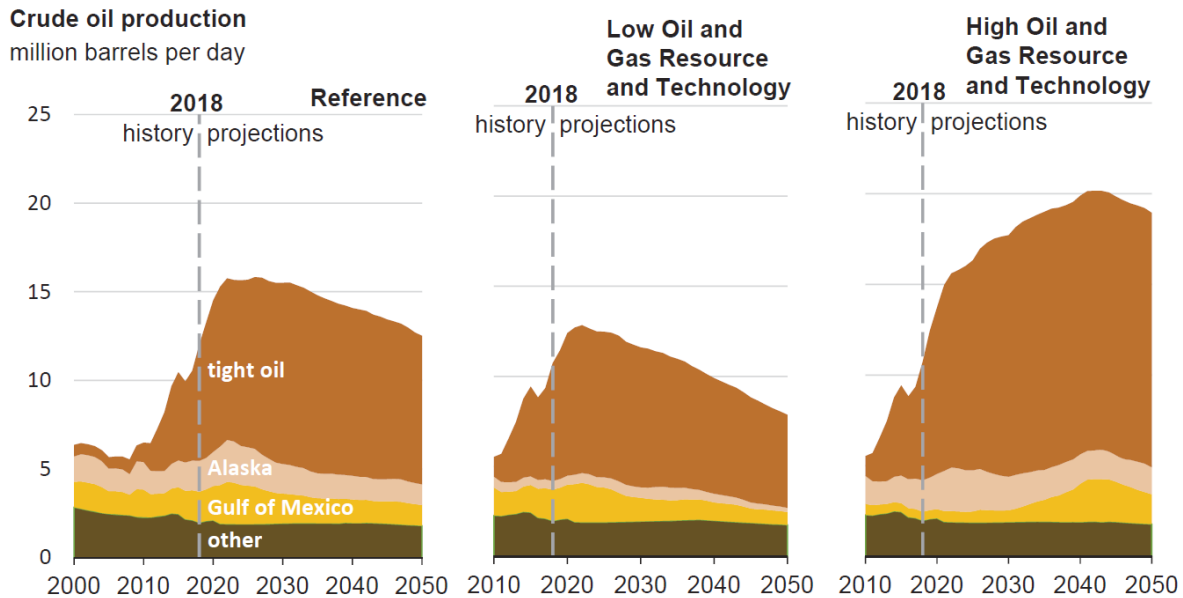
\$/b (real 2010 dollars, monthly average)



Sources: Bloomberg L.P., Thomson Reuters. Published by: U.S. Energy Information Administration.

Source: https://www.eia.gov/finance/markets/crudeoil/spot_prices.php

Which is better: low oil prices or high oil prices? Well, high oil prices are good for oil sellers and bad for oil buyers. Because a lot of productive sectors use a lot of energy, oil prices that are too high can be a drag on the global economy. It's not so bad for the US now that we produce so much oil; indeed, periodically people argue that we should be in OPEC so we can help drive up the price of oil to benefit our producers (though obviously this is kind of a contrarian opinion). But another thing is that the harder-to-get-at kinds of oil, like tar sands, tight (fracked) oil, and offshore, are only economical if oil prices are high enough to cover these costs. So that's an environmental downside of expensive oil. You can see in the figure below that US tight oil production is expected to continue to expand in the future years.



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Source: US Energy Information Administration Annual Energy Outlook 2019

Where does the price of oil come from? Oil is a globally-traded commodity, so its price is set on a global market. In some American political campaigns we hear talk about how allowing drilling in this or that place will bring gas prices back down to \$X per gallon. This is just political rhetoric. The US does produce a lot of oil so we can affect the global market price. But it is not the case that if we produce as much as we consume, we are isolated from things that happen on the global market; nor would we want it to! Most economists don't have much interest in "energy independence" per se—the idea of producing as much energy as we use. As long as there is a global market out there, the opportunity cost of energy produced here is still the global price of energy (unless we erect massive barriers to trade, which is not a good idea).

The last thing I want to mention about oil is an idea called "peak oil." Since the 1970's, people have argued that we are nearing or past the point at which the world's ability to produce oil is peaking, and thus oil production will diminish forever after. It's not clear to me that this is a meaningful concept. At some point, oil extraction and use will decline because it's a nonrenewable resource. But I don't think this a problem per se. Why? Because this is the way the allocation of a scarce resource ought to work. Producers have some idea how much oil is left in known wells and how much oil they expect to find with discovery activities, and they know that every unit extracted makes oil scarcer. This scarcity means that the opportunity cost of taking a unit of oil out right now is increasing, and thus the price of oil should rise to reflect that scarcity rent. At some point, the high price of oil will render the provision of energy from alternative sources economically profitable. At that point, we switch. The only question is whether we make that switch efficiently, and whether governments ought to be involved to ease the transition.

Now, let's summarize some of the pros and cons of oil.

Pros:

- Cheap
- Energy-dense
- Plentiful

Cons:

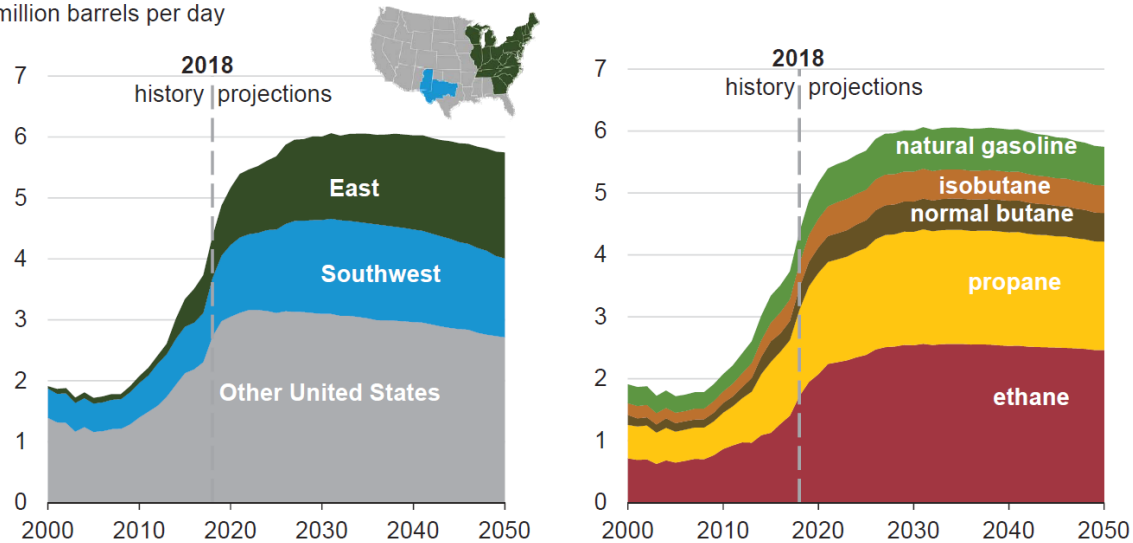
- Consumption externalities:
 - Burning creates greenhouse gases and other pollutants
- Extraction externalities:
 - Drilling, particularly offshore, may result in environmental damage and costs to health and safety of workers. (NOT external if the firms are held liable!)
 - Unconventional sources (such as tar sands and tight oil) may result in major environmental damage. The oil thus generated is also often dirtier (and thus creates worse consumption externalities when burned).
- Externalities in transporting the fuel:
 - Oil spills from pipelines or tankers (NOT external if firms are fully liable)
- Other concerns:
 - International security: oil revenues fund “problem states”
 - Energy dependence: it would be possible for major oil producers (mainly OPEC) to really hurt any particular country (even the US) if they wanted to
 - The market for oil is not perfectly competitive, although the environmental economic implications from this are not entirely bad!

