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WHAT WOULD IT TAKE TO REDUCE US GREENHOUSE GAS EMISSIONS 80% BY 2050?

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ABSTRACT

I investigate the cost and feasibility of reducing US GHG emissions by 80% from 2005 levels by 2050. The US has stated in its Paris COP 21 submission that this is its aspiration. I suggest that this goal can be reached at a cost in the range of $37 to $135 bn/year. I assume that the goal is to be reached by extensive use of solar PV and wind energy (66% of generating capacity), in which case the cost of energy storage plays a key role in the overall cost. I conclude tentatively that more limited use of renewables (less than 50%) together with increased use of nuclear power might be less costly.

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What would it take to reduce US greenhouse gas emissions 80% by 2050?

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Revised November 10 2016

Abstract

I investigate the cost and feasibility of reducing US GHG emissions by 80% from 2005 levels by 2050. The US has stated in its Paris COP 21 submission that this is its aspiration. I suggest that this goal can be reached at a cost in the range of $37 to $135 bn/year. I assume that the goal is to be reached by extensive use of solar PV and wind energy (66% of generating capacity), in which case the cost of energy storage plays a key role in the overall cost. I conclude tentatively that more limited use of renewables (less than 50%) together with increased use of nuclear power might be less costly.

Key words: greenhouse gas reductions, Paris agreement, renewable energy, energy storage, nuclear power.

Overview

In its submission to the Paris COP 21, the US expressed a desire to reduce its greenhouse gas emissions by 80% by mid-century. This was not a formal goal, rather an aspiration that is thought to be consistent with the goal of keeping global warming to less than 2°C. This makes it interesting to investigate the implications of attaining such a goal, which is what I seek to do in this paper. One way reducing emissions is to stop using fossil fuels. There is an alternative – continuing their use and capturing and storing the resulting carbon dioxide emissions. But currently moving away from carbon-based energy seems more likely of the two to be successful. In this paper I go some way towards exploring this alternative, and look into whether the US economy, one of the largest in the world and the second largest emitter of greenhouse gases, could possibly move largely away from carbon-based energy by 2050.

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[1] gmh1@gsb.columbia.edu. I am grateful to Frank Convery, George Crabtree and Sandy MacDonald for valuable comments on an earlier draft of this paper.

Let me be clear what I am not asking. I am not asking if the US 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 these. 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 am trying to do calculations that are correct to within orders of magnitude rather than being exact, probably the best one can do for events that are three decades in the future. I am also trying to do this in a way that is simple and transparent, so that anyone who is interested in the issues can reproduce the analysis with their own assumptions about costs and other key parameters.

To anticipate the outcome, my conclusion is that the US economy could reduce carbon emissions by 80% from 2005 levels within three decades, but that this requires improvements in energy storage technology, and also the investment of massive 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 $1.28tn or as high as $3.97tn depending on assumptions made about energy storage, which turns out to be crucial to the calculations.

Let me give some general background. The US has approximately one terawatt (1 tW = 10^{12} Watts) of electricity generating capacity, and this produces about four billion megawatt hours (4 bn mWh) of electric power each year. This is the US's largest source of greenhouse gases: 30% of greenhouse gases come from electricity generation, and 26% from transportation.[2] Coal produces 39% of electric power and also 77% of CO_2 from electricity production: 27% of electricity comes from gas,

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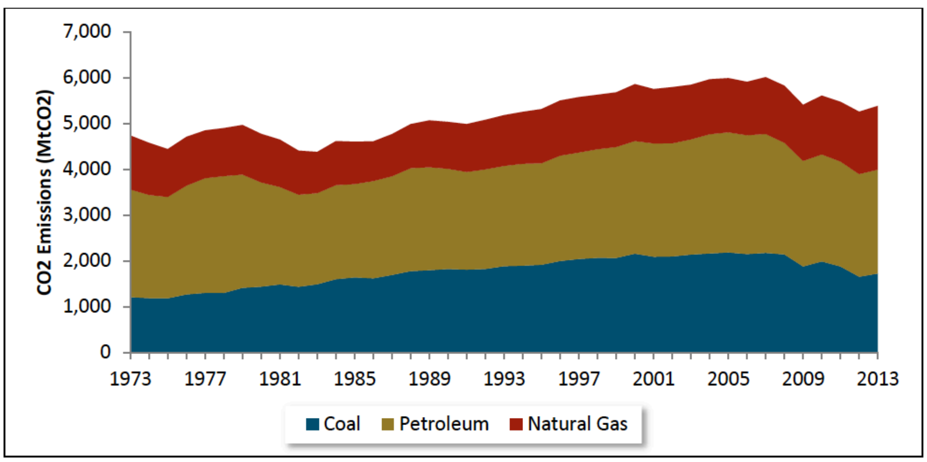
[2] These numbers cover all greenhouse gas emissions: for CO2 alone, electricity production accounts for 37% and transportation for 31% - see *US Environmental Protection Agency 4.*

