Reflections

What Would It Take to Reduce U.S. Greenhouse Gas Emissions 80 Percent by 2050?

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Introduction

In its submission to the Paris Conference of the Parties (COP) 21,[1] the United States expressed an aspiration to reduce its greenhouse gas (GHG) emissions by 80 percent from 2005 levels by 2050.[2] This is not a commitment, but rather a publicly stated goal thought to be consistent with the global goal of keeping the anthropogenic rise in global mean surface temperature to less than 2 °C. This article investigates the cost of attaining this goal. One way of reducing GHG emissions is to move away from using fossil fuels. Another option is to continue fossil fuel use but to capture and store the resulting carbon dioxide (CO_2) emissions. At this point, moving away from carbon-based energy would appear to be the more achievable of the two options. In this article, I go some way towards exploring this alternative and examine the financial implications of the U.S. economy, one of the largest in the world and the second largest emitter of GHGs, moving largely away from carbon-based energy by 2050.

First, let me be clear about what I am not doing here. I am not asking if the U.S. economy will of its own volition move away from fossil fuels (that question has been asked recently by Covert, Greenstone, and Knittel 2016). And I am not analyzing the policy measures that would be required to lead to a decarbonized economy, though I will make some remarks about them. What I am doing is investigating in a rather informal way some of the conditions necessary for a transition to a largely carbon-free economy over the next three decades. I try to make calculations that are correct to within orders of magnitude rather than being exact, which is probably the best one can do for events that are three decades in the future. I also try to do this in a

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[1]Conference of the Parties is the name of the annual meeting of the members of the United Nations Framework Convention on Climate Change (UNFCCC).
[2]See the U.S. submission to the COP 21 meeting of the UNFCCC at http://www4.unfccc.int/Submissions/INDC/Published%20Documents/United%20States%20of%20America/1/U.S.%20Cover%20Note%20INDC%20and%20Accompanying%20Information.pdf.

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way that is simple and transparent, so that anyone who is interested in these issues can reproduce the analysis with their own assumptions about costs and other key parameters.

To summarize the results of my calculations, I suggest that the US economy could reduce carbon emissions by 80 percent from 2005 levels within three decades, but that this requires improvements in energy storage technology and also the investment of large amounts of capital (between $3.3 trillion and $6 trillion) in new energy generating capacity, energy storage, and energy transmission. Some of this capital cost can be offset by reduced fuel costs as fossil plants are replaced by renewables with very low operating costs, and also by the need to replace many aging fossil plants, which will reach the ends of their lives in the near future. The net costs might be as low as $1.28 trillion or as high as $3.97 trillion, depending on the assumptions made about energy storage, which turns out to be crucial to the calculations.

Background on U.S. Energy Production and GHG Emissions

The United States has approximately one terawatt ($1\ TW = 10^{12}$ watts) of electricity generating capacity, which produces about four billion megawatt hours (4 billion MWh) of electric power each year. This is the largest source of GHGs in the United States, with 30 percent of GHGs coming from electricity generation.[3] Coal produces 39 percent of electric power and 77 percent of the CO_2 from electricity production, while natural gas produces 27 percent of electric power and 22 percent of the CO_2 from electricity production. Thus, in effect, the coal and gas used to generate electricity produce 30 percent of U.S. CO_2 emissions. The second largest source of CO_2 in the United States is the transportation sector, which accounts for 26 percent of emissions, almost all of which is generated by the combustion of oil in internal combustion engines. The remaining CO_2 emissions come from residential, commercial, and industrial uses of fossil fuels for space heating and process heating.[4] There are other sources of CO_2 emissions, such as cement manufacturing and agriculture, that contribute about 1.5 percent and 9 percent, respectively, to total emissions. However, because of the small contribution of these sources, I do not include them in my calculations.[5]

These data indicate that decarbonizing electricity production is the key to decarbonizing the whole economy, because once we have carbon-free electricity, we can have carbon-free electric vehicles and carbon-free electric space, water, and process heating. Thus I will begin in the next section with an analysis of what it would take to decarbonize electricity production.

Decarbonizing Electricity Production

As indicated in the previous section, the United States currently has 1 TW of generation capacity, which is used to produce about 4 billion MWh/year. The breakdown of electricity

[3]These numbers cover all GHG emissions: for CO_2 alone, electricity production accounts for 37 percent and transportation for 31 percent of emissions. See U.S. Environmental Protection Agency 2017b.
[4]All of these data can be found on the Energy Information Agency website: https://www.eia.gov.
[5]Note that about 11 percent of gross CO_2 emissions are offset by carbon absorption through land use change and forestry (Hanle, Jayaraman, and Smith, n.d.; U.S. Environmental Protection Agency 2017c), so that even if the emissions from cement manufacturing and agriculture continued unchanged, the United States could be carbon neutral overall.

Table 1 Nameplate (maximum) capacity and power output by fuel type

Power source	Percent of capacity	Percent of output
Coal	31.3	33
Natural gas	40.7	33
Nuclear	9.7	20
Hydro	7.1	6
Biomass	0.7	1.6
Geothermal	0.3	0.4
Solar	1	0.6
Wind	6	4.7
Petroleum	5.2	1

Notes: Capacity is from 2011; output is from 2015. Does not include residential solar.
Source: U.S. Energy Information Administration (2017b, 2017c).

generation capacity versus actual power output by fuel type in 2011 and 2015 is shown in table 1.