Natural Gas

Natural gas is another fossil fuel, so it has some of the same characteristics as oil: it's an energy-dense hydrocarbon. It's a cocktail of gases, primarily methane, that are often found with deposits of other things, so it's also called “associated gas.” Deposits of natural gas are distributed pretty widely across the globe. Some of the big uses historically for natural gas are electricity and heat. It's often used near its extraction site because of the difficulty in transporting it, since it's a gas. Now transportation of natural gas has become more feasible through pipelines, though it can also be carried in trucks and tankers. Natural gas can also be converted into LNG (liquefied natural gas) or CNG (compressed natural gas) for use as a transportation fuel. The figure below shows how its production has been and is expected to be distributed across the US, and also the mix of natural gas components.

U.S. natural gas plant liquids production (Reference case)

million barrels per day



U.S. Energy Information Administration

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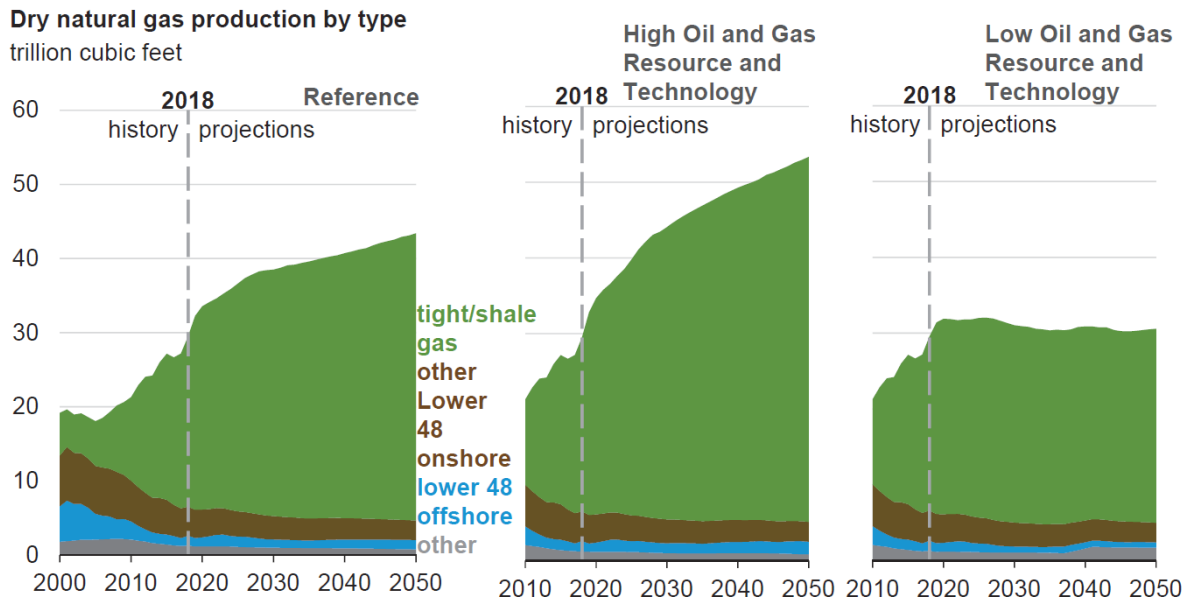
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Source: US Energy Information Administration Annual Energy Outlook 2019

One aspect of natural gas is that it is relatively “clean:” when burned, it produces less pollution (including less CO₂) per energy produced when compared to other fuels. On the other hand, if natural gas leaks out, that creates a pretty potent pollution problem: leaked natural gas is a much more potent greenhouse gas than CO₂. Leaks can occur in extraction, when the gas is stored in tanks, and when the gas is transported through pipelines. Expect more attention to be paid to this in the near future. Right now there’s vigorous academic debate about how bad these leaks are – some say they’re bad enough so that on net natural gas is no better than coal, but others say that’s overstating the issue.

In the US, our natural gas production has been transformed over the last two decades to be primarily based on fracking, as the figure below shows; we don’t know how extraction technology will develop over the coming decades, but at the very least we expect the role of fracked gas to stay strong, if not increase.



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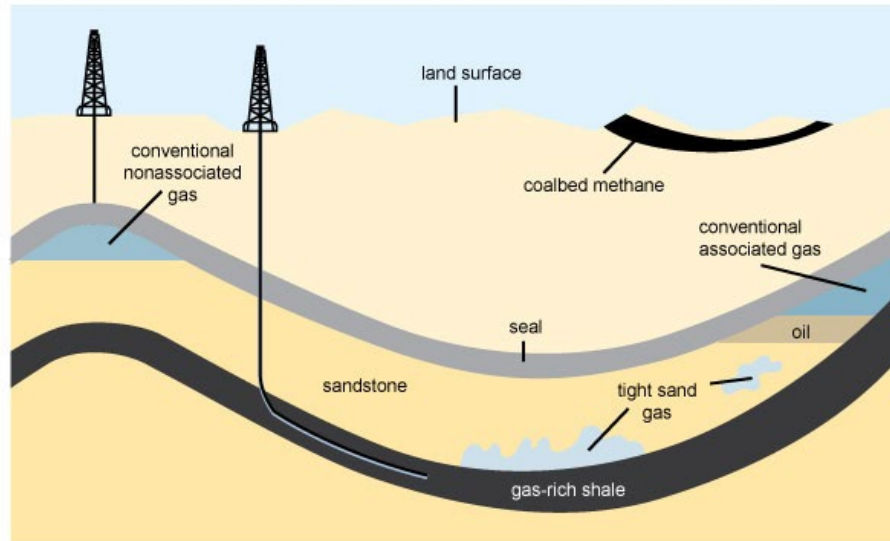
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Source: US Energy Information Administration Annual Energy Outlook 2019

Remember, natural gas is often found with oil or coal. When you see fires flaring atop an oil well, you're seeing excess natural gas being burning off. That gas can be captured and sold if it is profitable to do so, but often it is not. Shale gas is found laced through shale formations like the "Marcellus Formation" that underlies parts of New York, Pennsylvania, Ohio, Maryland, West Virginia, and Virginia. Tight gas is similar to shale gas, in that both are very hard to extract, but whereas shale gas is laced into soft, fine-grained rock, tight gas is stuck amid hard, impermeable rock. In both cases, innovations in extraction have made it possible to get the gas out in cases that may have been impossible in the past. Hydraulic fracturing (also known as "fracking") uses high-pressure water and chemicals to crack the rock in which the gas is hiding and force the gas to the surface, and this method, in combination with advances in ability to drill long horizontal shafts and discovery of vast reserves, has transformed the natural gas market. See the figure below to see how it works. The well on the left is a conventional well for natural gas; the one next to it is a fracked well that's targeting the "gas-rich shale" layer.