producing 22% of CO_2 from power generation. So in effect coal and gas used to generate electricity produce 30% of the US's CO_2 emissions (see figures 1 and 2). Of the 26% of CO_2 coming from transportation, almost all is generated by the combustion of oil in internal combustion engines. Remaining CO_2 emissions come from the residential, commercial and industrial uses of fossil fuels for space heating and process heating.

Decarbonizing electricity production is the key step in 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. So we begin with an analysis of what it would take to decarbonize electricity production.



Source: EIA , March, 2014 Monthly Energy Review

Figure 1: sources of US CO2 emissions by fuel (after Williams et al. 2014)

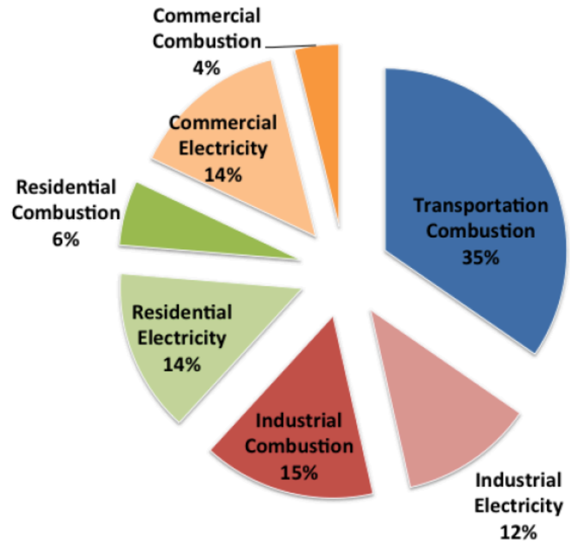


Figure 2: sources of US CO2 emissions by sector (after Williams et al. 2014)

There are other sources of CO2 emissions such as cement manufacturing and agriculture, but they are small enough that I will neglect them: cement making contributes about 1.5% to total emissions and agriculture about 9%. About 11% of gross emissions are offset by carbon absorption by land use change and forestry (Hanle et al., US Environmental Protection Agency 3), so that even if these two sources continued the US could be carbon neutral overall.

Decarbonizing electricity production

As I said above, we have 1 tW of generation capacity and use this to produce about 4 bn mWh per year. The breakdown of electricity generation capacity and of actual power output by power plant type was as shown in table 1 (US Energy Information Agency 1):

Power source	Percent of capacity	Percent of output
Coal	31.3	33
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

Table 1: nameplate capacity and power output by fuel type. Capacity from 2011, output from 2015. Does not include residential solar.

The fact that gas capacity is so much greater than gas output reflects that the fact that many gas plants are peakers and have a very low capacity factor, generally in the teens. Nuclear has the opposite characteristic, reflecting its high capacity factor. The petroleum generating capacity is rarely used and reflects legacy plants maintained largely in case there is a gas shortage, so for the calculations that follow I will neglect petroleum capacity.

To replace coal and gas by non-fossil fuels we would need to replace 72% if we use capacity figures or 66% if we use output figures. I will work with output figures on the grounds that these reflect how the different energy types are actually used. I therefore assume that we need to build new non-fossil capacity capable of generating 66% of current total output. I shall assume that this new capacity is divided 50/50 between wind and solar photovoltaic, so from each we need 33% of current output of 4 bn mWh/year. There are 8760 hours in a year, so this means that we need $0.33 \times 4 \times 10^{12}/8760 = 0.1506 \times 10^{9}$ kW of capacity from each fuel type. I shall assume that both wind and solar 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. According to the EIA these were respectively 32.5% and 28.6% on average for 2015 (US Energy Information Agency 2). Hence we need to construct 463.38×10^{6} kW of wind and 526.57×10^{6} kW of PV capacity. Note that these numbers may be too large: capacity factors for both wind and solar PV have risen sharply over the last decade and may continue to do so. The current averages used here reflect many legacy systems whose technologies are now obsolete. The capacity factors for wind farms built in 2105 averaged 38%.