Several features of table 1 stand out. First, natural gas capacity is much greater than gas output because many gas plants are peakers (i.e., used only to meet peak demand) and have a very low capacity factor,[6] generally in the teens. Nuclear has the opposite characteristic, reflecting its high capacity factor. Finally, the petroleum generating capacity is rarely used, reflecting legacy plants, which are maintained largely to protect against gas shortages. Thus, in the calculations that follow, I ignore petroleum capacity.

Methodology and Key Assumptions

In order to replace coal and gas with non-fossil fuels, we would need to replace 72 percent if we use capacity figures or 66 percent if we use output figures. I will work with output figures because these reflect how the different energy types are actually used. Thus I assume that we need to build new non-fossil capacity capable of generating 66 percent of current total output and that this new capacity is divided 50/50 between wind and solar photovoltaic (PV). This means that from each fuel type we need 33 percent of the current output of 4 billion MWh/year. There are 8760 hours in a year, thus we need $0.33 \times 4 \times 10^{12}/8760$ W $= 0.1506 \times 10^9$ kW of capacity from wind and the same amount of capacity from PV. I shall assume that both wind and PV power plants are constructed as utility-scale plants, something that is important for solar in particular, as its capital costs per unit of capacity drop sharply with the scale of the plant. To work out how much wind or PV capacity we need to build to produce an effective capacity of 0.1506×10^9 kW, we need to know the capacity factors of these plants. On average for 2015, these were 32.5 percent and 28.6 percent, respectively (U.S. Energy Information Administration 2017a). This means that we need to construct 463.38×10^6 kW of wind capacity and 526.57×10^6 kW of PV capacity. It is important to note that these numbers may be too large, as capacity factors for both wind and solar PV have risen over the last decade and may continue to do so.[7] The current averages used here reflect many systems whose technologies are now obsolete.

[6]Capacity factor is the ratio of the average output to the maximum output.
[7]For example, the capacity factors for wind farms built in 2015 averaged 41 percent (see U.S. Department of Energy 2016). For trends in solar, see http://costing.irena.org/charts/solar-photovoltaic.aspx, which shows efficiency increasing from 15 percent to 20 percent over 10 years.

Cost of New Wind and PV Capacity

I assume that wind farms cost $1700/kW, which is consistent with estimates from both Lawrence Berkeley Laboratories (2015) and the U.S. Department of Energy (2015). This means that 463.38×10^6 kW of capacity will cost $0.788 trillion. I assume that the cost of solar utility-scale installations is $1.91/watt, which is the figure given by the National Renewable Energy Laboratory (NREL) (see Chung et al. 2015) as the mean for first quarter 2015 single-axis installations (they cite $1.77/watt for fixed installations).[8] Hence the cost of 526.57×10^6 kW of solar PV capacity will be $1.005 trillion, for a total cost of $1.793 trillion.

Thus, in round numbers, building enough solar PV and wind capacity to replace the electricity now produced by fossil fuels will cost about $2 trillion. This is, of course, at current prices for solar PV and wind. However, since prices for both technologies have been falling fast for more than a decade, current prices probably overstate the costs. In fact, anecdotal evidence suggests that their prices are already significantly lower than the NREL first quarter 2015 figure. For example, there are reports of solar power plants being constructed in North America for $1.25/watt. If costs continue to fall at current rates and construction is spread over three decades, the total cost could be more like $1–$1.5 trillion.

In addition to the costs of generating capacity, we must consider the costs of additional transmission lines as well as the more complicated issue of the cost of energy storage capacity to address the issue that two-thirds of all U.S. electric power would be generated by intermittent power sources.[9] I examine these two issues in the next two sections.

Costs of Additional Transmission Lines

High-voltage transmission lines cost anywhere from $1 million to $3 million per mile (Pletka et al. 2014), depending on the voltage (higher-voltage lines cost more but suffer lower transmission losses) and on the cost of the land over which they run. The U.S. grid currently has more than 200,000 miles of high-voltage lines (Lott 2015). Extensive use of wind and solar power, the costs of which are lowest in specific areas of the country, might require the addition of another 25 percent of current transmission capacity. This means 50,000 miles of transmission lines; at an average of $2 million/mile, this would cost $100 billion. There would be additional capital costs associated with substations and interconnections between existing and new power lines, and some of these could cost as much as $500 million each. Thus it seems reasonable to think of grid extension costs as being in the range of $110–$120 billion, which is huge in absolute terms but small relative to the cost of the new renewable generation capacity.

Costs of Energy Storage Capacity

If we replace all fossil generation capacity with wind and solar PV, then we will need to deal with the intermittency of its output. Clearly, solar PV produces no power at night, but even

[8]Solar PV panels can be installed in a fixed position (as is almost always the case in rooftop installations) or they can track the sun on one or two axes (east–west and vertical–horizontal). Generally utility-scale installations track on an east–west axis.

