Will We Ever Stop Using Fossil Fuels?

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Fossil fuels provide substantial economic benefits, but in recent decades, a series of concerns have arisen about their environmental costs. In the United States, for example, the Clean Air Act in 1970 and 1977 addressed concerns over the emissions of so-called conventional pollutions, notably airborne particulate matter, by imposing fuel economy standards on vehicles and regulations to reduce emissions from stationary sources. During the 1980s, concerns mounted about how the combustion of fossil fuels could lead to acid rain and rising ozone levels. The Clean Air Act Amendments of 1990 created frameworks to reduce sulfur dioxide and nitrogen oxide from power plant emissions, as well as from the combustion of gasoline and diesel fuels in vehicles. However, in many of the world's largest cities in the emerging economies around the world, the conventional forms of air pollution from burning fossil fuels—especially particulates, sulfur oxides, and nitrogen oxides—are still exacting a heavy toll on human health (Chay and

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Greenstone 2003; Chen, Ebenstein, Greenstone, and Li 2013; Knittel, Miller, and Sanders forthcoming).

By the mid-1990s, concerns about the role of fossil fuels in generating emissions of carbon dioxide and other greenhouse gases gained traction. Approximately 65 percent of global greenhouse gas emissions are generated by fossil fuel combustion.[1] Of these emissions, coal is responsible for 45 percent, oil for 35 percent, and natural gas for 20 percent.[2] To reduce carbon dioxide emissions by enough to mitigate the chance of disruptive climate change in a substantial way, there would seem to be only two possible options. One is to find ways to capture carbon from the air and store it. To a moderate extent this can be done by expanding the size of the world's forests, for example, but if carbon capture and storage is to be done at a scale that will more than counterbalance the burning of fossil fuels, there would need to be very dramatic developments in the technologies so that it could happen at a cost-effective industrial level. The other option for reducing emissions of greenhouse gases is to reduce future consumption of fossil fuels in a drastic manner.

A few developed countries have implemented policies to limit fossil fuel consumption through a mixture of taxes, fees, or regulation on carbon emissions (in the case of the European Union, some US states, Japan, Canada, and Australia), subsidies for energy conservation (the United States and elsewhere), and the development of low- or no-carbon energy resources (the United States and elsewhere). In these and other OECD countries, data in the annual *BP Statistical Review of Energy* show that both oil and coal consumption are down about 10 percent, while natural gas consumption (which has lower carbon emissions) is up 10 percent from 2005 levels.[3]

There have been few policy responses to limit fossil fuel consumption in developing countries, even though many of them are experiencing very high and immediate costs from conventional air pollutants. Moreover, this group of countries has greatly expanded its use of fossil fuels in this period, with non-OECD coal, oil, and gas consumption up 46, 33, and 35 percent, respectively, since 2005. As a result, global consumption of fossil fuels rose 7.5 percent for oil, 24 percent for coal, and 20 percent for natural gas from 2005 to 2014.

Two primary market forces could moderate the need for an activist policy response to rising fossil fuel consumption. First, the ongoing consumption of fossil fuels could cause the marginal cost of extracting additional fuel to rise to where the marginal barrel of oil (or ton of coal or cubic meter of natural gas) will be more costly than clean energy technologies (for examples of this argument, see Rutledge

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[1] US Environmental Protection Agency at http://www3.epa.gov/climatechange/ghgemissions/global.html.
[2] Carbon Dioxide Information Analysis Center at http://cdiac.ornl.gov/ftp/trends/co2_emis/Preliminary_CO2_emissions_2012.xlsx.
[3] All country-level fuel consumption data in this article come from the *BP Statistical Review of World Energy 2015*, available at http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

2013; Murray and King 2012). We label this "the supply theory"—that is, the world will run out of inexpensive fossil fuels.

Second, scientific advances could improve the energy efficiency of existing technologies and develop newer, cheaper carbon-free technologies (for example, see the "McKinsey curve" in McKinsey 2009). We label this "the demand theory"— that is, the economy will stop demanding fossil fuels as alternatives become more cost-competitive. This line of thinking is appealing. After all, who wouldn't prefer to consume energy on our current path and gradually switch to cleaner technologies as they become less expensive than fossil fuels? But the desirability of this outcome doesn't assure that it will actually occur—or even that it will be possible.

In this article, we look back at the historical record to assess the power of natural supply-side and demand-side forces (forces unrelated to future policy intervention) to achieve significant reductions in fossil fuel consumption. To gain some initial perspective, consider the ratio of current proven fossil fuel reserves divided by current annual consumption. Proven reserves are defined as fossil fuels that are technically and economically recoverable at current prices, and so this ratio represents the number of years of current consumption that can be economically supplied by known fossil fuel deposits. The total amount of any category of fossil fuels that is in the ground and recoverable *at any cost* is fixed, of course, but reserves can increase or decrease depending on how extraction technologies and prices evolve.

Figure 1 plots reserves-to-consumption for oil, natural gas, and coal at the global level. The available data for oil and natural gas span 1980 to 2014; the data for coal begin in 1994. The striking feature of this graph is how constant the reserve-to-consumption ratio is for both oil and natural gas. It is an empirical regularity that, for both oil and natural gas at any point in the last 30 years, the world has 50 years of reserves in the ground. The corollary, obviously, is that we discover new reserves, each year, roughly equal to that year's consumption. This phenomenon seems to be independent of the enormous variation in fossil fuel price changes over the last 30 years. Coal, on the other hand, shows a dramatic decrease in its reserves-to-production ratio, but there remain many more years of coal reserves, at current consumption, than for either oil or natural gas. Furthermore, the decline in the reserve-to-consumption ratio for coal flattened in the early 2000s and more recently the ratio has even ticked upward a bit. The stability of the reserve-to-consumption ratio provides the first piece of evidence against the idea that the supply of or demand for fossil fuels are likely to "run out" in the medium term.

In the next section of the paper, we analyze the supply behavior for fossil fuels over the past three decades through the lenses of reserve growth and exploration success. The story seems clear: we should not expect the unfettered market to lead to rapid reductions in the supply of fossil fuels. Technical progress in our ability to extract new sources of fossil fuels has marched upward steadily over time. If the advance of technology continues, there is a nearly limitless amount of fossil fuel deposits—at least over the time scale that matters for climate change—that, while they are not yet economical to extract at current prices, could become economical in the future.