Schematic geology of natural gas resources



Source: Adapted from United States Geological Survey factsheet 0113-01 (public domain)

Source: US Energy Information Agency website

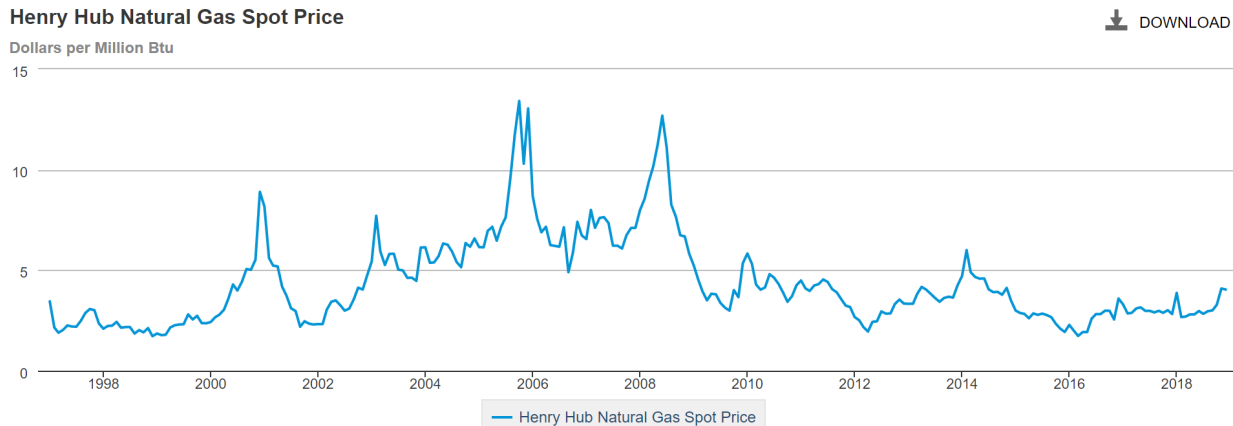
https://www.eia.gov/energyexplained/index.php?page=natural_gas_where

This change in natural gas technology is the biggest thing to happen in energy in a long time. As you've seen, natural gas has grown dramatically in recent years and that's predicted to continue, and that's largely because of shale gas. This not only changes the composition of our energy but also reduces energy prices, and perhaps climate pressures, too. Because natural gas is cleaner than coal (*if* leaks are minimal), power plant switches from coal to natural gas may be our main hope for near-term reductions in climate gas emissions, though there's a lot of research and debate about whether these benefits are really large. One downside is that the energy price reductions brought about by plentiful natural gas makes us delay making investments to build up renewable energy capacity.

Hydraulic fracturing, however, is incredibly controversial right now. The chemicals used in the process ("fracking fluids") are proprietary and thus not publicly disclosed; some fear they are toxic, although gas companies say they are largely inert. People also worry that both natural gas and these chemicals might get into the groundwater and into wells near the drilling site. There are also concerns about disposal of the leftover water and chemicals that were used in the drilling ("produced water"). Whether fracking should be allowed is hotly debated—drive over any portion of the Marcellus shale and you'll see tons of lawn signs both for and against fracking, citing a variety of reasons.

The local nature of natural gas has created some interesting institutional features over the years. Local natural gas suppliers in the US were often monopolies or near-monopolies in their local areas. The US government was concerned that customers were being exploited because of this market power. They were concerned about prices that they felt were too high. As a result, price controls were instituted. From 1954 to 1978, price ceilings were imposed in various ways. This caused severe shortages and common wisdom is that the price ceilings were a bad idea.

Here's what natural gas prices have looked like in the US over the last 20 years. You can see the same peak around 2008 when oil prices also were peaking. Other than that and the time leading up to it, natural gas prices have been generally lower, though fluctuating.



Source: US Energy Information Agency website <https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm>

Now, let's summarize some of the pros and cons of natural gas.

Pros:

- Cheap (and may stay cheap for a while)
- Energy-dense
- Plentiful
- “Local”
- Relatively clean (for a fossil fuel)

Cons:

- Externalities from leaked natural gas at all points in the process
- Consumption externalities:
 - Burning creates pollutants including greenhouse gases (albeit less than other fossil fuels)
- Extraction externalities:
 - Extraction of some associated and non-associated gas involves drilling or mining, which may damage some ecosystems, and accidents can happen.
 - Methods used to extract natural from shale deposits (“fracking”) may be particularly damaging because of groundwater contamination and disposal of “fracking fluids”
- Externalities in transporting the fuel:
 - Pipeline ruptures will happen occasionally (not external if producer is liable)
- Other concerns:
 - Geopolitics: Russia supplies a lot of natural gas to Europe, currently mostly through pipelines in Ukraine, though they're trying to build new pipelines. The whole process is very fraught and people are concerned about the possibility that Russia will use natural gas as a strategic weapon.

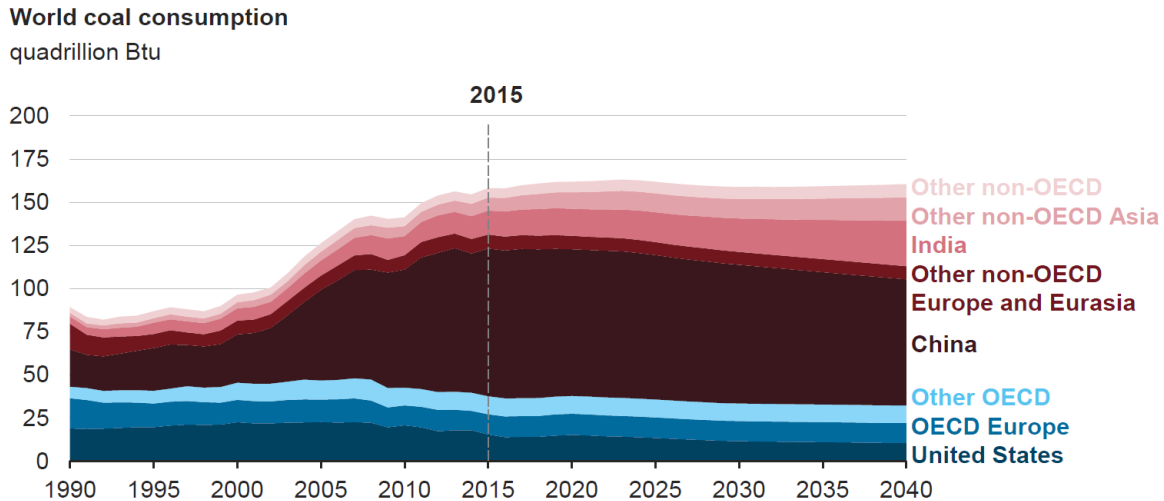
Coal

As noted above, coal is clearly on the decline because of falling costs of natural gas and renewable energy sources. Even without regulations, we should expect this decline to continue. However, it still has an important role in global energy, so we'll consider it.