[9]That is, power sources whose outputs vary significantly over time in ways that cannot be controlled by the power station operators.

during the day its output can drop because of cloud cover.[10] Wind blows more at night than during the day, but there can still be times when there is little or no power from solar or wind plants, and the remaining sources—nuclear, hydro, and geothermal—are inadequate to meet demand. Currently in the United States, any shortfall arising from a sudden drop in wind or solar power is typically met by gas combustion turbines. However, in Germany and Denmark, where renewable penetration is greater, such shortfalls are typically met by importing hydropower from Norway, which can generate in excess of its domestic needs. If the United States wants to adopt wind and solar on a large scale and avoid GHG emissions, then the obvious path forward is to invest in energy storage capacity (although there are alternatives, which I explore briefly in the next section).

Pumped Hydro and Compressed Air

Currently most grid-scale energy storage in the United States takes the form of pumped hydropower stations: water is pumped to a reservoir on top of a hill when there is spare electric power and allowed to run down and generate hydropower when there is a power shortage. Such plants are economically attractive, but require a hill with a flat top that is not currently being used for anything and a river at the bottom of the hill, a rare combination of circumstances. Most suitable sites have already been used.[11] Compressed air energy storage is also an option. Here, air is stored under pressure in an underground cavern when there is surplus power and released to drive a turbine when there is a power shortage. Again, this technology is very dependent on the availability of suitable geologic features.

Battery Storage

Going forward, additional storage capacity is most likely to be provided by batteries, as most sites suitable for pumped hydro or compressed air are already in use.[12] Battery storage capacities are typically measured in megawatt hours when used in the grid or kilowatt hours (kWh) in cars.[13] Megawatt hours measure the total amount of electric power that a battery can supply when fully charged; another dimension of battery performance is the maximum rate at which it can supply power, which is measured in megawatts (MW). To make an analogy with water storage, megawatt hours measure the capacity of a tank and megawatts measure the size of the exit pipe and thus the rate at which water can flow out of the tank. However, when considering storage as a way of backing up intermittent renewable energy, it is generally the total capacity in megawatt hours that matters.

Battery storage has historically been expensive, with costs in the range of $400–$500/kWh (Crabtree 2016). To get a sense of what this means, consider a typical wind turbine with a capacity of 2 MW. If we assume it has a capacity factor of 32.5 percent (the figure I used earlier), then on average the turbine produces 24×0.65 MWh daily, or 15.6 MWh/day. At a capacity cost of $1,700/kW, the turbine will cost $3.4 million. At a cost of $500/kWh, a battery

[10]Solar thermal power stations, also known as concentrating solar power (CSP), can produce power at night, but they have higher capital costs. I discuss this issue later.
[11]See http://www.industcards.com/ps-usa.htm for a list of pumped hydro plants in the United States.
[12]Indeed, some California utilities are already operating grid-scale batteries.
[13]A Tesla model S battery has a capacity of 70–90 kWh.

large enough to store one average day's output of electricity will cost $7.8 million, more than twice the cost of the turbine.[14]

We can do a similar calculation for solar PV. Using the figures cited earlier for costs and capacity factors (i.e., $1.91/watt and 28.6 percent), we can see that a 10 MW solar installation would cost $19.1 million and produce on average 24×2.86 MWh/day. At a cost of $500/kWh, a battery to store this would cost $34.3 million, or 1.7 times the cost of the installation.

For these calculations I have used the upper limit of the range of current costs of storage capacity (i.e., $500). Storage costs, like so much else associated with renewable energy, have been falling rapidly. When Tesla's gigafactory was announced, Elon Musk promised that it will produce batteries at $350/kWh, and there are companies promising to manufacture utility-scale reduction-oxidation (known as redox) flow batteries for as little as $150/kWh.[15] For a recent master of business administration class I profiled fifteen companies that claim to be bringing new and more efficient energy storage technologies to the market. Thus this technology is in a state of flux and it is difficult to produce a good estimate of what storage will cost over the next few decades.

To provide a sense of the numbers, at the promised price of redox flow batteries ($150/kWh), the cost to store a day's output from a 2 MW wind turbine or a 10 MW solar farm is $2.3 million and $10.3 million, respectively. These storage costs are less than the costs of the power plant, but still very significant additions to the capital costs of the plants. In fact, it appears that Tesla and other electric vehicle manufacturers are already buying their batteries for less than the $350 that Musk forecast, with recent contracts suggesting less than $300/kWh for electric vehicle battery packs and forecasts of $200/kWh or less by 2018–2020 (Nykvist and Nilsson 2015).

How Much Storage Capacity Is Needed?

How much energy storage capacity would the U.S. actually need in a world where two-thirds of its electric power comes from intermittent renewables? Here is one approach to answering this question. As discussed earlier, the United States currently consumes 4 billion MWh each year. In our scenario, two-thirds of this electricity would be from renewable energy by 2050. This means that on an average day, the United States would consume 7.3×10^6 MWh of renewable energy. If we had a probability distribution over the output of renewable energy, we could ask, how much storage capacity do we need to store to be 99 percent certain that we will always be able to meet demand? Unfortunately we don't have this probability distribution, and indeed the problem is far more complex than this. Different regions of the United States suffer wind or solar outages at different times. This means that in order to estimate how much storage is needed, we would need the joint probability distribution of output for each energy source in each region, the correlations between these outputs, and the grid interconnections between these regions. Suppose in theory that we can work this out and that the answer is that we need the capacity to store *x* days of renewable energy production. At the optimistic cost of $150/kWh, the capacity to store 1 day of renewable energy production would cost $1.095

[14]I will discuss the battery size that might be appropriate later.