Figure 1
Ratio of Proven Fossil Fuel Reserves to Production
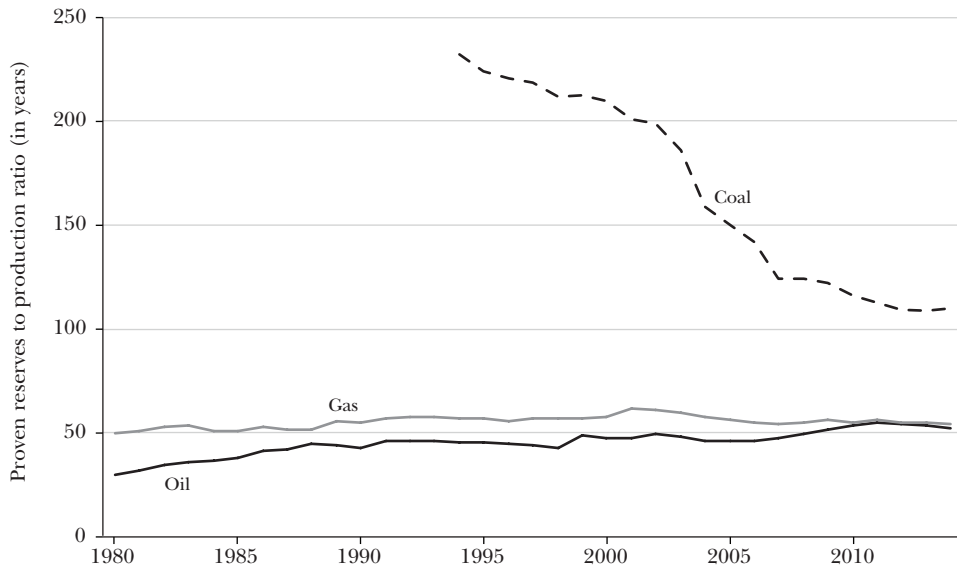
If we cannot rely on market-driven shifts in supply to reduce our consumption of fossil fuels, can we expect the demand for fossil fuels to fall? In the following section, we investigate the prospects for low-carbon alternatives to fossil fuels to become cost-competitive. Hydroelectric, solar, wind, and nuclear are obvious substitutes for fossil fuels in electric power generation. Reducing our demand for petroleum will also require low-carbon sources of transportation, potentially through the large-scale adoption of electric vehicles. We analyze trends in production costs for these cleaner technologies and find it implausible that these trends alone will sufficiently reduce fossil fuel consumption for the world as a whole.

Thus, we are driven to the conclusion that activist and aggressive policy choices are necessary to drive reductions in the consumption of fossil fuels and greenhouse gas emissions. We end the paper with a peek into the future of risks if we were to continue our heavy consumption of known deposits of fossil fuels without capturing and sequestering the emissions. The picture is alarming.

Supply: Peak Oil, Natural Gas, and Coal?

In the aftermath of the oil price shocks of 1973–74, a number of market observers began to warn of ever-dwindling oil resources. A robust debate ensued with geologists and environmentalists often citing Hubbert's (1956) theory of "peak oil" as the basis for the concern. President Jimmy Carter (1977) reflected these

concerns when he told the nation in a televised speech: "World consumption of oil is still going up. If it were possible to keep it rising during the 1970's and 1980's by 5 percent a year, as it has in the past, we could use up all the proven reserves of oil in the entire world by the end of the next decade."

Economists, on the other hand, stressed the ongoing tension between consumption and technological progress. Yes, taken literally, there is a finite amount of any one fossil fuel. Each barrel of oil or cubic foot of natural gas that is taken out of the ground cannot be replaced in a relevant time scale. However, over time we are able to extract more fossil fuels out of the ground as technology improves, and the ultimate resources of planet Earth are both highly uncertain and very large. This observation is perhaps most closely connected with the work of Morris Adelman (1993).

Indeed, two enormous sources of modern oil production—oil from tar sands and oil (as well as gas) from shale deposits—only recently were categorized as "reserves," having previously not been on the radar as economically relevant energy sources. Though these two "unconventional" sources of hydrocarbons currently represent a substantial fraction of total production in the US and Canada and approximately 10 percent of world oil and gas reserves, their economically useful existence was driven entirely by recent technological advances.

Canadian geologists first studied the possibility of production of oil from bituminous sands (also referred to as tar sands or oil sands) in the 19th century (Atkins and MacFadyen 2008). Though the commercial potential for this viscous mixture of heavy oil, sand, and clay had long been recognized, it took scientists several decades to figure out how to economically mine the mixture, separate out the heavy hydrocarbons and "upgrade" them to light, sweet crude oil. It wasn't until 1967 that a small-scale commercial production and upgrading facility began operation (10,000 barrels, hereafter "bbls," per day) and it took until 1999 for Canadian energy authorities to recognize the growing number of tar sands projects as reserves. This decision increased total Canadian oil reserves by 130 billion bbls and total world reserves by about 10 percent. Now, the Canadian Association of Petroleum Producers estimates tar sands production in 2014 was more than 2 million bbls/day.[4]

A similar pattern occurred in the development of oil and gas from shale and other low-permeability rock formations in the United States. These resources had long been known to contain tremendous quantities of hydrocarbons (Shellberger, Nordhaus, Trembath, and Jenkins 2012). However, their low permeability inhibited the rate at which oil and gas molecules could flow out of conventionally designed vertical wells drilled into them. In the 1980s, engineers working in the Barnett natural gas shale formation in Texas began experimenting with hydraulic fracturing and horizontal drilling as tools to solve the permeability problem. By the early 2000s, thousands of wells had been successfully drilled and "fracked" into the Barnett, and the technique

[4] This figure includes synthetic "upgraded" crude oil as well as raw bitumen production, according to data from the Canadian Association of Petroleum Producers at http://statshbnew.capp.ca/SHB/Sheet.asp?SectionID=3&SheetID=233.

Figure 2
Proven Reserves of Oil, Natural Gas, and Coal over Time
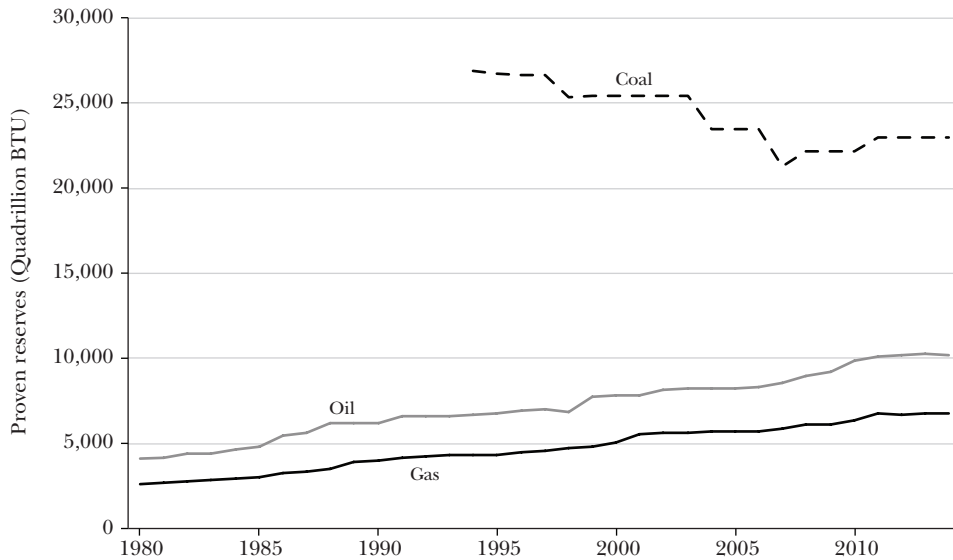
Source: BP Statistical Review of World Energy, 2015.
Note: The figure plots annual reserve estimates in absolute terms for oil, natural gas, and coal.