I assume that wind farms cost $1700/kW, consistent with estimates from both Lawrence Berkeley Laboratories and the US Department of Energy (US Department of Energy, Lawrence Berkeley Laboratory). So 463.38x10^6 kW of capacity will cost $0.788 tn. The cost of solar utility-scale installations I take to be $1.91 per watt: this is the figure given by NREL as the mean for Q1 2015 single axis installations (they cite $1.77/watt for fixed installations, see Chung et al.). Hence the cost of 526.57x10^6 kW of solar PV capacity will be $1.005 tn., for a total of $1.793 tn. So 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: as prices have been falling fast for over a decade in both areas, current prices probably overstate the costs. In fact anecdotal evidence suggests that prices are already significantly lower than the NREL Q1 2015 figure: 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 tn. In addition to these costs of generating capacity, we have to consider the costs of additional transmission lines and of energy storage capacity to deal with the fact that two thirds of electric power would be generated by intermittent power sources. We turn to these next, transmission costs first as they are the simpler of the two.

Transmission costs

High voltage transmission lines cost anything from $1m/mile to $3m/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 US grid currently has over 200,000 miles of high voltage lines (Lott, 2015), and extensive use of wind and solar power, whose costs are lowest in specific areas of the country, might require the addition of another 25% of current transmission capacity. This means 50,000 miles and at an average of $2m/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 $500m each. So it is probably reasonable to think of grid extension costs as in the region of $110-120 billion – huge but small by comparison with the cost of the new renewable generation capacity.

Energy Storage

If we replace all fossil generation capacity by wind and solar PV, we will need to deal with the intermittency of its output. Clearly solar PV produces no power at night, and even during the day its output can drop because of cloud cover. (Solar thermal power stations, also known as concentrating solar power or CSP, can produce power at night but have higher capital costs: I return to this below.) Wind blows more at night than in 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 any shortfall arising from a sudden drop in wind or solar power is typically met from gas combustion turbines in the US: in Germany and Denmark, where renewable penetration is greater, it is typically met by importing hydro power from Norway, which can generate in excess of its domestic needs. If the U.S. wants to adopt wind and solar on a large scale and avoid GHG emissions, then the obvious route to follow is to invest in energy storage capacity, although there are alternatives, explored briefly in the next section.

Currently most grid-scale energy storage in the US takes the form of pumped hydro power 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 hydro power when there is a power shortage. Such plants are economically attractive, but require a hill with a flat top not currently used for anything and a river at the bottom of the hill, a rare combination of circumstances. Most suitable sites have already been used.[3] Compressed air energy storage is also an option: air is stored at pressure in an underground cavern when there is surplus power and released to drive a turbine

[3] A list of pumped hydro plants in the US can be found here: http://www.industcards.com/ps-usa.htm

when extra power is needed. Again this technology is very dependent on the availability of suitable geological features. Going forward, additional storage capacity is most likely to be provided by batteries: indeed some grid-scale batteries are already in operation with California utilities.

Battery storage capacities are typically measured in megawatt hours (mWh) when used in the grid, or kilowatt hours in cars. (A Tesla model S battery has a capacity of 70-90 kWh depending on the options chosen.) 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, measured in megawatts. Making an analogy with water storage, mWh measure the capacity of a tank and mW measure the size of the exit pipe and so the rate at which water can come out of the tank. When considering storage as a way of backing up intermittent renewable energy, it is generally the total capacity in mWh that matters.