[15]Flow batteries store electric charge in a liquid held in tanks that are not in contact with the anode or cathode of the battery. Enervault (www.enervault.com) is one of the manufacturers of these batteries in the United States.

trillion. Using Elon Musk's forecast of $350/kWh, it would cost $2.555 trillion, and in this case, 2 days of storage would cost $5.110 trillion.

Of course, we don't know what storage prices will be in the future, nor do we have a solid basis for saying how much storage capacity we will need, but these numbers clearly suggest that the costs of storage will be very high and might even dominate the capital costs of replacing fossil fuels with renewables. This makes it particularly important to estimate how much storage capacity we will actually need. It certainly seems that we should have enough stored energy to cover several days of very low solar and wind outputs. Thus in my calculations I will assume that we need enough storage to replace 2 average days of renewable energy production.[16] Although there is not a very solid scientific basis for this number, it seems consistent with the results emerging from the limited literature on storage needs.

Literature on Electricity Storage Needs

A study of the role of variable renewable energy in the Texas grid examined the consequences of having 80 percent of the state's energy come from solar PV and wind and concluded that storage that could meet 24 hours of demand was the ideal from the perspective of grid management (Denholm and Hand 2011). Another study of the integration of wind and solar into the western U.S. grid concluded that without any storage it would be possible to accommodate 35 percent variable renewable energy at very low cost (GE Energy 2010). This study emphasized the importance of enlarging balancing areas.[17] It also emphasized demand-side management in the context of managing intermittent energy sources.[18] Another interesting study of the western grid (Makarov et al. 2012) concludes that the intermittency of 88 GW of wind capacity can be fully offset by 68 GWh of storage capacity. Assuming again that the capacity factor for wind is 32.5 percent, this wind capacity will produce an average of 686 kWh/day. This means that the recommended storage is 10 percent of average daily wind energy production.

Potential for Solar Thermal Power Stations

At this point I want to return to an issue raised earlier, namely that solar thermal (or CSP) power stations can produce power after the sun has set. These power stations operate by concentrating the sun to heat a liquid—generally liquid salt—and then use this to run a conventional steam turbine. Not all of the hot liquid has to be used when it is heated: some of it can be stored underground in heavily insulated storage spaces and used to generate electric power at some future time.

[16]In response to the growing proportion of renewable energy in the California energy supply, the California Public Utilities Commission recently passed a mandate that requires utility investments in 1.3 gigawatts (GW) of energy storage by 2020.

[17]Balancing areas are the areas over which demand and supply are equated—the larger the area, the greater the probability that it will contain intermittent energy sources with outputs that are not closely correlated. Thus large areas reduce the risk of energy supply failures by a mechanism that is similar to the one by which portfolio diversification reduces the risk of loss.

[18]Demand-side management refers to mechanisms by which a utility shifts end-user demand from one time of day to another, or displaces it altogether, in accordance with a prior agreement with the user.

This is clearly a big plus from the perspective of grid management. The downside is that, according to the International Renewable Energy Agency (2012), these power stations have higher capital costs than solar PV (about $9000–$10,000/kW) for plants with the capacity to store power for up to 15 hours. However, if they reduce the need for construction of separate storage capacity, they may still make economic sense. A report by the International Renewable Energy Agency (2012) provides details on the capital costs of CSP plants with and without heat storage capabilities, and from this it is possible to calculate the capital cost of storage, at least for 2012. It is very close to what was then the cost of battery storage—in the range of $500/kWh. The authors do not expect these costs to fall significantly, thus the best approach appears to be to use solar PV and a separate storage technology, with the cost of both likely to fall.

Alternatives to Storage

Electricity storage is clearly expensive. An alternative might be to build more non-fossil fuel capacity—hydro, geothermal, and nuclear—that reduces the dependence on intermittent power sources and hence the need for storage. However, hydro and geothermal are situation specific. Although their use can probably be expanded, there are geologic limits to what they can offer and it seems unlikely that they can provide significantly more power in the United States. That leaves nuclear. Is nuclear power more or less expensive than renewable power with storage?

Unfortunately, the answer depends on how much storage we need. The U.S. Energy Information Administration (EIA) estimates the overnight capital cost (i.e., without financing costs) of a nuclear reactor to be $5530/kW and the capacity factor to be 92 percent (U.S. Energy Information Administration 2017a). Although the EIA does not include financing costs in its estimates of capital costs, industry sources estimated these to be about $8500 in 2008 (Schlissel and Biewald 2008).[19] Adjusting by the capacity factor results in a capital cost of $9239 per effective kilowatt for nuclear versus $6678 for solar PV.[20] If we continue to assume that we need 2 days of storage to complement a renewables-intensive system, we would have to more than double the estimated capital cost of solar PV to allow for the cost of storage, which would make nuclear less expensive than solar. Note, however, that this calculation does not take into account the end-of-life costs associated with decommissioning nuclear reactors, which are generally on the order of $0.5–$1.0 billion per reactor (Organization for Economic Cooperation and Development 2016). The conclusion is that nuclear power is certainly an alternative to solar or wind with storage and could be significantly less expensive if storage capacity on the order of one or more days of output is required. As indicated in the studies described earlier, storage needs increase nonlinearly with the penetration of intermittent

[19]These costs are probably higher today.