later spread to the Marcellus natural gas shale formation in Pennsylvania and the Bakken oil shale formation in North Dakota. As a result, US oil and gas reserves expanded 59 and 94 percent, respectively, between 2000 and 2014. This technology-driven growth in reserves also caused increases in production. In 2014, US natural gas production was greater than ever before and oil production was at 97 percent of the peak reached in 1970.

These two technological advances are at least partially responsible for a more general long-term pattern of worldwide reserve growth. Figure 2 plots annual reserve estimates in absolute terms for oil, natural gas, and coal. The steady rise of proven oil and natural gas reserves is striking. The average growth rate in reserves is 2.7 percent for both oil and natural gas. In only one year did total proven oil reserves fall, and this year was immediately followed by a growth in reserves of 12.2 percent the following year. Natural gas reserves fell in only two years, but by less than half of 1 percent in both cases. Coal reserves, on the other hand, fell consistently through the late 1990s to 2008 but have since shown fairly constant positive growth.

A potential concern about the consistency of this pattern is that individual countries do not consistently scale back reserve estimates when low prices cause existing discoveries to be unprofitable. While there is no uniform standard that all countries use in calculating reserves, there are at least two reasons to believe that these data are informative about the scale of fossil fuel resources readily available in the future. First, securities regulators in developed countries heavily regulate

reserve estimates published by publicly traded oil and gas companies, and these numbers are regularly revised downward following oil price crashes. For example, in 1986 and 1998, when oil prices fell 46 and 30 percent, respectively, US oil reserves fell by 3 and 6 percent, respectively. Second, even in the absence of truth-telling regulation in reserve estimates (for example, in the case of oil owned by national oil companies), the country-level data in the *BP Statistical Review* still shows a meaningful number of downward revisions in a typical year. In the history of oil reserve changes in the *BP Statistical Review*, a full quarter of countries report decreases in reserve estimates in the average year. However, the converse of this statement is what is important for understanding how hydrocarbon reserves may change in the future. The BP data show that most countries seem to find significantly more oil (and gas) than they consume in most years.

If the past 35 years is any guide, not only should we not expect to run out of fossil fuels any time soon, we should not expect to have less fossil fuels in the future than we do now. In short, the world is likely to be awash in fossil fuels for decades and perhaps even centuries to come.

An alternative measure of technological progress in the exploration and exploitation of fossil fuel resources is the success rate associated with exploring for new oil and natural gas formations. Without technological progress in this area, present-value considerations will cause firms to drill lower-risk prospects before higher-risk prospects. As a result, the probability of successful exploration falls over time as the "easy" wells are exhausted and oil and gas prices rise to equilibrate supply and demand. In contrast, if technology advances and lowers exploration costs and/or risks, it is possible for the probability of successful exploration to stay constant, or even rise over time, independent of the path of prices.

We are unaware of any systematic data on the history of exploration and development costs for oil or gas, given that it is difficult to observe private company costs for seismic studies, drilling, and other inputs to the exploration process. However, the US Energy Information Administration and the data and consulting firm IHS do publish data on the number of successful and failed exploration and development wells in the United States, so it is possible to measure changes in risk over time. Figure 3 plots the fractions of successful exploration and development wells in each year from 1949 to 2014. The probability of a successful exploratory well did drift downward from about 20 percent in 1949 to 16 percent in the late 1960s. But in 1968, the highly successful Alaska North Slope field was discovered, leading to a near doubling in the probability of exploratory drilling success by 1979.

Similar technological events preceded other periods of growing drilling success. These include the development of ultra-deep water fields in the Gulf of Mexico during the 1980s, hydraulic fracturing technology for natural gas formations in the 1990s, and the same technology for oil formations in the 2000s. By 2007, 69 percent of exploratory wells yielded successful oil or gas production. Though the probability of successful exploration has drifted down to about 50 percent in recent years, it is still markedly higher than in much of the history of US fossil fuel exploration. Figure 3 also shows that the fraction of successful development wells has also

Figure 3

Fraction of Development and Exploratory Wells that are Successful in the United States
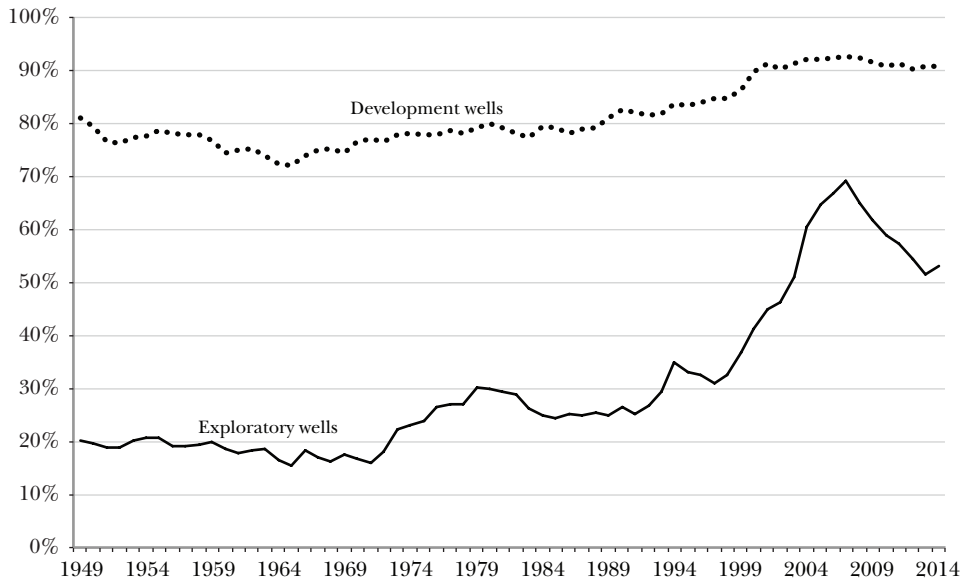
Source: US Energy Information Administration and IHS.
Notes: Development wells are drilled into formations that have already been explored and thus are known to contain oil or gas. Exploratory wells are drilled into formations that have not yet been explored and which might not contain oil or gas.

grown over time. Though these wells are drilled into formations already known to contain oil or gas, there is still risk that a development well faces technical difficulties and produces no output. Growth in this number is also important, since there have been 10 to 20 times as many development wells compared to exploratory wells in recent years. In the United States, at least, it appears that technical progress has consistently helped increase the supply of fossil fuels, in spite of price volatility and the exhaustion of existing fossil fuel formations.