Battery storage has historically been expensive, in the region of $400-$500 per kWh. To get a sense of what this means consider a wind turbine with capacity of 2mW, a typical turbine. Assume it has a capacity factor of 32.5%, the figure we used earlier: then on average it produces 24x0.65mWh daily, 15.6mWh/day. At a capacity cost of $1,700/kW it will cost $3.4m. At $500/kWh a battery large enough to store one average day's output will cost $7.8m, more than twice the cost of the turbine. I will discuss how large a battery might be appropriate later. We can do a similar calculation for solar PV: using the figures cited earlier for costs and capacity factors, we can see that a 10 mW solar installation would cost $19.1m, produce on average 24x2.86 mWh daily, and that at $500/kWh a battery to store this would cost $34.3m, 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 - $500. Storage costs, like so much else associated with renewable energy, have been falling rapidly. Elon Musk promised when Tesla's gigafactory was announced that it will produce batteries at $350/kWh, and there are companies promising to manufacture utility-scale redox[4] flow batteries for as little as $150/kWh. For an MBA class I recently profiled 15 companies that are claiming to be bringing new and more efficient storage technologies to the market, so this technology is in a state of flux and it is hard to produce a good estimate of what storage will cost over the next few decades. At the promised price of redox flow batteries, $150/kWh, the costs to store a day 's output from a 2mW wind turbine or a 10mW solar farm are respectively $2.3m and $10.3m, less than the costs of the power plant but still very significant additions to the capital costs. In fact it seems that Tesla and other electric vehicle manufacturers are already getting their batteries at less than the $350 that Musk forecast: recent contracts suggest under $300/kWh for electric vehicle battery packs, with forecasts of $200/kWh or less by 2018-2020 (Nykvist and Nilsson 2015).

How much energy storage capacity would the US actually need in a world where two thirds of its electric power comes from intermittent renewables? One heuristic approach to this problem is as follows. The US consumes 4 bn mWh each year, of which in our scenario two thirds would be from renewable energy. This means that on an average day it 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% certain that we can always meet demand? Unfortunately we don't have this probability distribution, and indeed the problem is far more complex that this summary suggests. Different regions of the US suffer wind or solar outages at different times, so we would need the joint distribution of output for each energy source in each region (ISO or perhaps Interconnect), the covariances between these, and the grid interconnections between these regions in order to work out how much storage is needed. Suppose hypothetically 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 one day of renewable energy production would cost $1.095 trillion. At Elon Musk's forecast $350/kWh it costs $2.555 trillion. And of course in this case two days of storage would cost $5.110 trillion. We don't know

[4] Reduction-oxidation

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 number do make clear that the costs of storage will be very large and could possibly dominate the capital costs of replacing fossil fuels by renewables. This makes it particularly important to understand how much storage capacity we will actually need. It does seem reasonable that we might need enough stored energy to cover several days of very low solar and wind outputs, so I assume below that we need enough storage to hold two average days of renewable energy production.[5] There is no very solid scientific basis for this number, but it seems consistent with the results emerging from the limited literature on storage.

A study of the role of variable renewable energy in the Texas grid looked at the consequences of 80% of Texas' energy coming from solar PV and wind, and concluded on the basis of detailed modeling of the entire grid that storage that could meet 24 hours of demand was the ideal from the perspective of grid management (Denholm and Hand). Another study of the integration of wind and solar into the western grid concluded that without any storage it would be possible to accommodate 35% variable renewable energy at very low cost and without storage (GE Energy). This study emphasized the importance of enlarging balancing areas and of demand side management in the context of managing intermittent energy sources. Balancing areas are the areas over which demand and supply are equated: the bigger such an area, the larger the probability that it will contain intermittent energy sources whose outputs are not closely correlated. Large areas reduce the risk of energy supply failures by diversification. 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. Another interesting study of the western grid (Makarov et al) concludes that the intermittency of 88 gW of wind capacity can be fully offset by 68 gWh of storage capacity. Assuming again the capacity factor for wind of 32.5%, this wind capacity

[5] The California Public Utilities Commission recently passed a mandate that requires utility investments in 1.3 GW of energy storage by 2020

will produce on average 686 kWh/day, so that the recommended storage is 10% of average daily wind energy production. At a less scholarly level, the following headlines are of interest in the context of the need for storage: "Portugal runs for four straight days on renewable energy alone,"[6] "Windpower generates 140% of Denmark's electricity demand,"[7] "Germany reached nearly 100% renewable power on Sunday."[8] None of these countries have significant amounts of storage capacity.

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. The hot liquid does not all have to be used when it is heated: some of it can be stored underground in heavily insulated storage spaces and used at some future time to generate electric power. This is clearly a big plus from the perspective of grid management: the downside is that these power stations have higher capital costs than solar PV – about $9000-$10,000/kW according to International Renewable Energy Association for plants with the capacity to store power for up to fifteen hours. But if they reduce the need for separate storage capacity, they may still make economic sense. A 2012 report (International Renewable Energy Agency 2012) gives details of the capital costs of CSP plants with and without heat storage capabilities, and from this it is possible to back out the capital cost of storage, at least for 2012. It is very close to what was then the cost of battery storage – in the region of $500/kWh. There does not seem to be a widespread expectation that these costs will fall, so that the better route seems to be to use solar PV and a separate storage technology, the cost of both of which are likely to fall.