[20]It is important to note that nuclear costs are very uncertain. Reactors currently under construction in Europe and the United States are all vastly over budget and will eventually cost more than the International Energy Agency's estimates (see, e.g., https://www.bloomberg.com/news/articles/2017-02-02/costly-delays-upset-reactor-renaissance-keeping-nuclear-at-bay). However, the Korean Electric Power Company (KEPCO) is close to completing new reactors in the United Arab Emirates and claims to be on budget, at around $4000/kW (http://www.reuters.com/article/us-kepco-emirates-nuclearpower-exclusive-idUSKBN1801ZD).

energy sources and can be quite low or even zero for penetration levels up to 30–50 percent; however, storage needs increase quickly after that. This suggests that there might be a case for replacing fossil fuels with intermittent renewable energy up to about 50 percent of total generating capacity and then filling the remaining gap with nuclear power. [21] Thus it is important to better understand how much storage capacity is needed to support intermittent energy.

Spatial Diversification of Wind and Solar

Another alternative to storage is to use spatial diversification of wind and solar sites to even out the total energy generated by these sources. If the statistical correlations between the outputs of these power sources are sufficiently small, or even negative, then the variability of total power output will be smaller than the variability of any one site or region (Heal 2016). This means that it is possible that there will always be renewable power available somewhere in the grid and that by building enough capacity and a sufficiently interconnected grid it may be possible to ensure uninterrupted power everywhere without storage. Chang, Spees, and Weiss (2010) explore the trade-off between storage and capacity, and MacDonald et al. (2016) show that it is possible to meet U.S. electricity demand without the use of fossil fuels or storage provided that a high-voltage direct current (HVDC) grid integrates the entire country and sufficient renewable capacity is built at various crucial nodes of the system.

Heal (2016) models this idea formally and examines how much renewable capacity we would have to build, given a fully integrated grid, to be 95 percent certain of meeting an exogenously given level of demand. He concludes that we would need to install a level of capacity that is sufficiently high to ensure that mean output is more than twice the level of demand. It is probably too early to draw firm conclusions about the investments that would be needed based on this line of argument. However, it seems possible that building extra generating capacity in the right places and connecting all energy sources and sinks through a high-capacity low-loss grid could be an alternative to the extensive use of storage to smooth the output of renewable sources.[22] Nevertheless, storage has additional benefits. For example, it can be used to meet peak demands and thus can reduce the need for uneconomical “peaker” plants, which operate just a few hours per year to meet summer peak demands.[23]

Role of Cost Offsets

There is an important aspect in which the numbers I have presented thus far overstate the cost of moving to renewable energy. This is because when we install solar or wind generating capacity, we are in effect prepaying our electric power for the next 20–30 years, depending on the life of the power station. These power stations have no fuel costs and only minimal operating costs, which means that each power station provides a stream of electricity at zero marginal cost over its lifetime. Thus there is a fuel cost savings relative to continuing

[21]I am assuming that the existing nuclear capacity remains in place or is replaced as it reaches the end of its life. Thus I am referring here to additional nuclear capacity.

[22]For more details on this line of argument, specifically for the Pennsylvania–New Jersey–Maryland interconnect, see Budischak et al. (2013).

[23]Note that 20 percent of U.S. generating capacity operates less than 100 hours/year.

to use fossil fuels, and we can estimate this savings. One kilowatt hour requires the combustion of (on average) 0.00052 short tons of coal or 0.01011 million cubic feet (mcf) of natural gas. Taking the price of coal to be $40/short ton and gas to be $2.75/million BTU,[24] and assuming that a 50/50 mix of coal and gas would have produced the power that is instead to be produced by renewable energy, the zero marginal costs of renewables would save $64.153 billion per year in fuel costs once renewables have fully replaced fossil energy sources. Assuming that renewables replace fossil sources linearly over 30 years, the average saving will be a half of this. Over 30 years this totals to $0.9625 trillion, which means that the fuel cost savings offset about $1 trillion of the costs of going carbon free.

Another figure to be offset is the cost of replacing fossil fuel plants that will come to the end of their lives over the next three decades, a category that certainly includes most coal plants in the United States. Most U.S. coal plants were built before 1975 and are thus already at least 41 years old, with an expected life of 40–50 years. Most of the rest of the coal plants were built before 1990, making them at least 26 years old and thus also due for retirement during the period we are considering. In addition, more than 20 percent of all gas generators were more than 10 years old as of 2010, making them candidates for replacement by the end of the period we are considering (U.S. Energy Information Administration 2011).