The supply curve for fossil fuels has constantly shifted out over large stretches of time, both because of new discoveries (like the large-scale development of new oil sources or oil and gas from Alaska and from the North Sea in the 1970s) as well as from new techniques like deep-water drilling, hydraulic fracturing, and extracting oil from tar sands. What might be next on the horizon?

Besides measuring fossil fuel reserves, geologists also measure fossil fuel "resources"—that is, fossil fuel deposits that are known to exist but are not currently economical to extract. McGlade and Ekins (2015) summarize reported resources by the Federal Institute for Geosciences and Natural Resources, the International Energy Agency, and the Global Energy Assessment. The range of oil resources is from 4.2 to 6.0 trillion barrels, which is 2.8 to 4 times larger than the existing

reserves of roughly 1.5 trillion barrels. The range of natural gas resources is also immense, ranging from 28,000 trillion cubic feet to over 410,000 trillion cubic feet. For comparison, current global reserves of natural gas are roughly 7,000 trillion cubic feet (according to the US Energy Information Administration's International Energy Statistics).[5] Finally, the estimate range for coal resources is from 14,000 to 23,500 gigatons, compared to existing reserves of around 1,000 gigatons.

These existing "resources" for currently exploited fossil fuel technologies could potentially, if technological progress continues to advance, allow the supply curves for fossil fuels to continue to shift outward for quite some time. In addition, two notable additional resources have not yet been commercially developed, but are known to exist in large quantities: oil shale and methane hydrates.

"Oil shale" is defined by the US Geological Survey as "fine-grained sedimentary rock containing organic matter that yields substantial amounts of oil and combustible gas upon destructive distillation" (Dyni 2006). Despite the similarity in nomenclature, "oil shale" is fundamentally different from the earlier-mentioned "shale oil" which is currently being extracted using hydraulic fracturing techniques in North Dakota, Texas, and Oklahoma. The production technology for oil shale is similar to that of oil sands. In both cases, a heavy hydrocarbon (bitumen in the case of oil sands and kerogen in the case of oil shale) exists in sand, clay, or sedimentary rock. Heat is used to separate the hydrocarbon from the surrounding material. The resulting bitumen or kerogen then goes through additional refining steps to become a final consumer product. Oil shale resources are enormous. A US Geological Survey report from 2006 estimates that 2.8 trillion barrels of oil shale exist (that is, almost 50 percent of the high-end estimate of oil resources), and some private estimates are much larger. If oil shale became economical in the near future, it could cause oil reserves to nearly triple. Because of the use of heat in the extraction phase and the extra steps required for refining, carbon emissions for producing oil from oil shale are greater than for conventional sources of oil. Some estimates suggest that the emissions are 21–47 percent greater per unit of energy produced compared to conventional sources (Brandt 2008).

Methane hydrates are a solid mixture of natural gas and water that forms in low-temperature and high-pressure environments, usually beneath seafloors. Geologists have recognized methane hydrates as a potential source of hydrocarbons since the 1960s, and testing on whether the resource might be commercially viable dates back to the 1970s. The technology to extract methane hydrates at a commercial price does not currently exist, although a number of countries are actively pursuing technology in this area (Boswell et al. 2014). If this technology eventually achieves commercial success, the potential scale of methane hydrate resources ranges from 10,000 trillion cubic feet to more than 100,000 trillion cubic feet, according to US Geological Survey estimates (US Energy Information

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[5] The page of the International Energy Statistics on which this data is found is: http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=3&pid=3&aid=6&cid=ww,&syid=2011&eyid=2015&unit=TCF.

Administration 2012). For comparison, current global reserves of natural gas are roughly 7,000 trillion cubic feet.

The status of oil shale and methane hydrates today is similar to that of oil sands and shale gas in the 1980s. Geologists knew of their existence, but oil and gas companies did not yet know how to recover them in a cost-effective manner. The remarkably successful history of innovation in oil and gas exploration makes it seem more than possible that oil shale and methane hydrates will become commercially developed.

Even without the emergence of new technology for oil shale and methane hydrates, the use of existing technology to develop shale gas and shale oil resources outside of the United States is just now starting. The US Energy Information Administration (2013) estimates that 93 percent of shale oil and 90 percent of shale gas resources exist outside of the United States. Further, these resources represent 10 and 32 percent, respectively, of total world resources for oil and gas. As shale technology spreads across the world, these resources are likely to become economically productive reserves.

The policy implications of this ongoing expansion of fossil fuel resources are potentially profound. Even if countries were to enact policies that raised the cost of fossil fuels, like a carbon tax or a cap-and-trade system for carbon emissions, history suggests that technology will work in the opposite direction by reducing the costs of extracting fossil fuels and shifting their supply curves out.

Demand: Will Low-Carbon Energy Sources Knock Fossil Fuels Out of the Money?

Absent large upward shifts of the supply curve for fossil fuels, deep cuts in fossil fuel consumption will have to come from inward shifts in their respective demand curves.[6] In this section, we analyze the recent changes in the relative prices of carbon-free and fossil-fuel–based energy technologies and characterize what future relative prices are necessary to reduce demand for fossil fuels in a substantial manner. We focus on the electricity and transportation sectors, which are major users of fossil fuels. In the United States, for example, the electricity sector consumes over 90 percent of total coal consumption and 30 percent of natural gas, while the transportation sector consumes over 60 percent of total US oil consumption.[7]

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[6] We admittedly are confounding shifts in the supply curve with changes in the slope. That is, a shift would represent the addition of zero-marginal-cost supplies. In practice, the marginal cost of many of the new resources is nonzero, implying that the supply curve shifts, or becomes flatter, at some strictly positive price.

[7] US statistics on the end-uses of fossil fuels are readily available at the website of the US Energy Information Administration. For example, coal statistics are available at from the *Quarterly Coal Report* at http://www.eia.gov/coal/production/quarterly; natural gas statistics from the "Natural Gas Consumption by End-Use" page at http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm; and oil statistics at the "Petroleum and Other Liquids" webpage at http://www.eia.gov/dnav/pet/pet_cons_psup_dc_nus_mbbl_a.htm.