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[6] The Guardian, May 18th 2016, https://www.theguardian.com/environment/2016/may/18/portugal-runs-for-four-days-straight-on-renewable-energy-alone

[7] The Guardian, 10th July 2015, https://www.theguardian.com/environment/2015/jul/10/denmark-wind-windfarm-power-exceed-electricity-demand

[8] Energy Transition: the German Energiewende, http://energytransition.de/2016/05/germany-nearly-reached-100-percent-renewable-power-on-sunday/

Alternatives to Storage

Storage is clearly expensive. An alternative might be to build more non-renewable, non-fossil capacity and reduce the dependence on intermittent power sources. Suitable power sources are hydro, geothermal and nuclear. Hydro and geothermal are situation-specific: their use can probably be extended but there are geological limits to what they can offer and it seems unlikely that they can provide significantly more power in the U.S. That leaves nuclear: is nuclear power more or less expensive than renewable power with storage? The answer unfortunately depends on how much storage we need. The EIA gives the overnight capital cost of a nuclear reactor as $5530/kW, and the capacity factor as 92% (US Energy Information Agency 2). The EIA does not give capital costs including financing costs, but industry sources give these as about $8500 in 2008. (They are probably higher today.) Adjusting by the capacity factor gives a capital cost of $9239 per effective kW for nuclear as opposed to $6678 for solar PV. If we were to assume as above that we need two days of storage to complement a renewables-intensive system, we have to more than double this capital cost to allow for the cost of storage, making nuclear less expensive than solar. Note however that this calculation does not take account of end-of-life costs associated with decommissioning the reactors, which are generally of the order of $0.5-1.0bn per reactor (OECD 2016). The conclusion here is that nuclear power is certainly an alternative to solar or wind with storage, and could be significantly less expensive if storage capacity of the order of one or more days of output is required. As the studies referred to above demonstrate, storage needs increase with the penetration of intermittent energy sources, and can be quite low or even zero for penetration levels up to 30-50% but increase quickly after that. So there might be a case for replacing fossil fuels by intermittent renewable energy up to about 50% of total generating capacity and then filling the remaining gap with nuclear power. This discussion emphasizes the importance of understanding better how much storage capacity is needed in connection with intermittent energy.

Another approach is to use spatial diversification of wind and solar sites to even out the total energy generated by these sources. If the correlations between the outputs of these power sources are sufficiently small, or even negative, then the variability of total power output is smaller than that of any one site or region of the country (Heal, 2016). It is then possible that there is always renewable power available somewhere in the grid, and by building enough capacity and a sufficiently interconnected grid it may be possible to ensure sufficient power everywhere all the time without storage. Chang et al explore the tradeoff 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 an HVDC grid integrates the entire country and sufficient renewable capacity is built at various crucial nodes of the system. Heal (2016) applies statistical decision theory, asking how much renewable capacity we would have to build, together with a fully integrated grid, to be 95% certain of meeting an exogenously given level of demand. It is probably too early to come to a conclusion from this line of argument, but it seems possible that building extra generating capacity in the right places and connecting all sources and sinks through a high-capacity low-loss grid could be an alternative to extensive use of storage to smooth the output of renewable sources. However storage has additional benefits: it can be used to meet peak demands and so to cut back on the use of uneconomical "peaker" plants that operate few hours per year just to meet summer peak demands (20% of U.S. generating capacity operates less than 100 hours/yr).

Cost Offsets

There is an important respect in which these numbers overstate the cost, and this is that 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. There are no fuel costs and only minimal operating costs to these power stations, so each power station provides a stream of electricity at zero marginal cost over its lifetime. There is therefore a saving of fuel costs relative to continuing with fossil fuels. We can estimate this saving. One kWh requires the combustion of on average 0.00052 short tons of coal or 0.01011 mcf of natural gas. Taking the price of coal to be $40/short ton and gas to be $2.75/mmBTU[9] and assuming that a 50/50 mix of coal and gas would have produced the power to be produced by renewable energy, the zero marginal costs of renewables would save fuel costs to the value of $64.153 bn per year once renewables have fully replaced fossil energy sources. Assuming that renewables replace fossil sources linearly over thirty years the average saving will be a half of this, and over thirty years that is a total of $0.9625 tn. So fuel savings offset about $1 tn of the costs of going low carbon.

