The Cost of a Carbon-Free Electricity System in the U.S.

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Abstract

I calculate the cost of replacing all power stations in the U.S. using coal and gas by wind and solar power stations by 2050, leaving electric power generation in the U.S. carbon free. Allowing for the savings in the cost of fossil fuel arising from the replacement of fossil fuel plants this is roughly $55 billion annually. Allowing in addition for the fact that most fossil plants in the U.S. are already old and would have to be replaced before 2050 even if we were not to go fossil free, this annual cost is reduced to $23 billion.

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1 Introduction

In 2017 I published a paper estimating the investment required to make all electric power generation in the US carbon-free by 2050 (Heal 2017). I gave a wide range of estimates, the best case being $1.28 trillion and the worst being $3.97 trillion. In the short time since that paper was published, costs have fallen faster than I anticipated, both for renewable energy sources such as wind and solar photovoltaic, and also for energy storage devices such as lithium ion batteries. I am therefore redoing my earlier calculations with the best current cost estimates. Over the three decades between now and mid century, costs will of course change again, so that the numbers here are still only suggestive estimates. With one exception, I am taking U.S. Energy Information Agency current costs, as of mid 2019, and projecting these forward. As costs have tended to fall rather than rise, I expect that this will produced an overestimate of the cost of a carbon-free power system, but any estimate of the size of the error is guesswork.

My conclusion is that the likely net investment required to go carbon-free is now as little as $0.74 trillion. I no longer think it is useful to give a worst case scenario, as the drop in costs and increases in efficiency over the last decade now seems obviously irreversible, and it is clear that prices will only move one way. This figure of $0.74 trillion includes offsets from fuel savings as we no longer need to buy coal or gas, and also includes capital cost offsets reflecting the fact that most coal plants in the US have to be replaced well before 2050 as they are already near the ends of their useful lives. The cost of replacing them should therefore not be charged to the conversion to non-carbon energy sources. Each of these offsets is of the order of one trillion dollars, so they have big impacts on the final numbers. Although the cost of replacing old coal plants should not be regarded as a cost of conversion to carbon-free energy sources, it is nevertheless a real cost that has to be paid, and if we include it in the total then the cost increases from $0.74 trillion to $1.75 trillion. But the bulk of this is replacing very old power plants that are unsafe and obsolete, and need to be replaced whether we convert to clean energy or not. My earlier estimates also included both of these offsets, so the cost including both offsets has fallen from $1.28 trillion to $0.74 trillion. This low number reflects the fact that renewable power from wind and solar PV plants is now less expensive than power from gas, coal or nuclear plants, as documented for example by Lazards' studies of the levelized cost of electricity from alternative sources (Lazard 2018). If it were not for the intermittency of renewables, we would save money by converting to clean power. As it is, we need to invest in storage to manage the intermittency and this leaves us with a small net cost to converting the power sector to non-carbon energy sources.

2 Methodology

The method that I use for these calculations is the same as in the earlier paper, and is entirely straightforward. I calculate the amount of wind and solar PV nameplate capacity that would be needed to produce all the mWh of electricity currently produced by coal and gas plants,[1] and then calculate the cost of this capacity. I then make an estimate of the amount of storage capacity needed to deal with the intermittency of the renewable sources. Together with an allowance for improving the grid, this gives the total gross cost of the transition to to renewables. Against this I set the offsets mentioned in section 1: the savings in fossil fuel costs that result from replacing coal and gas by wind and solar, and also the allowance for the fact that all coal-fired power stations and

[1] Coal and gas produce 66% of total annual mWh, and total annual mWh are about 4 billion.

many gas-fired ones would anyway have to be replaced before 2050, so that the cost of replacing them is not properly attributable to the energy transition. I assume that the savings in fossil fuel costs grow linearly from now to 2050, and that fossil fuel plants are replaced at a constant rate.

The most debatable assumption in this process is the assumption about how much storage would be needed to cope with the intermittency of the renewable capacity that we install during the transition. Unfortunately there is no firm formula for calculating the storage needed to manage the integration of renewables into the grid. The number depends on the extent to which demand can be managed by appropriate incentive programs, the number of dispatchable power plants, and the covariances between the outputs of the renewable energy plants in use: clearly large negative covariances will reduce the need for storage. I assume that we need sufficient storage capacity to hold the output that all renewable plants produce over a period of two days. There are studies that suggest that this is an appropriate amount, and indeed is perhaps too large. For a review of the issues this raises and references to the literature see (Heal 2016). A recent paper by Shaner et al (2018) studies the possibility of meeting US power demand purely from renewable energy from an engineering perspective and looks at the trade-off between storage and "overbuilding," i.e. constructing more renewable capacity than is strictly needed to meet demand, so as to take advantage of spatial diversification. They assume **all** demand is met from renewable energy or storage, whereas here I am merely replacing output from existing fossil fuel plants by renewables, keeping in place existing hydro, geothermal and nuclear capacities. So about 66% of the annual output of mega-watt hours is coming from renewables and storage. Shaner et al cite several earlier engineering studies of the possibility of meeting US demand purely from renewables: these generally conclude that by choosing locations to exploit low or negative covariances is it easily possible to meet 80% of demand from renewables without storage, and that meeting the last 20% purely from renewables is very expensive, with the last 2% being especially so.[2] I am avoiding this problem by assuming existing non-fossil supplies to remain in place.