Thus the costs of these plant replacements, which would have to be carried out anyway, should be subtracted from the overall capital costs I have estimated here. The EIA estimates the capital costs of coal and gas plants to be $3000/kW and $1000/kW, respectively (U.S. Energy Information Administration 2013), implying that the cost of replacing plants that will reach the limits of their useful lives is $0.99 trillion for coal and $0.066 trillion for gas, for a total (in round numbers) of $1.06 trillion.

The Overall Cost of Carbon-Free Electricity

Thus far I have estimated the capacity costs, transmission costs, and storage costs of making the U.S. power grid carbon free. I am going to assume that when the grid is carbon free, we will need the capacity to store 2 average days of renewable power generation: this figure has no rigorous scientific basis but seems to pass a "laugh test." All of these costs are summarized (and added together) in table 2.

Whether we focus on the best- or worst-case scenario, the numbers in table 2 are large. More specifically, if we were to replace fossil fuels over the next three decades, these numbers imply annual expenditures in the range of $37.6 billion–$135 billion (net of the fuel and capital cost offsets). To put this into perspective, in 2015, U.S. capital expenditure on new electric generating capacity (wind, solar, gas, coal, and nuclear) was about $42 billion; this does not include expenditures on upgrading transmission or on energy storage. Thus, in the best-case scenario, we are on track in terms of annual expenditure. But in the worst-case scenario we would need to scale up the level of expenditure on new generating capacity in the United States by a factor of about three. These estimates have at least two striking characteristics.

[24]These data are from the EIA website.

Table 2 Electricity generation, transmission, and storage costs of making the U.S. power grid carbon free

Category	Best-case scenario	Worst-case scenario
Capacity	$1 trillion	$1.79 trillion
Transmission	$0.1 trillion	$0.2 trillion
Storage	$2.2 trillion	$4 trillion
Total	$3.3 trillion	$5.99 trillion
Fuel savings offset	$0.96 trillion	$0.96 trillion
Plant replacement offset	$1.06 trillion	$1.06 trillion
Net total	$1.28 trillion	$3.97 trillion

Notes: Best case assumes a 25 percent reduction below the best current costs of $1500/kW for wind and $1.25/W for solar, a capacity factor of 38 percent for wind and 28.6 percent for solar, and 2 days of stored renewable output at a cost of $150/kWh. Worst case assumes capacity factors of 32.5 percent and 28.6 percent and costs of $1700/kW and $1.91/W for wind and solar, respectively, and 2 days of stored renewable output at a cost of $280/kWh.

Sensitivity of Total Cost to Storage Needs

The first characteristic is the sensitivity of the total cost to the cost and quantity of storage needed. While we have some sense of the storage costs, there has been little analysis of how much storage would be needed in the grid as a whole once renewables replace fossil fuel. I have assumed enough storage to replace all renewable energy for 2 average days, but this is no more than a thoughtful guess. Doubling this to 4 days would add $2 trillion and $4 trillion to the best- and worst-case scenarios, respectively. It is also important to note that the amounts of storage capacity we are talking about here are huge—4.8×10^6 MWh/day—so 2 days is almost 10^7 MWh.[25] Some researchers have suggested that we would need even more storage—1 week of power in reserve—but this number seems to have no more scientific basis than mine.[26] Note that my worst-case scenario for storage assumes a cost of $280/kWh, which seems to reflect current or emerging costs (Nykvist and Nilsson 2015). Moreover, it seems very likely that these costs will fall. For example, the cost of lithium ion batteries was $3000/kWh as recently as 1995, but researchers anticipate changes in battery technology that will reduce cost and increase energy density within a few years (Crabtree 2016).

Offsets from Fuel Savings and Plant Replacement

A second striking characteristic of these results is the size of the offsets from fuel savings and plant replacement. Net of these offsets, the costs of the best-case scenario are totally manageable. This reflects the fact that solar PV and wind costs are now very competitive with conventional fossil fuels and that most fossil plants would need to be replaced within the three decades we are considering (quite independent of the need to transition to carbon-free energy). Instead of replacing fossil plants with similar equipment, we are replacing them with renewable plants, which in many locations have lower levelized (lifetime average) costs of electricity. Thus we are actually saving money in the process. To provide a sense of how competitive renewable energy sources are relative to fossil fuels, note that in its most recent comparison of levelized costs, Lazard (2015) indicates 3.2 and 4.3 cents/kWh as the best-case

[25]For a comparison, a large pumped hydro storage plant has a capacity of several thousand megawatt hours.
[26]See Murphy's (2011) analysis in A Nation-Sized Battery at http://physics.ucsd.edu/do-the-math/2011/08/nation-sized-battery/.

costs of power from wind and solar PV, respectively, compared with 5.2 and 6.5 cents/kWh for natural gas combined cycle and advanced superpulverized coal, respectively.

Decarbonizing the Transport Sector

The key players in the U.S. transport sector in terms of CO_2 emissions are boats, trains, cars, and planes.[27] Trains are already mainly electric, and planes are most unlikely to be electric for a very long time, if ever. The same is true of boats: their range is such that battery power is impractical. So most of the action in decarbonizing this sector will concern cars (and light trucks), which in any case is where most of the CO_2 emissions originate. Light-duty vehicles (cars, sport utility vehicles, and pickup trucks) account for 59 percent of U.S. transport-related GHGs (cars, 33 percent; light trucks, 26 percent), while heavy-duty vehicles account for 22 percent (U.S. Department of Transportation n.d.). There is currently no drive toward widespread electrification of heavy-duty vehicles.