Another figure to be offset against the costs calculated above is the cost of replacing fossil fuel plants that come to the ends of their lives over the next three decades, a category that certainly includes most coal plants in the U.S. Most coal plants in the U.S. were built before 1975 and are already at least 41 years old, against an expected life of 40-50 years. Most of the rest were built before 1990, making them at least 26 years old and again due for retirement within the period we are considering. In addition over 20% of all gas generators were over 10 years old as of 2010, making them candidates for replacement by the end of the period we are considering (U.S. Energy Information Agency 4). So the costs of these replacements, which would have to be carried out anyway, should be netted from the overall capital costs calculated above. The capital costs of coal and gas plants are given by the EIA as $3000/kW and $1000/kW respectively (U.S. Energy Information Agency 3), implying that the cost of replacing plants that will reach the limits of their useful lives is $0.99 tn for coal and $0.066 tn for gas, for a total of $1.06 tn in round numbers.

The Overall Cost of Carbon-Free Electricity

I have now reviewed the capacity costs, transmission costs and storage costs of making the U.S.'s power grid carbon free. I am going to assume that when the grid is low carbon we will need the capacity to store two average days of renewable power generation: this figure has no rigorous scientific basis but seems to pass a "laugh test." Adding these up we get the following (Table 2):

[9] All data from the U.S. Energy Information Agency web site.

Category	Best Case	Worst Case
Capacity	$1 tn[10]	$1.79 tn[11]
Transmission	$0.1 tn	$0.2 tn
Storage	$2.2 tn[12]	$4 tn[13]
Total	$3.3 tn	$5.99 tn
Fuel savings offset	$0.96 tn	$0.96 tn
Plant replacement offset	$1.06 tn	$1.06 tn
Net total	$1.28 tn	$3.97 tn

Table 2: Costs of emissions reductions in connection with electricity generation, transmission and storage.

Whichever case we focus on, these are large numbers. We are considering replacing fossil fuels over three decades, implying that (allowing for the fuel and capital cost offsets) annual expenditures would be in the range $37.6 bn to $135 bn. In 2015 U.S. capital expenditure on new electric generating capacity (wind, solar, gas, coal and nuclear) was about $42 bn: this does not include expenditures on upgrading transmission or on energy storage. So in the best case we are on track: in the worst, we are scaling up the U.S.'s level of expenditure on new generating capacity by a factor of about three.

There are several striking points to note about these numbers. One is the sensitivity of the cost to the cost and quantity of storage needed. While we have some sense of where storage costs are going, there is little analysis of how much 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 two average days, but this is no more than a thoughtful guess. Doubling this to four days would add $2tn and $4tn to the

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[10] This is a 25% reduction below costs of $1500/kW for wind and $1.25/w for solar and 38% wind capacity factor

[11] Assuming capacity factors of 32.5% and 28.6% and costs of $1700/kW and $1.91/w for wind and solar respectively

[12] Assuming two days renewable output stored at $150/kWh

[13] Assuming two days renewable output stored at $280/kWh

best and worst cases respectively. The amounts of storage capacity we are talking about here are huge – 4.8×10^6mWh/day, so that two days is almost 10^7mWh. (A large pumped hydro storage plant has a capacity of several thousand mWh.) Some commentators have suggested that we would need even more – one week's power in reserve in storage, but this number seems to have no more scientific basis than mine.[14] Note that the worst case for storage is premised on a cost of $280/kWh, which seems to reflect current or emerging costs (Nykvist and Nilsson 2016). It seems very likely that these costs will fall: the costs of lithium ion batteries were $3000/kWh as recently as 1995 (Crabtree 2016).

Another striking feature of these results is the extent of the offsets from fuel savings and plant replacement. Net of these, the best-case costs 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 independently of the need to transition to carbon-free energy. Instead of replacing fossil plants by similar equipment we are replacing them by renewable plants, which in many locations have lower levelized costs of electricity, and so we are actually saving money in the process. To get some sense of how competitive renewable energy sources are relative to fossil fuels, note that Lazard's most recent comparison of levelized costs (Lazard) give 3.2 and 4.3 cents/kWh as the respective best-case costs of power from wind and solar PV, compared to 5.2 and 6.5 cents/kWh for natural gas combined cycle and advanced super-pulverized coal.