Coal is another fossil fuel, a nonrenewable energy-dense hydrocarbon. Some coal is naturally cleaner (less sulfur) and some is dirtier (more sulfur). Thus when coal is burned (generally to generate electricity), we produce not just greenhouse gases like CO₂ but also sulfur and nitrogen compounds (SO_x and NO_x). These pollutants also contribute to acid rain in regional areas and health damages (including premature death) in local areas. When coal is burned, however, power plants can take abatement actions to reduce emissions, including installing scrubbers. There is some other clean coal technology that's been proposed, but my understanding is that a lot of it really has not been fully developed or tested. One that's talked about a lot, which would work equally well for natural gas, is carbon capture and storage (storing CO₂ emissions underground rather than emitting into the atmosphere), though that's really still at the pilot stage at best, with still a lot of research and development needed (Darmstadter and Mares, 2017).

Coal is scattered around the world in localized deposits, and is extracted, often at relatively low cost, through mines. Scarcity doesn't seem to be a real problem with coal yet. However, we are moving toward harder-to-extract sources, and this includes techniques like mountaintop removal. Underground mining can be very dangerous for the miners; this is particularly a problem in countries where safety regulations are poor or not well-enforced. With good safety regulations, measures taken to work safely just increase the cost of mining, but of course even in the US there have been fatal mining disasters in recent years.

Coal has remained a reliable source of energy worldwide in recent years. Coal use declines in the US and other OECD countries as well as China is projected to be offset by increases in China and the rest of the world, as developing countries build power plants to expand electricity access. See the figure below.



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Source: EIA, *International Energy Outlook 2017* (U.S. Energy Information Agency, 2017)

Now, let's summarize some of the pros and cons of coal.

Pros:

- Cheap (may get modestly more expensive)
- Energy-dense
- Plentiful
- “Local”

Cons:

- Consumption externalities:
 - Burning creates pollution that causes climate change, acid rain, and serious health problems
 - Clean coal technology may be costly and is untested
- Extraction externalities:
 - Simple coal mining can be damaging to habitats and dangerous for workers (not external if firm is liable)
 - Mountain-top removal mining may have serious environmental externalities

Nuclear Power

Nuclear energy uses nuclear fission to break up atoms into smaller atoms, in the process releasing a lot of energy from a small amount of fuel. We use nuclear energy to generate electricity. The fuel is uranium ore that has been enriched. Uranium exists abundantly in the earth. But since uranium can also be enriched to provide ingredients for nuclear bombs or “dirty bombs,” there’s a lot of concern about security of enriched uranium.

Nuclear power is generated in immense reactors that perform fission on the uranium fuel. Building a reactor is expensive, so nuclear is associated with very high fixed costs, but because each unit of fissioned fuel produces so much energy, the marginal costs of energy production are low.

Nuclear energy is considered a “no-carbon” fuel source by some, since no fossil fuels are burned to generate the energy. It is considered “low-carbon” by others, since it takes energy to build and operate the plant, and that energy generally comes from fossil fuel sources. (I think that’s not quite fair, since that energy could arguably come from cleaner sources.)

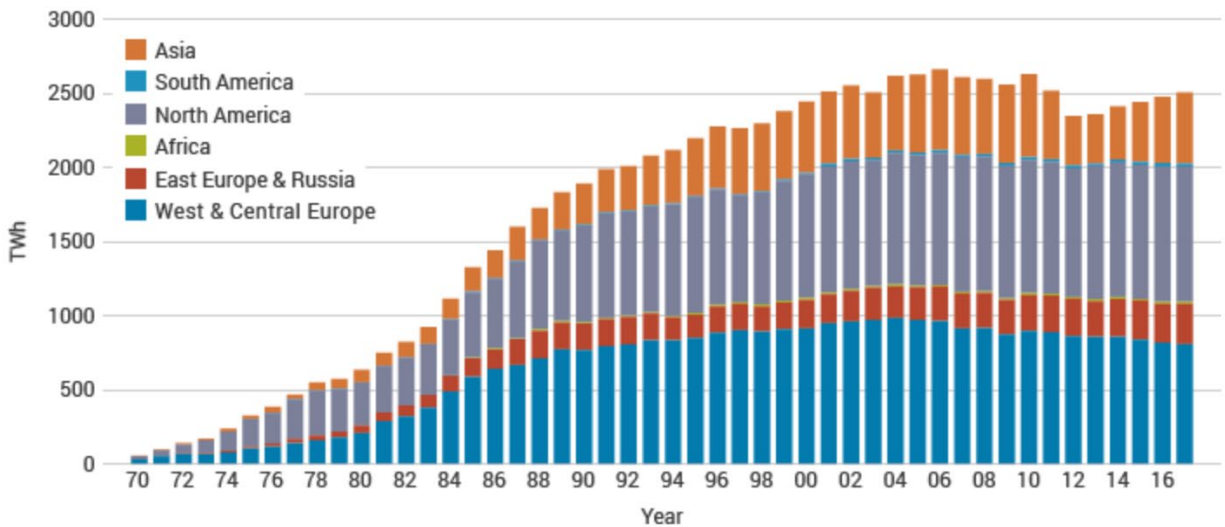
There are three main problems with nuclear energy. First, it’s not always economical to use nuclear energy. This is because of the massive fixed costs. Governments nearly always are involved in building or at least financing nuclear power plants, and that’s because these high fixed costs make nuclear energy even more of a natural monopoly than other energy sources. In fact, I’ve seen it argued that with energy prices as low as we expect them to stay for the near future (because of natural gas), building new nuclear plants now may not make a lot of sense, at least in the US.