Battery Technology

In the last few years, electric vehicles have emerged as serious competitors in the U.S. automobile market. In particular, the success of the Tesla Model S has forced manufacturers and analysts to rethink the potential for battery electric vehicles (BEVs), and all major manufacturers have now announced that they will produce multiple BEV models. The commercial success of these vehicles depends crucially on the development of battery technology.

Until recently there were three major obstacles to progress with BEVs: inadequate driving range, excessive cost, and long charging times.[28] The first two obstacles are in the process of being overcome, with Tesla, General Motors, Nissan, and Porsche all offering cars with ranges of more than 200 miles per charge. And as prices have fallen from more than \$500/kWh to less than \$300/kWh, the cost issue has been at least partly addressed. If prices fall to less than \$200/kWh, as has been forecast (Nykvist and Nilsson 2015), then the cost issue will also be close to resolution. That leaves the issue of the long charging time, which is currently several hours using chargers at normal voltages. But Stor-Dot, an Israeli start-up that supplies phone batteries that can be charged in 1 minute, claims to have developed a car battery with a 300-mile range that can be fully charged in 5 minutes.[29] This suggests that all of the obstacles associated with battery performance may possibly be overcome within just a few years.

Prospects for BEVs

Given these recent developments in battery technology, what are the prospects for most cars and light trucks in the United States being BEVs by 2050? The U.S. vehicle fleet turns over roughly every 15 years; this means that there are two vehicle "generations" between now and 2050. In order to have an all-BEV car and light truck fleet by 2050, from 2035 on, 100 percent

[27]In the case of transport, we can refer to GHG emissions and CO_2 emissions interchangeably since 97 percent of the transport sector's GHG emissions are CO_2 (Kahn Ribeiro et al. 2013).

[28]The first two were related—reasonable driving range cost too much at the then-prevailing battery prices.

[29]See www.Stor-Dot.com and also http://fortune.com/2015/08/19/electric-car-battery-charges-minutes/.

of new vehicle sales would have to be BEVs. Could BEVs (or for that matter other EVs such as fuel cell EVs) possibly claim 100 percent of the new U.S. car market in 18 years? Clearly, any answer to this question is a guess. What are the "guesses" people in the field are making? Bloomberg New Energy Finance (BNEF) recently suggested that by 2040, BEVs would constitute 35 percent of global (not U.S.) new car sales.[30] In a more optimistic assessment, Goldman Sachs has suggested that BEVs will account for 22 percent of global sales by 2025. McKinsey, which is the most bullish on EVs of this group, suggests that by 2030, EVs will account for 50 percent of all light vehicles sold in the United States (Roelofson et al. n.d.).

Thus there is certainly a widespread expectation of rapidly increasing EV sales and a significant market share, but 100 percent by 2035 definitely seems to be a stretch given current trends. However, the prospect of EVs accounting for more than 50 percent of the fleet by 2050 does appear to be consistent with the experts' current projections. Cars and light trucks account for about two-thirds of all transport-related emissions (U.S. Environmental Protection Agency 2017a), so a 50 percent EV share would reduce transport emissions by about one-third, or about 9 percent of total GHG emissions.

Implications for Grid Capacity

Large numbers of BEVs will clearly require grid capacity for charging: could this be a problem? U.S. vehicles are driven about three trillion miles per year and a typical BEV uses about 30 kWh per 100 miles driven.[31] Thus, if all vehicles were BEVs, then they would consume on the order of 9×10^8 MWh/year. This is about 22 percent of the total megawatt hours generated in 2015, a significant enough number to require an increase in capacity. Sufficient extra capacity to produce 9×10^8 MWh/year would cost on the order of \$620 billion.[32] But this would replace the gasoline refining and distribution system, leading to significant cost savings.

Role of Biofuels

One possibility that I am not exploring here is the replacement of regular gasoline by biofuels. Currently, roughly 10 percent of U.S. gasoline is corn-derived ethanol, and in Brazil, sugar-based ethanol provides more than one-quarter of light vehicle fuel. Thus biofuels can provide an alternative to conventional gasoline. However, there is considerable debate about the extent to which the current generations of biofuels actually reduce GHG emissions (Bullis 2011), and second- and third-generation biofuels, which seem likely to be more climate friendly, are not yet widely commercialized. Thus the potential for biofuels to play a major role in decarbonization of the U.S. ground transport sector seems small.

[30]The forecast is at http://about.bnef.com/press-releases/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040/.

[31]Data from Edmunds.com, The True Cost of Powering an Electric Car, http://www.edmunds.com/fuel-economy/the-true-cost-of-powering-an-electric-car.html.

[32]It is not clear that extra capacity would be needed for this if recharging were carried out mainly at night, when there is already substantial spare generating capacity.