Replacing Natural Gas and Coal in Electricity Generation

Solar photovoltaics, wind turbines, and nuclear fission power plants are the current leading candidates to replace coal and natural gas in electricity generation. However, nuclear fission has already been commercially exploited for almost 75 years. In spite of this maturity, the rate of new nuclear power plant construction has significantly slowed down since the 1980s, and its share of power generation in most countries has actually fallen over the last decade due to decreasing cost competitiveness (Deutch et al. 2009; in this journal, Davis 2012; see also US EIA International Energy Statistics). Thus, we focus here on the recent history of cost improvements in solar photovoltaics and wind turbines.

We compare costs using *levelized cost of energy* estimates across different technologies. The levelized cost of energy is the present discounted value of costs associated with an energy technology divided by the present discounted value of production—that is, it is a measure of the long-run average cost of the energy source.[8] This measure offers a way of adjusting for the fact that renewable energy sources and fossil fuel plants have a different profile of costs over time. For both renewable plants and fossil fuel plants, the single largest cost occurs in the first year a plant is built, representing the up-front capital cost of the plant. However, for renewable technologies, the operating costs in the remaining years are small, as there are no fuel inputs necessary, only maintenance. In contrast, fossil fuel technologies like natural gas and coal require ongoing fuel costs. Thus, a comparison between the levelized cost of energy for a renewable energy technology and a fossil fuel technology hinges on the difference in up-front capital costs between the two technologies relative to expected fuel costs for the fossil fuel technology.

We report forecasts of the levelized cost of electricity generation published by the US Energy Information Administration during the last two decades. For each year in our data, these forecasts report a projected levelized cost of energy for coal, natural gas, nuclear, and wind for electricity generation plants to be built 5–10 years in the future. The forecast for solar is on a similar timeframe, but for a specific year (usually 4–7 years in the future).[9] We prefer this set of estimates of levelized costs of energy to others that are available for a number of reasons: they are produced annually; the methodology is clearly explained and documented; a wide range of electricity-generating technologies is compared; and the time series is relatively long.

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[8] Specifically, the levelized cost of energy cost of energy is calculated as:

$$LCOE = \frac{\sum_{t=0}^{T} \delta^t C_t}{\sum_{t=0}^{T} \delta^t q_t},$$

where δ is the discount factor, T is the lifetime of a generating technology, and C and q are the technology's per-period costs and production, respectively.

[9] For 2007, the projection is for 2014; for 2008 through 2011, it is for 2016; for 2012 it is for 2017; 2013 for 2018; and, 2014 for 2019. Therefore, the average across all of these years is a six-year forecast, while the last four years report a five-year forecast.

Figure 4

Levelized Cost of Energy (LCOE) Forecasts from the US Energy Information Administration
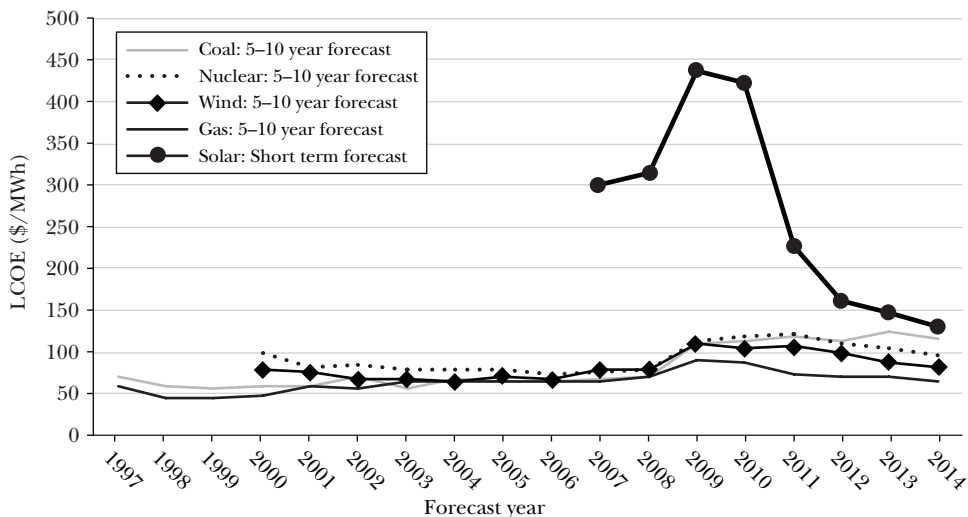
Source: EIA Annual Energy Outlook reports from 1997 to 2014.

One could certainly argue that a longer-term cost outlook would be more appropriate. We focus on estimates 5–10 years out for at least two reasons. First, many analysts believe that it is important to reduce CO_2 emissions in the next decade to mitigate the odds of disruptive climate change. Second, while longer-term costs estimates might exist (although we are unaware of a reasonably long series), they are believed to be very imprecise.

Figure 4 plots the forecasts from the US Energy Information Administration for the last 18 years. Perhaps the most striking finding shown in the figure is the dramatic fall in the cost of solar energy during the past five years. The 2009 forecast for the near-term levelized cost of solar power was nearly $450/MWh of electricity generated, while the 2014 number is under $150/MWh. The speed of these reductions appears to have subsided, but the downward trend continues.

The decline in the costs of solar energy is indeed rapid, but it seems plausible. For example, the current cost of solar energy can be inferred from auctions of photovoltaic installations—in which the prices imply long-run average cost per megawatt-hour of electricity generated. For example, in November 2014, Dubai's state utility held an auction for 100 MWs of photovoltaic power over a 25-year period. The lowest bid was $59.8/MWh. More generally, Bollinger and Seel (2015) document that utilities in the southwestern parts of the United States are now routinely acquiring power from new solar photovoltaic projects at prices in the range of $40–$50/MWh. Though these new projects receive a federal investment tax credit

equal to 30 percent of construction cost, their implied "real" costs are still near or below the levelized cost of energy estimates for natural gas generation in Figure 4.

However, these examples of highly competitive prices for solar energy are from specific locations that are exceptionally well-suited for generating solar energy. In contrast, Figure 4 reports the *average* forecast across locations, including locations where solar exposure may be limited or wind speeds may be slow. Thus, the *average* levelized cost of solar—even given that more favorable sites are being chosen for solar—is still twice that of natural gas in the United States. Wind power seems close to cost competitive with fossil fuel generation in many locations. As with solar, it is complicated to calculate the exact underlying costs of wind power, due to the availability of investment and production tax credits and support from state renewable portfolio standards.

The levelized cost for an electricity technology is only one dimension to be taken into account in making comparisons. Three additional challenges exist. First, both the intensity of sunlight and the speed of the wind vary tremendously across space,[10] meaning that the same solar panel or wind turbine installed in one location will generate vastly different amounts of electricity than if it were installed in another location. This implies that the long-run marginal cost of solar and wind will be upward sloping and large-scale deployment in some areas is likely to be infeasible.