Decarbonizing the Transport Sector

The key players here are boats, trains, cars and planes. Trains are already mainly electric, and planes are most unlikely to be electric for a very longtime, if ever. The same is true of boats: their range is such that battery power is impractical. There are however moves to supplement marine internal combustion engines with wind power. So most of the action will be in cars (and light trucks), which is anyway

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14 See Tom Murphy's analysis in *A Nation-Sized Battery* at http://physics.ucsd.edu/do-the-math/2011/08/nation-sized-battery/

where most of the emissions originate. Light duty vehicles (cars and SUVs and pickup trucks) account for 63% of U.S. transport-related greenhouse gas emissions (cars 34% and light trucks 28%): heavy-duty vehicles account for 21% (U.S. Department of Transportation), and currently there is no drive for electrification in this area. We can talk of greenhouse gas emissions and carbon dioxide emissions interchangeably in the case of transport as 97% of transport's GHG emissions are CO2 (IPCC).

In the last few years electric vehicles have emerged as serious competitors in the automobile market: the success of the Tesla Model S has forced manufacturers and analysts to rethink the potential for battery electric vehicles (BEVs), and now all major manufacturers have announced multiple BEVs. The commercial success of these depends crucially on the development of battery technology. Until recently there were three major obstacles to the progress with BEVs: inadequate driving range, excessive cost (these two were related – reasonable driving rage cost too much at the battery prices then ruling), and long charging times. The first two obstacles are en route to being overcome, with Tesla, General Motors, Nissan and Porsche all offering cars with a range of over 200 miles per charge. And as prices have fallen from over $500/kWh to under $300, the cost issue has been partly addressed. If prices fall to less than $200/kWh, as several sources forecast (Nykvist and Nilsson 2016), then the cost issue will be close to resolution too. That leaves charge time, which is currently many hours using chargers at normal voltages. But Stor-Dot, and Israeli start-up that supplies phone batteries that can be charged in one minute, is claiming to have a car battery with a 300-mile range that can be charged fully in five minutes.[15] This suggests that all the obstacles associated with battery performance may be overcome within a few years.

Given this, what are the prospects that by 2050 most cars and light trucks will be BEVs? The vehicle fleet turns over roughly every 15 years, which means that there are two "vehicle generations" between now and then. To have the car and light truck

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

fleet be all BEVs by 2050 would mean that from 2035 on, 100% of new vehicle sales are BEVs. So could BEVs (or for that matter other EVs such as fuel cell EVs) possibly claim 100% of the new car market in eighteen years? Obviously any answer to this question is a guess. Given this, what are the guesses people in the field are making? Bloomberg New Energy Finance (BNEF) recently guessed that by 2040 BEVs would constitute 35% of global (not US) new car sales.[16] Goldman Sachs, in a more optimistic assessment, suggests that BEVs will account for 22% of global sales by 2025. McKinseys, the most bullish of this group on EVs, suggest that by 2030 EVs will be 50% of all light vehicles sold in the US (Roelofson et al). So there is certainly an expectation of rapidly increasing sales and a significant market share, but 100% by 2035 seems a stretch on current trends. However over 50% of the vehicle fleet by 2050 does seem to be consistent with experts' current expectations. Cars and light trucks account for about two thirds of all transport-related emissions (US Environmental Protection Agency 1), so this would reduce transport emissions by about one third or about 9% of total emissions.

Large numbers of BEVs will clearly require grid capacity for charging: could this be a problem? US vehicles drive about three trillion miles per year. A typical BEV uses about thirty kWh per 100 miles driven,[17] so that if all vehicles were BEVs then they would consume somewhere of the order of $9x10^8$ mWh/yr. This is about 22% of the total number of mWh generated in 2015, a significant enough number to require an increase in capacity. Sufficient extra capacity to produce $9x10^8$ mWh per year would cost of the order of $620 billion.[18] This would replace the gasoline refining and distribution system.

A possibility that I am not exploring here is the replacement of regular gasoline by biofuels: currently roughly 10% of US gasoline is corn-derived ethanol, and in Brazil sugar-based ethanol provides over one quarter of light vehicle fuel, so biofuels can

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

[17] 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

[18] 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 space generating capacity.

provide an alternative to conventional gasoline at scale. However there is considerable debate about the extent to which the current generations of biofuels actually reduce greenhouse gas emissions, and second and third generation biofuels, which seem likely to be more climate-friendly, are not yet widely commercialized.