The other assumption that I am making is that there is no seasonality to patterns of demand and supply: I can just work with annual totals. This is a simplification, and from some preliminary calculations seems to be one that does no great violence to the total costs involved.

The key facts and assumptions that underlie the calculations that follow are the following:

1. The U.S. produces about 4 billion mWh of electric power each year
2. 66% of this comes from coal and gas
3. I assume that we replace the 66% of 4 bn mWh from coal and gas by wind and solar in equal amounts
4. I assume that we need enough storage capacity to hold two days of the output of renewable energy
5. I assume that we need to increase the milage of high voltage grid lines by 25%
6. Total electricity production remains constant from now to 2050.

3 Data

The following table lists all the key parameters used in the calculations, and their values.

[2] Note that to use low or negative covariances of output at renewable power stations to reduce storage needs, it is necessary to construct extra capacity, known as "overbuilding."

Parameter	**Value**
Cost of wind capacity	\$1,600/kW
Wind capacity factor	0.42
Cost of solar PV capacity	\$1.9/W
Solar PV capacity factor	0.26
Cost of storage	\$75/kWh
Cost of high voltage lines	\$2,000,000/mile
Miles of HV lines needed	50,000
Cost of coal capacity	\$3,000/kW
Cost of coal	\$50/ton
Cost of gas capacity	\$1,000/kW
Cost of gas	\$3/mmbtu

With the exception of the cost of storage, all of these represent current values as given by the Energy Information Agency or an equivalent source.[3] It is reasonable to expect equipment costs to fall and capacity factors to rise over the next three decades, so that these figures are probably overestimates of the costs we will encounter. [4] The one case where I have not taken current costs is the cost of storage, which today is in the region of \$175/kWh, but is widely expected to be at or below \$100/kWh by the end of 2020, and to continue falling after that. So looking forward as far as 2050, a cost of \$75/kWh does not seem unreasonably optimistic. The declines in the cost of storage are likely to be more significant than those in the costs of wind and solar power, and so seem to merit anticipation.

[3] The figure for the cost of solar capacity is the EIA figure: industry sources that I talk with suggest that it is out-of-date and far too high. Many sources cite actual costs of close to \$1/W.

[4] https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf and https://www.energy.gov/eere/wind/downloads/2017-wind-technologies-market-report, presentation, slide 38,

4 Results

All calculations are available in an Excel spreadsheet on my web site.[5] The following table shows the various elements of the calculations:

Category	**Cost $ trillions**
Capacity costs	$1.68
Storage costs	$1.08
Grid costs	$0.1
Fuel savings	-$1.12
Capacity replacement offsets	-$1.01
Total fuel offsets only	**$1.75**
Total all offsets	**$0.74**
Annual rate all offsets	$0.023
Annual rate fuel offsets only	$0.055

These figures show that the annual incremental cost of transitioning to fossil-fuel-free electricity generation system, if the total investment is spread over the period from 2019 to 2050, is $23 billion. This is about half of what the US currently invests in the energy sector. This incremental cost estimate does not include the cost of replacing fossil fuel power plants that come to the ends of their lives, as these would have to be replaced, and these costs incurred, even if there were no transition to carbon-free electricity. Hence the costs of these replacements are not properly attributable to decarbonization. However these costs do have to be incurred, as the power plants will need to be replaced, and if we included these costs the total annual investment rises to $55 billion. This difference emphasizes the fact that many fossil fuel plants will need replacement in the period from now to 2050. The total of $55 billion a year is roughly equal

[5] https://geoffreyheal.com/publications/publications-on-climate-change/

to current energy infrastructure investment levels. But it must be emphasized that the increase from $23 billion to $55 billion has nothing to do with the cost of the transition to clean energy: it reflects the fact that we have a lot of very old power stations that badly need to be replaced. It is important to distinguish the cost of failing to keep our infrastructure up-to-date from the costs of the energy transition.[6]

Some of the cost figures I have used are almost surely too high. For example, I took the cost of utility-scale solar PV from the EIA as $1.9/W, whereas in the industry a figure of $1/W is widely assumed.[7]

The Solar Energy Industry Association's annual review for 2018 gives the average cost of utility-scale solar PV tracking installations as just over $1/W. Using this figure reduces the total costs to $0.22 trillion and $1.23 trillion for the cases including and excluding the capital cost offsets, with corresponding annual costs of $2.2 billion and $102 billion.

References

[1] Geoffrey Heal. Notes of the economics of energy storage. Working Paper 22752, NBER, https://www.nber.org/papers/w22752, October 2016.

[2] Geoffrey Heal. What would it take to reduce us greenhouse gas emissions 80 *Review of Environmental Economics and Policy*, 11(2):319–335, July 2017.

[6] A similar issue arises with the U.S.'s nuclear power stations, which provide about 20% of the megawatt hours generated annually in the U.S. All but two or three will also be well beyond their usable lives by 2050, and will have to be replaced. I am implicitly assuming here that they are replaced by non-fossil, non-renewable power (nuclear, hydro, geothermal, etc.), as replacing them by renewables would probably increase the need for storage and or grid enhancements.

[7] See for example https://news.energysage.com/solar-farms-start-one/ and https://www.seia.org/research-resources/solar-market-insight-report-2018-year-review figure 2.4.

[3] Shaner M.R. Davis S. J. Lewis N. S. Caldeira K. Geophysical constraints on the reliability of solar and wind power in the united states. *Energy and Environmenal Science*, 11(914), 2018.

[4] Lazards. Levelized cost of electricity v 12, November 2018.