Second, solar and wind energy are inevitably intermittent, which requires either increases in backup generation (often supplied by natural gas generators) or increases in energy storage that aren't typically reflected in the numerator of the basic levelized cost of energy calculation. These costs will depend upon a variety of factors, such as the level of penetration, the degree of variation in generation from the renewable resources, and the correlation in generation across renewable resources. While more research on magnitude of these costs is needed, some estimates exist; these estimates are likely to be very site-specific since they depend on the variability in solar and wind availability. The bulk of this research simulates electricity systems under varying penetration levels of renewables assuming a specific location. Mills and Wiser (2010) simulate the costs of operating an electricity system under different penetration of renewables using detailed simulated output from Midwestern solar and wind installations. They find that for a 10 percent penetration of solar photovoltaic power, intermittency can add as much as $39 per MWh, when the solar is installed in one location, to as little as $3 per MWh when it is installed across 25 different sites. The intermittency costs of a 10 percent penetration of wind across 25 sites are simulated to be below $2 per MWh. In contrast, Wolak (2015) suggests that the costs of intermittency in California are likely to be high because the benefits from diversifying site locations are small.

Finally, because the generation from solar (and wind) resources in a given area tend to be positively correlated, large-scale penetration of either resource will

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[10] It is also possible for fossil fuel technologies to have different localized cost of energy in different places as a result of fuel transportation constraints. For example, natural gas prices and coal prices vary significantly across the United States (as shown by US Energy Information Administration data).

Figure 5
California ISO's "Duck Curve"
(Net load–March 31)
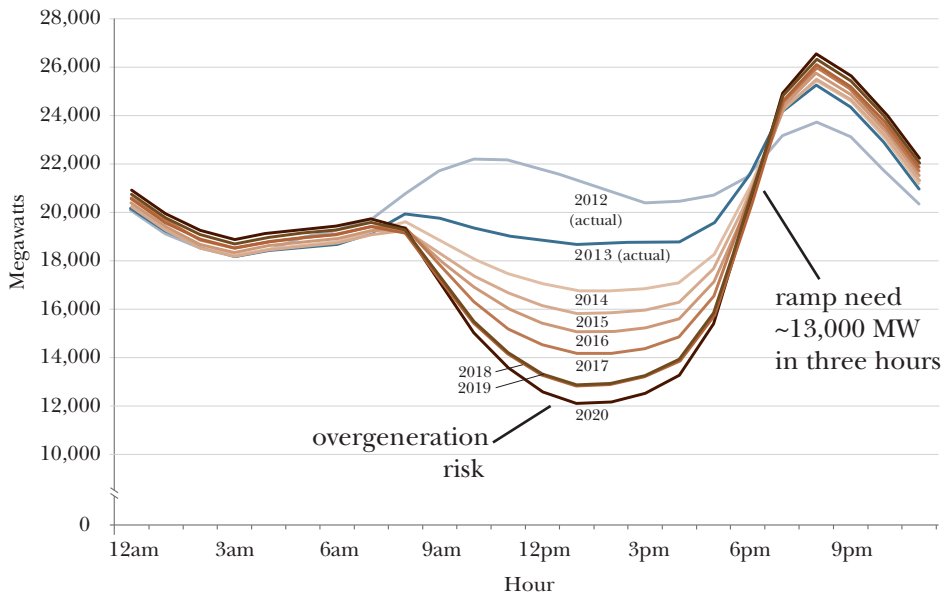
Notes: This graph shows net electricity demand (load), across the hours of the day on March 31, as California approaches penetration of 30 percent renewables by 2020. Because the renewables will predominately be solar, and solar generation peaks during the day, net demand will continue to fall during the day.

inevitably reduce the value of incremental capacity additions. The impact of this on net demand for electricity (after netting out the supply of solar resources) within California has generated what is being referred to as the California Independent System Operator's (CAISO) "Duck Curve," represented in Figure 5. The CAISO has forecast demand for electricity, net of renewable generation, in each year through 2020, when the required amount of generation from renewables hits 30 percent. Figure 5 shows these forecasts for March 31. The figure illustrates that as progressively more and more renewables hit the market, net demand will be lowest during daytime hours and prices during those hours will obviously fall, making additional investments in renewables less valuable.

Intermittency and the large reductions in net demand during peak generation periods imply that, absent economical storage technologies, solar and wind power are ill-suited for baseload generation which is currently covered by coal, natural gas, nuclear, and hydroelectric power.

The levelized costs for fossil fuel technologies presented above also ignore externalities. How much would pricing the externalities associated with carbon

dioxide emissions change these conclusions? Based on Greenstone, Kopits, and Wolverton (2013), the US government applies a social cost of carbon of $43 per metric ton of carbon dioxide in 2015 dollars. Using this value, the carbon dioxide externality for the typical natural gas plant is $20 per MWh, while the externality for the typical coal plant is $40 per MWh. But the US Energy Information Administration forecasts that the gap between average levelized costs for solar and natural gas will still be about $50 per MWh in the near-term.

Replacing Oil Usage in Motor Vehicles

While there are many substitutes for fossil fuels in electricity generation, the primary path for moving away from them in the transportation sector is the use of battery powered electric vehicles, which in turn requires several technology breakthroughs to occur. First, even if oil prices were at $100 per barrel, the price of batteries that store the energy necessary to power these vehicles needs to decrease by a factor of three. Second, the time needed for these batteries to charge must be shortened. Third, the electricity that is fueling these cars will need to have sufficiently lower carbon content than petroleum. Otherwise, we could transition from oil-based transportation with moderately high carbon emissions to coal-fired-electricity-based transportation with even higher carbon emissions. As noted in Graff Zivin, Kotchen, and Mansur (2014), effective carbon emissions from electric vehicles that are powered by the existing US power plant fleet are generally higher than emissions from high-efficiency gasoline-powered vehicles. Only 12 percent of fossil-fueled power plants have low enough carbon emissions that electric vehicles powered by them would have lower emissions than a Toyota Prius.

The large-scale adoption of electric vehicles, instead of petroleum-based internal combustion engine vehicles, seems likely to require all three of these events. To date, none of them have happened. The previous subsection discussed the prospects for greening the electrical grid. Refueling times, as well as the absence of an abundant refueling infrastructure, remain challenges. First we will explore the necessary innovation in batteries.

What is the magnitude of the necessary improvement in storage technologies? Here, we describe some back-of-the-envelope calculations that provide a sense of the present discounted value of operating an internal combustion engine, compared with the present discounted cost of operating an electric vehicle. The bottom line from these calculations is that truly dramatic improvements in battery technology are necessary to bring these technologies into cost parity.