Comparisons

There are few other studies with which the results of this paper can be compared. One interesting comparator is Williams et al 2014,[19] which studies the cost and feasibility of attaining the 80% reduction target by 2050. Their methodology is radically different: 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% emissions reduction: these are based on renewables, nuclear, carbon capture and storage and a mix of all of these. The scenario considered here corresponds roughly to their renewables scenario. Although the methods differ sharply, the conclusions of their study are very similar to those reached here. Decarbonization is feasible, and will cost in their median estimates about 0.8% of GDP, currently about $136 bn. My estimates are from $35.6 to $135 bn, on average slightly less than 1% of current GDP. They 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 consequences of a national grid that allows the integration of wind and solar power nationwide, and combines this with detailed data on the geographical distribution of wind and solar power. Their conclusion is that wind and solar power together with a suitably integrated grid could meet U.S. electricity demand at no increase in the levelized cost of power. Their study demonstrates that intermittent power sources can be managed at the grid level provided that the balancing areas are sufficiently large (the entire U.S.) and that the grid is capable of moving power on a large scale between distant areas.

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[19] The results of the Deep Decarbonization Pathways Project sponsored by two environmental groups and conducted by Energy and Environmental Economics, Lawrence Berkeley National Laboratory and Pacific Northwest National Laboratory.

Conclusions on the Potential for US Carbon Reductions

The U.S. aspires to reduce its CO_2 emissions by 80% from 2005 levels by 2050.[20] 2014 levels were already 9% below 2005 levels US (Environmental Protection Agency 2), leaving a further 71% reduction needed to achieve this goal. This is not a commitment, but 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. Replacing fossil by renewable energy sources would reduce emissions by 30% from current levels, and transforming 50% of the car and light truck fleet to BEVs would reduce them by another 9%, for a total of about 40%. With appropriately supportive policies these two outcomes seem attainable by 2050. Complete replacement of internal combustion engines by electric motors in light vehicles gains another 9% for a total of about 50%.

The US's current emissions are 30% from power generation, 26% from transportation, 21% from industry and 12% from residential uses (the balance being agriculture and land use change). If industrial and residential emissions could be halved on the basis of switching from fossil fuels to electricity, then this could save a further 16.5%. Their complete elimination would of course remove another 16.5%, and implementing all these measures would lead to a drop of about 81% below current levels, depending on the progress with vehicle electrification. Tables 3 and 4 summarize.

Decarbonize	Resulting drop in emissions					
Electricity	30%	30%				
50% Light Vehicles	9%		39%			

[20] See the US'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

100% Light Vehicles	18%			48%		
50% Industrial & Residential	16.5%				64.5	
100% Industrial & Residential	33%					81%

Table 3: reductions in emissions corresponding to various combinations. The single numbers in columns (30%, …., 81%) show total reduction if all steps in that row and rows above are taken. Note that we include either 50% or 100% for light vehicles and Industrial and Residential but not both. Reductions are from 2014 levels: add 9% to compare with 2005.

Decarbonize	Resulting drop in emissions		
Electricity	30%	X	X
50% Light Vehicles	9%	X	
100% Light Vehicles	18%		X
50% Industrial & Residential	16.5%	X	X
100% Industrial & Residential	33%		
		55.5%	64.5%

Table 4: Last row of columns 3 and 4 show total emissions reductions corresponding to the combinations of measures indicated by an X in that column. Reductions are from 2014 levels: add 9% to compare with 2005.

What conclusions does this suggest about the realism of the US's aspiration to reduce emissions by 80% from 2005 levels by mid century? Clearly very significant reductions are entirely possible. Given that we are already 9% of the way there, it is easy to think of a 50% reduction. That would involve replacing most but not all fossil fuel power plants by renewables, electrifying half the light vehicle fleet, and half 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, though 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% is clearly more of a challenge – it would probably require the same drops in renewable energy and storage costs as mentioned, plus a more rapid conversion of the 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 need very strong financial incentives, but with appropriate incentives seems feasible. The total net costs of reducing emissions by 80% are manageable: in the range $37.6-$135bn/year, less than 0.66% of current GDP. These numbers are not based on a cost-minimizing strategy and are driven to a large degree by the cost of energy storage. It might be possible to reduce them by a decarbonization strategy that reduces the need for storage, for example one using more nuclear power than the strategy explored here, or one with more grid integration (MacDonald et al 2016).[21]

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[21] Williams et al 2014 also finds that the nuclear route to decarbonization is less expensive than the renewables route.

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