Second, people are very concerned about safety of nuclear power. Nuclear power plant designs have improved greatly over the years. Of course, improved safety measures also increase the fixed costs associated with nuclear energy. But I’m sure we won’t soon forget the Fukushima Dai’ichi disaster of 2011, when a Japanese nuclear power plant had a massive failure and the local area was subjected to radioactive contamination. Other nuclear disasters in the past, such as the Chernobyl disaster of 1986, have left some people dead set against the value of nuclear power, period. Some people also point out that aside from the inherent safety of a nuclear reactor, we have to consider the possibility of a terrorist attack that targets nuclear facilities. After Fukushima Dai’ichi, Japan and Germany both declared an end to nuclear power in those countries, and France and Sweden also have sworn off nuclear. Of course, at least in Germany I’ve seen that this means an increase in coal use, which increases air pollution with concomitant bad effects. And Japan has been reopening nuclear power plants over the last few years.

Third, after nuclear fuel has been used, we are left with radioactive waste that must be disposed of. Some elements of this waste will remain radioactive for hundreds or thousands of years, while other elements may last much longer. The basic goal with nuclear waste is to store it in a very well-sealed container deep underground. People have concerns that these containers may leak or that unsuspecting future generations may come across them somehow. Nuclear waste that has not yet been disposed of is a security concern: it can be stolen and used in a “dirty bomb.” Thus nuclear waste security is also an issue of international concern.

How has the use of nuclear power evolved over the decades? It boomed through the 1970’s and 1980’s, and has flattened out since then; it looked like it was declining, but then picked up again in recent years.

Nuclear Electricity Production



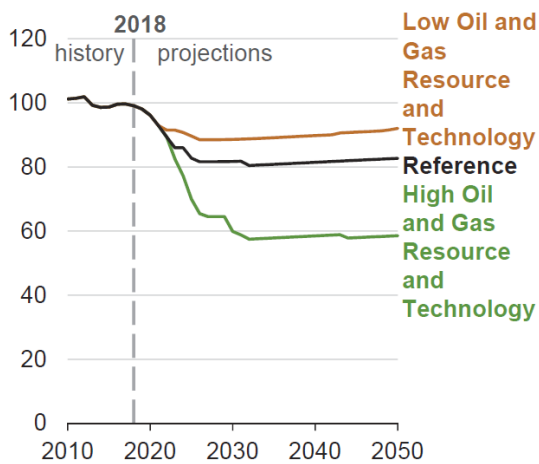
Source: IAEA PRIS

Source: <http://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx>

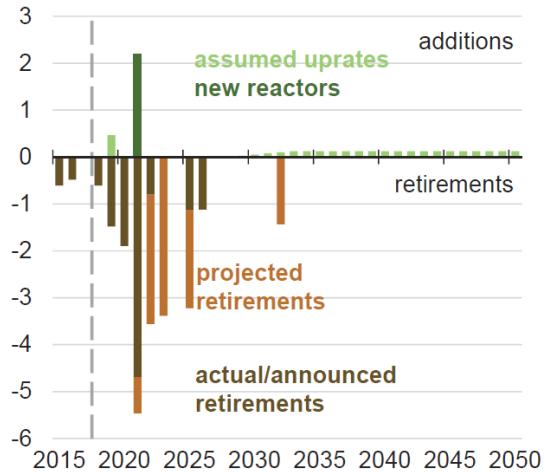
It may be that the post-1970 increase was driven by a desire to reduce our worldwide dependence on oil (remember the 1973-4 oil embargo that was so unpleasant to the US). The decreasing rate of opening new reactors seems to have started after the 1986 Chernobyl disaster. There really have not been a lot of new nuclear plants built worldwide in the last couple of decades, though in February 2012 the US approved our first new nuclear plants since 1978. Plants are having their operating lives extended, but many plants are finally being closed as they reach the end of the time in which they could conceivably operate.

The figure below shows projections of nuclear generating capacity as well as opening and closing of nuclear plants for the coming decades for the United States.

Nuclear electricity generating capacity
gigawatts



Year-over-year nuclear capacity changes (Reference case)
gigawatts



U.S. Energy Information Administration

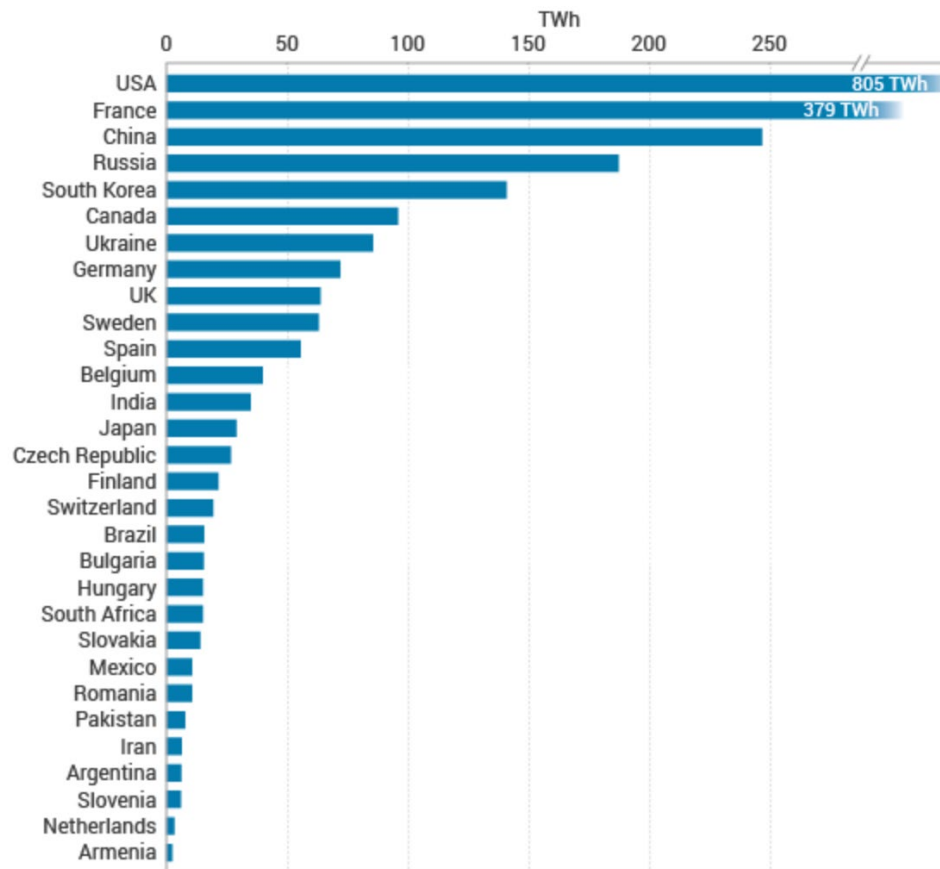
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Source: US Energy Information Administration Annual Energy Outlook 2019

Let's look at how nuclear power is distributed across the world. In raw numbers, the US generates the most nuclear energy, although of course we generate more of all kinds of energy because we're such a big economy. Percent-wise, France is the most dependent on nuclear energy; there, the state is heavily involved with nuclear power. Japan used to be in third place, but both they and Germany lowered their nuclear generation significantly, though as noted above, Japan is picking back up.