Comparisons of Estimates

There are few studies whose results can be compared with those I have presented here. Williams et al. (2014)[33] examine the cost and feasibility of attaining an 80 percent reduction in GHGs in the United States by 2050. However, their methodology is radically different from mine. More specifically, their study is based on a detailed engineering model of the energy system (PATHWAYS) coupled with an integrated assessment model (GCAM). They study four different scenarios for reaching an 80 percent emissions reduction, which are based on renewables, nuclear, carbon capture and storage, and a mix of these scenarios. The scenario I have presented here corresponds roughly to their renewables scenario. Although the methods are sharply different, the results of their study are very similar to those presented here. They conclude that decarbonization is feasible and, for their median estimate, will cost about 0.8 percent of gross domestic product (GDP), currently about $136 billion. My estimates are that the cost of decarbonization ranges from $35.6 billion to $135 billion, averaging slightly less than 1 percent of current GDP. Williams et al. (2014) also find that the nuclear route to decarbonization may be less expensive than the renewable route.

Another study of similar scope is MacDonald et al. (2016), which investigates the impacts of a national grid that allows for the integration of wind and solar power nationwide and combines this with detailed data on the geographic distribution of wind and solar power. They conclude that wind and solar power, together with a suitably integrated grid, could meet U.S. electricity demand at no increase in the cost of power. In particular, MacDonald et al. (2016) demonstrate that intermittent power sources can be managed at the grid level provided that the balancing areas are sufficiently large (the entire United States) and that the grid is capable of shifting power on a large scale between distant locations.

Conclusions About the Potential for U.S. Carbon Reductions

At the Paris COP 21, the United States indicated its aspiration to reduce its CO_2 emissions by 80 percent from 2005 levels by 2050. In 2014, U.S. emissions levels were already 9 percent below 2005 levels (U.S. Environmental Protection Agency n.d.), leaving an additional 71 percent reduction to achieve this target.

I have shown here that replacing fossil fuels with renewable energy sources would reduce emissions by 30 percent from current levels and that transforming 50 percent of the car and light truck fleet to BEVs would reduce emissions by another 9 percent, for a total reduction in CO_2 emissions of about 40 percent. With appropriate supportive policies, these two outcomes appear to be attainable by 2050. A complete replacement of internal combustion engines by electric motors in light vehicles would achieve a further reduction of 9 percent, for total emissions reductions of about 50 percent.

Industrial and residential uses currently account for 21 percent and 12 percent, respectively, of U.S. CO_2 emissions. If industrial and residential emissions could be cut in half by

[33]These are the results of the Deep Decarbonization Pathways Project, sponsored by two environmental groups (Institute for Sustainable Development and International Relations [IDDRI] and Sustainable Development Solutions Network) and conducted by Energy and Environmental Economics, Lawrence Berkeley National Laboratory, and Pacific Northwest National Laboratory.

Table 3 Reductions in emissions corresponding to various scenarios

Sector to decarbonize	Resulting decrease in emissions	Cumulative decrease in emissions
Electricity	30%	30%
50% of light vehicles	9%	39%
100% of light vehicles	18%	48%
50% of industrial and residential	16.5%	64.5%
100% of industrial and residential	33%	81%

Notes: Reductions are from 2014 levels; to compare with 2005, add 9 percent to the reduction.

switching from fossil fuels to electricity, then this could reduce emissions by an additional 16.5 percent. Of course, the complete elimination of industry and residential emissions would reduce emissions by another 16.5 percent. Implementing all of these measures—that is, decarbonizing electricity production, electrifying the car fleet, and eliminating industrial and residential emissions—would reduce emissions by about 81 percent below current levels, depending on the progress with vehicle electrification (see table 3 for a summary).

What conclusions can be drawn from these results about the achievability of the U.S. aspiration to reduce GHG emissions by 80 percent from 2005 levels by midcentury? Clearly, very significant reductions are entirely possible. Given that we are already 9 percent of the way there, it is easy to think of a 50 percent reduction. That would involve replacing most but not all fossil fuel power plants with renewables and electrifying 50 percent of the light vehicle fleet and 50 percent of residential and industrial uses of fossil fuels, largely for space and water heating (or some combination of moves like these). If the costs of renewable energy and energy storage continue to drop, and if suitable financial incentives are in place, then these are attainable goals, although they will require appropriate governmental policies—for example, a carbon tax and financial incentives for the energy storage industry, which is still in its emergent stage.

A reduction of 80 percent is clearly more of a challenge. It would likely require the same reductions in renewable energy and storage costs just mentioned, plus a more rapid conversion of the U.S. light vehicle fleet to BEVs than is currently forecast, and extensive progress in replacing the residential and commercial uses of fossil fuels. All of this would almost certainly require very strong financial incentives. However, with appropriate incentives, an 80 percent reduction appears to be feasible. More specifically, the total net costs of reducing emissions by 80 percent are manageable— in the range of $37.6 billion–$135 billion per year, which is less than 0.66 percent of current U.S. GDP. These numbers are not based on a cost-minimizing strategy and to a large extent they are driven by the cost of energy storage. It might be possible to reduce these costs through a decarbonization strategy that reduces the need for storage; for example, a strategy using more nuclear power than considered here or a strategy with more grid integration (MacDonald et al. 2016). The bottom line is that a major reduction in U.S. GHG emissions is certainly possible at reasonable cost by midcentury.

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