We want to compare the operating costs of an electric vehicle to an internal combustion engine. We assume a 3,000-pound vehicle. (For comparison, the 2015 Honda Accord has four doors and a four-cylinder engine, weighs about 3,200 pounds, and gets a combined-fuel economy of 33 miles per gallon.[11]) We

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[11] The official fuel economy rating is 31 miles per gallon, while the user-reported fuel economy is 33.8 miles per gallon. See the US Department of Energy website at https://www.fueleconomy.gov/feg/PowerSearch.do?action=noform&path=7&year=2015&make=Honda&model=Accord&srchtyp=ymm.

assume both the electric car and the internal combustion engine car are driven 15,000 miles per year, and we use a discount rate of 5 percent.

For the internal combustion engine, we assume that it presently gets 30 miles per gallon. For the electric vehicle, we consider a battery size for a range of 250 miles, which of course is still shorter than driving range of most current internal combustion vehicles. We use a price for purchasing electricity of 12.2 cents per kWh, which is consistent with the average US retail price in 2014. The electric vehicle is assumed to consume 0.3 kilowatt-hours electricity per mile. Finally, because internal combustion engines tend to be more costly than electric motors, we "credit" electric vehicles by $1,000 (Peterson and Michalek 2013).

Current battery costs for an electric vehicle are roughly $325 per kWh. This estimate is consistent with the cost of Tesla's Powerwall home battery, which retails for a price of $350 per kWh for the 10 kWh model (and does not include the price of an inverter for use in the home). This cost estimate may be lower than an average battery cost. For example, Tesla charges $3,000 for an extra 5 kWhs of battery capacity in its Model S, which is $600 per extra kWh; however, this incremental price may also include some level of price discrimination on the part of Tesla. In a 2014 "EV Everywhere Grand Challenge" study, the US Department of Energy finds that the current battery cost is $325 per kWh.[12] At a battery cost of $325 per kWh, the price of oil would need to exceed $350 per barrel before the electric vehicle was cheaper to operate.[13] During 2015, the average price of oil was approximately $49 per barrel. At present, the costs of batteries make large-scale penetration of electric vehicles unlikely.

How is this comparison between the operating costs of an internal combustion engine and an electric vehicle likely to evolve into the future? In these kinds of comparisons, a common mistake is to compare *future* costs of an electric vehicle with *current* costs of an internal combustion engine. But this is the wrong test. Future electric vehicles will be competing against future combustion engine vehicles, not current ones. There will be technological progress in all areas, not only for low-carbon technologies.

The historical record suggests that we should expect persistent innovation in the efficiency of combustion engine vehicles, just as it suggests that there will be continued innovation in the extraction of fossil fuels. For the internal combustion engine, we assume that the fuel economy grows at 2 percent per year, which is consistent with Knittel (2011).

As a basis for estimating the future price trajectory of batteries, Nykvist and Nilsson (2015) survey 85 peer-reviewed estimates of current and future battery costs published since 2008. They also report battery cost estimates for the Nissan Leaf,

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[12] A presentation connected to the study gives a range of $325–500 per kWh. http://energy.gov/sites/prod/files/2014/03/f8/5_howell_b.pdf.
[13] To connect the price of gasoline to the price of oil, we regress the log of historic gasoline prices on the log of oil prices to capture the nonlinear relationship between gasoline and oil prices. We use data from the US Energy Information Administration from April 1993 to July 2015. The estimated intercept is −1.57; the slope is 0.6046. The R^2 is 0.98. The general conclusions are unchanged if we instead assume a linear relationship between gasoline and oil prices.

Figure 6
Break-even Oil and Battery Costs
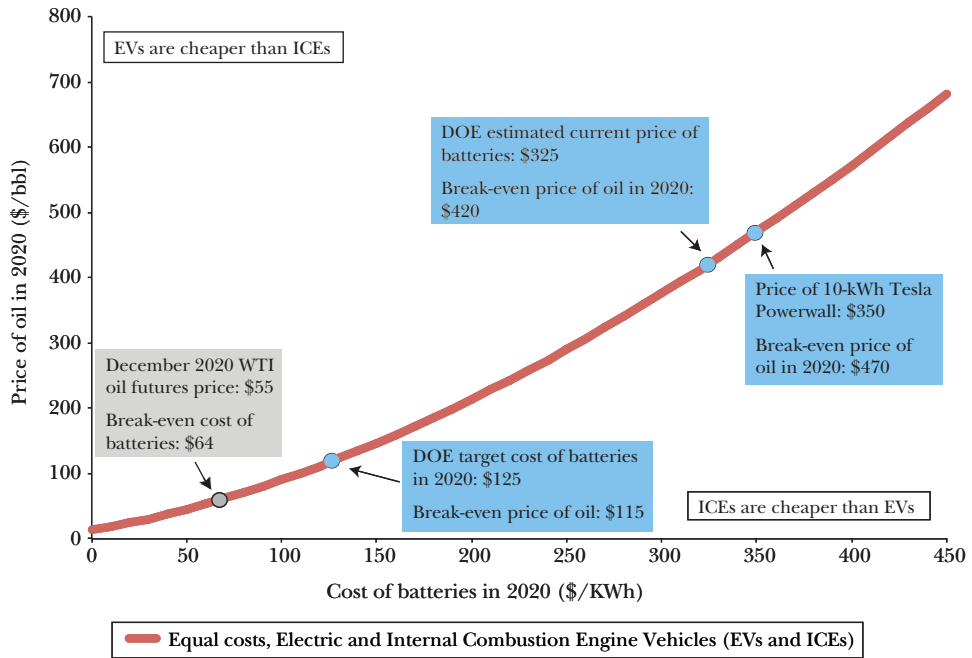
Notes: This graph plots the relationship between oil prices and battery costs such that the present discounted value of owning and operating an internal combustion engine vehicle equals the present discounted value of owning and operating an electric vehicle assuming the year is 2020. We assume the vehicle is driven 15,000 miles per year. We use the average retail price of electricity of 12.2 cents per kWh to charge the electric vehicle. We estimate the relationship between oil prices and gasoline prices using monthly data from 1993 to 2015 and assume a log–log relationship. We size the battery such that the electric vehicle has a range of 250 miles, assuming electricity consumption of 0.3 kWh per mile. The cost of the electric vehicle is reduced by $1,000 to reflect the lower costs associated with electric motors relative to the internal combustion engine vehicle. The fuel economy of internal combustion engines is assumed to grow at an annual rate of 2 percent, consistent with Knittel (2011).