Nuclear Generation by Country 2017



Source: IAEA PRIS Database

Source: <http://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx>

Now, let's summarize some of the pros and cons of nuclear power.

Pros:

- A lot of energy from a little fuel
- Fuel is relatively abundant
- Low-carbon or no-carbon
- Very low marginal costs of energy provision once the reactors are built

Cons:

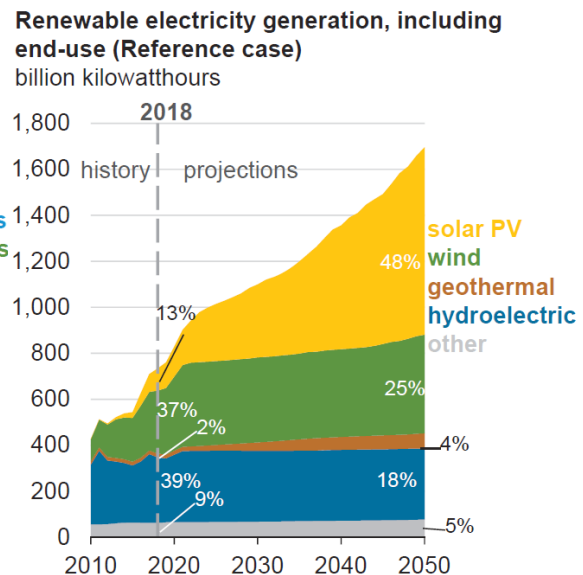
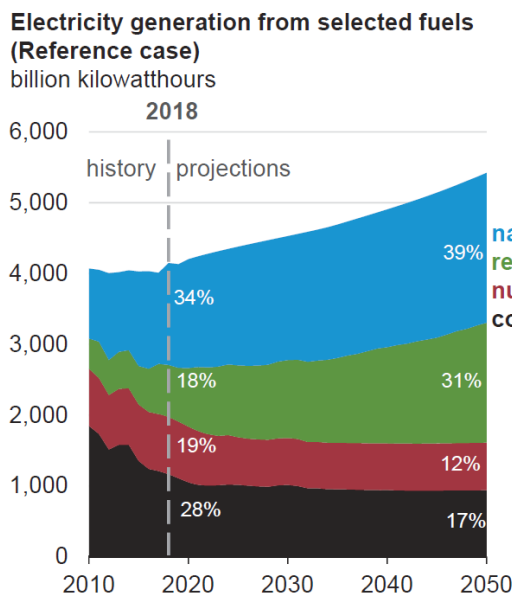
- Production externalities:
 - Small possibility of nuclear reactor accident (small chance of very large damages) – not external if firms are liable
 - Spent fuel is radioactive waste, and must be safely stored for an extremely long time (10,000 to 1 million years). Accidents can happen with this spent fuel.
- Extraction externalities:
 - Some accidents occur in mining nuclear fuel, as with any other kind of mining
- Other concerns:

- Very high fixed (start-up) costs; government generally must be involved
- Security concern with fuel, reactors, and waste: reactors could be terrorist targets, and the fuel and waste could be used as weapons
- Concern about letting “trouble states” (e.g. Iran) develop nuclear power because they may enable the regime to develop nuclear weapons

Renewables

This phrase refers to a variety of sources that either can regenerate or are basically not affected by our use of them. Solar, hydroelectric, wind, and geothermal are low-carbon/no-carbon energy renewable resources: they create very little pollution in their consumption. Biofuels are renewable hydrocarbon fuels. Mostly we think about renewables with regard to electricity; they can be used for other energy needs (e.g. solar cars or biomass heat), but that’s kind of at the margins; mostly, if we want to use renewables to power things, we find ways to make those things be electric-powered.

Below I reproduce again the same figure I showed above to look at the sources of renewable electricity generation.



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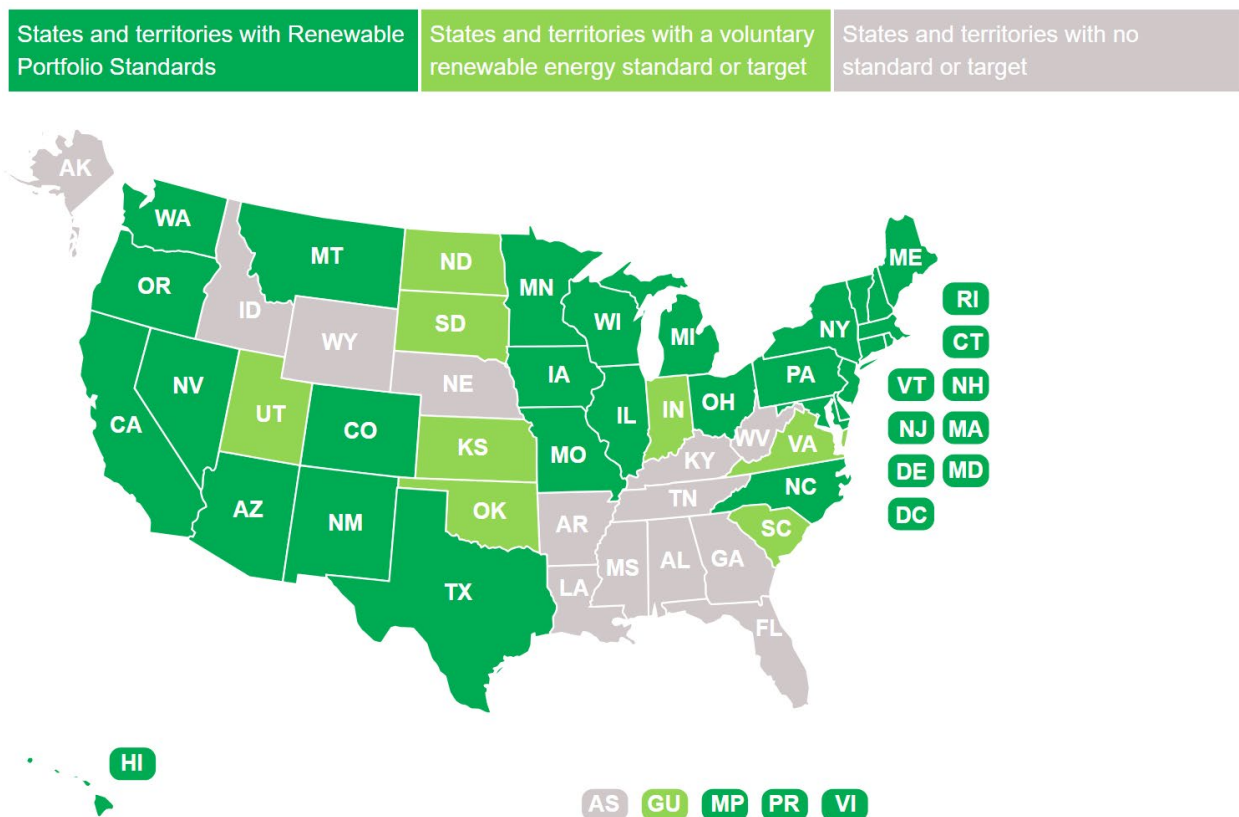
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Source: US Energy Information Administration Annual Energy Outlook 2019

Renewable energy sources are generally more expensive (per unit of energy generated) than fossil fuels, which is why they are not in heavy use, although some are quite viable in some places, hence their increasing adoption. Use of renewable may inevitably increase as scarce fossil fuels rise in price and we innovate to make renewables cheaper, more efficient, and more reliable. Renewables are our “backstop technology:” once fossil fuels are expensive enough, we will switch to renewables not out of the goodness of our hearts but because it’s simply cheaper.