Tesla S, and other electric vehicles. They find large reductions in battery costs over the past 10 years. However, their data also suggest battery costs are predicted to level off between $150 to $300 per kWh over the next 15 years. The same US Department of Energy (2014) "EV Everywhere" presentation discussed above defines a "target" battery cost of $125 per kWh by 2022.

We can extend the calculation above for a variety of oil-price–battery-cost pairs by calculating the indifference price of oil for a given battery cost. Figure 6 plots this relationship across battery costs of 0 to $400 per kWh. For this graph, we compare the technologies in 2020 allowing for the efficiency of internal combustion engine vehicles to increase by 2 percent per year. Even at the US Department of Energy target price for 2020, oil prices would have to rise to $115 per barrel for electric

vehicles to be cost-competitive with internal combustion engines under the assumptions discussed above. If battery costs remain at $325 per kWh, oil prices would have to exceed $420 per barrel. For comparison, the current December 2020 oil futures price using the West Texas Intermediate benchmark (observed on December 18, 2015) was $55/barrel, requiring a battery cost that would fall to $64 per kWh.

These basic calculations make it clear that at least for the next decade or two, electric vehicles face an uphill battle. Not only are large continuing decreases in the price of batteries necessary, but oil prices would have to increase by more than financial markets currently predict.

Other barriers to widespread electric vehicle adoption are not reflected in these calculations. First, the estimates are built on a battery with a range of 250 miles, which for some drivers would not be enough. Second, we assume that there is no disutility associated with longer recharging times of electric vehicles relative to fueling times for internal combustion engines. Finally, oil prices are endogenous, so substantial penetration of electric vehicles would reduce demand for oil. Provided that the supply curve for oil is upward sloping (as it is in almost all markets), this drop in demand would translate into lower oil prices, making gasoline vehicles more attractive.

How does this comparison change if we include the social cost of carbon dioxide emissions? Assume that 20 pounds of carbon dioxide is emitted into the atmosphere for every gallon of gasoline burned. (Most of the weight of the carbon dioxide arises when the car emissions of carbon atoms in the gasoline combine with oxygen in the air, which is why a gallon of gasoline weighing about 6 pounds can produce 20 pounds of carbon dioxide.) As we noted above, a battery price of $125 kWh implies $115/barrel of oil as a break-even price for an internal combustion engine. If we account for the social cost of carbon and make the extreme assumption that electricity for the electric vehicle is carbon free, the break-even price for oil falls to $90 per barrel.

Our emphasis in this section has been on the scope for battery technologies to unseat oil in transportation as well as solar and wind resources as noncarbon methods of generating electricity. There are other noncarbon alternatives for producing energy. In some parts of the world, including Africa and South America, some proportion of the rising demand for electricity might be met by hydroelectric power. Certain regions may have possibilities for electricity generated by geothermal energy or ocean thermal gradients. We mentioned earlier that we were setting aside any discussion of nuclear power in this paper, given the high and rapidly rising costs of nuclear power generation in recent decades. We are generally supportive of research and development into all of these other noncarbon methods of generating electricity. However, the International Energy Administration Agency (2015) projects that fossil fuels will account for 79 percent of total energy supply in 2040 under the current, business-as-usual policies, which already takes into account some rise in these alternative noncarbon energy production technologies. In the medium-run of the next few decades, none of these alternatives seem to have the potential based on their production costs (that is, without government policies to raise the costs of carbon emissions) to reduce the use of fossil fuels dramatically below these projections.

Discussion

Our conclusion is that in the absence of substantial greenhouse gas policies, the US and the global economy are unlikely to stop relying on fossil fuels as the primary source of energy. The physical supply of fossil fuels is highly unlikely to run out, especially if future technological change makes major new sources like oil shale and methane hydrates commercially viable. Alternative sources of clean energy like solar and wind power, which can be used both to generate electricity and to fuel electric vehicles, have seen substantial progress in reducing costs, but at least in the short- and middle-term, they are unlikely to play a major role in base-load electrical capacity or in replacing petroleum-fueled internal combustion engines. Thus, the current, business-as-usual combination of markets and policies doesn't seem likely to diminish greenhouse gases on their own.

What are the consequences of a continued reliance on fossil fuels? We conducted some back-of-the-envelope calculations of the potential warming associated with using all available fossil fuels. This requires estimates of total reserves and resources of each fossil fuel, carbon conversion factors, estimates of historical emissions, and a model to convert carbon dioxide emissions into temperature changes. It is important to note that this exercise is based on high levels of greenhouse gas emissions for many decades beyond 2100. For example, our calculations are based on total carbon emissions ranging from 12,744 to 17,407 gigatons of CO_2. For comparison, the business-as-usual scenario from IPCC (2013) has cumulative emissions of 6,180 gigatons of CO_2 between 2012 and 2100. The calculations are described in detail in a web appendix.[14] Our headline finding is that the combustion of currently known fossil fuels would increase global average temperatures by 10°F to 15°F, depending on the choice of carbon conversion factors and model. Such scenarios imply difficult-to-imagine change in the planet and dramatic threats to human well-being in many parts of the world. Further, these estimates do not account for advances in fossil fuel extraction techniques that could make other deposits economically accessible; for example, the use of oil shale and methane hydrate deposits would add another 1.5°F to 6.2°F of warming. Research on the economic consequences of such changes in temperatures is an important area that is rapidly advancing (for example, Deschênes and Greenstone 2011).

What are the prospects for avoiding this dystopian future? At a high level, there are two market failures—greenhouse gas emissions are not priced adequately, and basic or appropriable research and development is too often underfunded—and the corresponding solutions of pricing emissions and subsidizing basic research and development are easy to identify. However, the politics of implementing such policies are complex, particularly because energy consumption is projected to grow the most in low- and middle-income countries during the coming

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[14] This appendix is available with this paper at http://e-jep.org. Alternatively, see the following link for details on these calculations: https://epic.uchicago.edu/sites/default/files/Calculating%20the%20 Temperature%20Potential%20of%20Fossil%20Fuels.pdf.

decades, and thus the majority of emissions cuts would need to take place in those countries. Without direct compensation, global emissions cuts will require the poorer countries to use and pay for more expensive energy sources. The last several decades have seen limited global progress in tackling these policy problems.

The Conference of Parties (COP21) climate conference in Paris in December 2015 has set out the broad outlines of what could constitute a dramatic change in global climate policy. Whether this high-level voluntary agreement leads to the climate policies necessary to correct the market failures related to greenhouse gases around the globe will be determined in the coming years and decades. Ultimately, their enactment would greatly reduce the probability that the world will have to contend with disruptive climate change. The alternative is to hope that the fickle finger of fate will point the way to low-carbon energy sources that rapidly become cheaper than the abundant fossil fuels on their own. But hope is too infrequently a successful strategy.

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