However, because of the externalities and whatnot from burning fossil fuels, we probably want the transition to renewables to occur earlier and faster than it would just from the free market, so that calls for policy intervention. Remember, fossil fuels impose a cost that's not part of their explicit market price tag, and as a result it's not a level playing field; add to that the subsidies I've already mentioned on fossil fuels and you see there's room for lots of important policy work.

Some of those policies are in place already. One of the one that directly pushes for increases in renewable energy is a Renewable Portfolio Standard, which requires that a at least certain percentage of a region's electricity to come from renewable sources by a certain date. As shown in the figure below, many states have these standards; several other countries have them as well, including the UK, Poland, Sweden, Italy, Belgium, and Chile.



Source: <http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx>

Let's look at biofuels and then at the other renewables.

Biofuels

Biofuels is a broad class of hydrocarbon fuels that don't come from fossil sources. Essentially, you find a plant source, process it in some way, and then you burn it. Biofuels were long favored by some green-oriented people, but now the picture of their environmental impact is not as clear. The net carbon impact of these fuels is very tricky to calculate: for each biofuel, you plant some plants, and perhaps use fossil fuel-based fertilizers, and use energy for tractors and what not. The

plants absorb carbon dioxide for the time they grow; then you harvest them and burn them. And demand for biofuels may force some land that would otherwise be standing forests to be cleared periodically (for wood biofuels) or to be converted to agriculture (for corn or other agricultural biofuels). Some analyses have shown that biofuels are not only not good, but perhaps actively bad for the environment; others debate this, and the debate is quite vigorous. Still, biofuels are renewable if they are managed sustainably, which can't be said for fossil fuels.

One popular kind of biofuel is ethanol, which is an alcohol used as a fuel or a fuel additive. It can come from corn, sugar cane, beets, or other sources. Corn is a big source of it in the US right now, and it is heavily subsidized. In some places in the US, gasoline is required by law to have a percentage of ethanol added, ostensibly with the goal of environmental goodness. However, it has been argued that ethanol policy in the United States is largely political: agricultural lobbies are strong, and support of farm state voters is coveted by politicians. Whenever corn prices are high, the ethanol mandates look like a particularly bad idea, feeding through into increased gas prices and taking corn out of the food market.

Another popular biofuel is biodiesel: vegetable oils (palm oil, corn oil, soybean oil) that can be used as a liquid fuel in diesel-type engines. Some people celebrate used cooking oils (collected from restaurants) as a fantastic fuel for cars; my feeling is that it's nice as far as it goes, but it's obviously not going to fuel the entire US vehicle fleet or anything above a small fraction of it.

Various kinds of solid biomass can also be used, including biomass from wood or waste wood (which comes largely from the paper industry). Other sources people have been exploring range from algae to switchgrass to garbage.

One of the big problems with biofuels is the interaction between the production of these fuels and the production of agricultural products for food. If biofuels are grown on land that would otherwise have been used to grow food, or are derived from products that could otherwise be used for food, these biofuels will drive up the price of food.

Also, there are many conflicting estimates, but it's unclear to me how economically important biofuels will be. It takes a lot of space and resources to grow them, so how much can we scale them up? Of course, as discussed above, we shouldn't think that we're trying to meet all of our energy needs with one alternative source, be it biofuel or anything else. The question is: can enough biofuels be provided (without too much of an impact on food production) to make a substantial portion of our energy portfolio?

Now, let's summarize some of the pros and cons of biofuels.

Pros:

- Somewhat cheap (but note that ethanol is heavily subsidized)
- Renewable
- May or may not be less polluting on net

Cons:

- Not yet quite economically competitive (i.e. they are still more expensive, at least without subsidies)
- Consumption externalities:
 - Burning creates greenhouse gases and other pollutants
- “Extraction” externalities:
 - Intensive agriculture may hurt habitats, generate carbon-type pollution, and generate water pollution
- Other concerns:
 - May drive up food prices
 - How much energy can we get from it, really?

Solar, Wind, Hydropower, and Geothermal

The other main kinds of renewable energy are solar, wind, hydropower, and geothermal. I will not discuss wave and tide power, since they don’t seem to be in great use right now and I don’t know much about them. All of these sources are “no-carbon” or “low-carbon” in just the same way that nuclear power is: in operation they do not generate greenhouse gases, but to start generating energy, the plants (or panels or windmills) must be built, and that building takes energy, which often comes from fossil fuels. Again, as our energy portfolio changes over the next few decades, this will be much less true.

Hydropower is an old source and is the most established, and most used, of the renewable energy sources. It captures kinetic energy from flowing water and turns it into electricity. This often involves damming up a water source, and thus changes the flow of a river. These changes, which often include flooding one area and limiting the flow where the river has historically run, can be quite environmentally damaging and can have tremendous effects on people living either in the area of the dam or in downstream areas where flow patterns are changed. The good thing about hydropower is that of the renewables, it’s one of the few that’s really reliable for generating a lot of power all day – that is, it’s not intermittent. On the other hand, hydropower plants also are capital-intensive to build (high fixed cost and low marginal cost), and thus governments tend to have to be involved. Obviously, hydropower only works in some areas; the electricity thus generated must be transported to regions that don’t have access. As a side note, hydropower plants may need to consider changing patterns of water availability caused by climate change. Also, there is a new trend to create more small dams that will produce less energy but cost less and have less of a negative local impact.

Solar energy captures energy from the sun and makes it available to us, usually in the form of electricity or sometimes heat. Electricity from solar energy generally uses panels made up of photovoltaic cells to convert energy from the sun into electricity. Solar energy has improved over the years, but it needs to become more efficient before it’s cost-competitive. China is now producing pretty cheap solar panels, but they are subsidizing the industry quite a bit, and overall solar is still more expensive than other energy sources. But the costs of solar panels have come down over the last decade or so, and this is in large part because of innovation in China to improve the technology, as well as the competitive pressure that put on solar producers in other countries. There is some really nasty pollution associated with the construction of solar panels,

so controls must be in place for that. There has historically a lot of concern about whether solar can produce enough energy to be really meaningful; you need to cover a lot of area with panels to get a meaningful amount of energy. Should solar panels be distributed across rooftops? Would that be enough? Probably not. Should we build massive solar farms in the desert? That could have a big environmental impact on habitats and species. But solar has been expanding faster than anyone projected and is expected to continue to expand for the foreseeable future. The other big problem with solar energy is that it only works where and when the sun shines, i.e., it is intermittent. We must collect the energy while the sun shines and then store it so we can use it later. Efficient energy storage (batteries) is a focus of research and development right now, but we just don't have efficient enough storage technology yet.

Wind power uses windmills to capture kinetic energy from wind and convert into electricity. Wind is really beloved in some areas, because there are few externalities associated with it, although bird populations can be hurt (less with newer turbines than with the older ones). Starting up a wind farm doesn't require a huge investment up front, particularly since wind farms can be built in a piecemeal fashion (you can add a windmill at a time). Some people feel that windmills destroy a landscape's visual or spiritual qualities; others say that the sound of massive windmills is disturbing and some say causes ill health effects (it's called "wind turbine syndrome," and evokes a lot of skepticism); so wind installations get a lot of protest. Here in Massachusetts, major wind projects offshore near Boston (Cape Wind) and proposed ones out here in the Berkshires have been very controversial. Wind power still is somewhat "too expensive" so more cost reductions are needed, although wind is much closer to being on competitive terms with the fossil fuels. Wind is also intermittent and also only works in some places, and so storage technology must improve. In addition, I understand that windmills still tend to break down a lot.

Geothermal energy converts the energy of subterranean heat into electricity. One way of getting this energy out is to find areas where geothermal steam is naturally available at the ground level, and another is to generate geothermal steam by pumping water into the ground through one hole and capture the heated steam that comes out another hole. You then essentially extract energy from the steam. It's not in terribly great use worldwide, although some countries use it quite a bit (Iceland gets 25% of their energy from geothermal,³ and the Philippines uses a lot as well). Geothermal is another source that has high fixed costs to build a plant but may have lower marginal costs of generation. It's not clear to me how much potential geothermal has as a worldwide energy source—it seems particular to the geological characteristics of a region.

For the US, the EIA has come up with estimates of the expected costs of each energy source in the near term. Prices vary regionally, but it's still useful to look at the average values in the final column—total system levelized costs for each energy source. Look at the table below, the column "Total system LCOE." You can see that geothermal, onshore wind, and solar photovoltaic are looking quite competitive.

³ <https://nea.is/geothermal/>

Table 1a. Estimated levelized cost of electricity (capacity-weighted average¹) for new generation resources entering service in 2022 (2017 \$/MWh)

Plant type	Capacity factor (%)	Levelized capital cost	Levelized fixed O&M	Levelized variable O&M	Levelized transmission cost	Total system LCOE	Levelized tax credit ²	Total LCOE including tax credit
Dispatchable technologies								
Coal with 30% CCS ³	NB	NB	NB	NB	NB	NB	NA	NB
Coal with 90% CCS ³	NB	NB	NB	NB	NB	NB	NA	NB
Conventional CC	87	13.0	1.5	32.8	1.0	48.3	NA	48.3
Advanced CC	87	15.5	1.3	30.3	1.1	48.1	NA	48.1
Advanced CC with CCS	NB	NB	NB	NB	NB	NB	NA	NB
Conventional CT	NB	NB	NB	NB	NB	NB	NA	NB
Advanced CT	30	22.7	2.6	51.3	2.9	79.5	NA	79.5
Advanced nuclear	90	67.0	12.9	9.3	0.9	90.1	NA	90.1
Geothermal	91	28.3	13.5	0.0	1.3	43.1	-2.8	40.3
Biomass	83	40.3	15.4	45.0	1.5	102.2	NA	102.2
Non-dispatchable technologies								
Wind, onshore	43	33.0	12.7	0.0	2.4	48.0	-11.1	37.0
Wind, offshore	45	102.6	20.0	0.0	2.0	124.6	-18.5	106.2
Solar PV ⁴	33	48.2	7.5	0.0	3.3	59.1	-12.5	46.5
Solar thermal	NB	NB	NB	NB	NB	NB	NB	NB
Hydroelectric ⁵	65	56.7	14.0	1.3	1.8	73.9	NA	73.9

¹The capacity-weighted average is the average levelized cost per technology, weighted by the new capacity coming online in each region. The capacity additions for each region are based on additions in 2020–2022. Technologies for which capacity additions are not expected do not have a capacity-weighted average and are marked as *NB* or not built.

²The tax credit component is based on targeted federal tax credits such as the PTC or ITC available for some technologies. It reflects tax credits available only for plants entering service in 2022 and the substantial phase out of both the PTC and ITC as scheduled under current law. Technologies not eligible for PTC or ITC are indicated as *NA* or not available. The results are based on a regional model, and state or local incentives are not included in LCOE calculations. See text box on page 2 for details on how the tax credits are represented in the model.

³Because Section 111(b) of the Clean Air Act requires conventional coal plants to be built with CCS to meet specific CO₂ emission standards, two levels of CCS removal are modeled: 30%, which meets the NSPS, and 90%, which exceeds the NSPS but may be seen as a build option in some scenarios. The coal plant with 30% CCS is assumed to incur a 3 percentage-point increase to its cost of capital to represent the risk associated with higher emissions.

⁴Costs are expressed in terms of net AC power available to the grid for the installed capacity.

⁵As modeled, hydroelectric is assumed to have seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season.

CCS=carbon capture and sequestration. CC=combined-cycle (natural gas). CT=combustion turbine. PV=photovoltaic.

Source: U.S. Energy Information Administration, *Annual Energy Outlook 2018*.

Source: https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf

So we know we will be switching to these different energy technologies over the coming years, and we know that we need research and development to improve those technologies. The government reasonably has a role in promoting research and development in general, because innovation is a public good; and of course the externalities associated with fossil fuels make that even more sensible in the context of clean energy sources. So governments should help bring these new technologies forward. The difficulty is that we don't know what innovations will come in the future, so we don't know *which* energy sources will be the best in the future – so which do we subsidize? We don't want to subsidize one energy source (say, hydrogen fuel cells) and have

that turn out to be a dud. That's what's called "picking a winner." We want the market to pick the winner: all other things equal, the cheapest and most efficient technology should win out because that's what would be most profitable in a level-playing-field world. So the trick is to structure subsidies so that they reward innovation in general without preferring one technology over another. Indeed, if we simply priced the pollution and other externalities associated with the energy sources we're trying to get off, then that would generate this same kind of incentive to innovate.

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