The US Power Sector in a Net Zero World

Analyzing pathways for deep carbon reductions

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[ABSTRACT]

The power sector is the single biggest source of carbon emissions in the United States, responsible for approximately 30 percent of total greenhouse gas emissions. Cutting these emissions is therefore critical to reaching net zero emissions by the middle of the century, in line with global climate goals. Our research analyzes pathways to cut US power sector carbon dioxide emissions by 90 percent or more by 2050, under different technology cost and performance assumptions, and finds that significantly ramping up renewable energy is critical to meeting these goals cost-effectively. We also show that the power sector can contribute to economy-wide reductions through increased electrification of many energy end-uses, including in the transportation, residential, commercial and industrial sectors. The insights from our analysis are broadly instructive for U.S. and global efforts to reduce global warming emissions.

[INTRODUCTION]

The 2015 Paris Agreement has focused world-wide attention on the urgent need to cut global heat-trapping emissions to limit some of the worst impacts of climate change. Countries have committed to the aim of "*holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*." To achieve this temperature goal, the long term goal, as articulated in the agreement, is to "*achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century*" (UNFCCC 2015).

Developed countries like the United States have a special leadership role and responsibility in helping to realize this goal, which argues for their reaching net zero global warming emissions earlier, by mid-century. Reaching net zero global warming emissions in the US will require action to drive down all energy-related emissions, as well as safeguard and enhance the land sink. Our focus in this paper is the role of the US power sector in reducing emissions—both as a result of decarbonizing the electric system and through the electrification of many end uses of energy in other sectors.

Numerous studies show that deep, economy-wide, emission reductions in the energy sector are feasible with robust policies to reduce emissions, accelerate the shift to zero and low carbon technologies, and encourage clean energy innovation (IEA 2015; Mai et al. 2014; Williams et al. 2015). The power sector can play a pivotal early role because of the numerous cost-effective options available today to reduce emissions in this sector, such as increasing energy efficiency and switching to low carbon resources like renewable energy and nuclear power (EPRI 2016; Kreigler et al. 2014; Williams et al. 2014). In the decades ahead, other options could also become more widely available at a lower cost, including energy storage and fossil-fired generation with carbon capture and storage. The power sector can also contribute to reducing emissions in other sectors through electrification of transportation, heating and other commercial and industrial energy uses (Dennis, Colburn and Lazar 2016; Williams et al. 2014), provided there is closer coordination of policies and actions across sectors. This in turn will contribute to growing demand for power, most of which must also come from carbon-free sources. Closer coordination between the power sector and other sectors will be needed to achieve these outcomes.

The US power sector is the single biggest source of US heat-trapping emissions, responsible for approximately 30 percent of total greenhouse gas (GHG) emissions. In 2015, US electricity-related carbon dioxide emissions were 1,919 million metric tons, a level that was 21 percent below 2005 levels (EIA 2016a). The reduction in emissions over the past decade was driven in large part by a shift away from coal toward cheaper, lower carbon electricity generation resources like natural gas and renewable energy, along with increased energy efficiency. While this is an encouraging trend, the reality is that much deeper cuts in emissions are needed. An overreliance on natural gas also poses significant challenges because it is still a fossil fuel whose use results in both carbon dioxide and methane emissions.

In this paper, we model the impact of a carbon price in the power sector that drives this sector's carbon dioxide emissions down to 90 percent below 2005 levels by 2050. Although we model a carbon price, this is not meant to be a policy prescriptive analysis; rather the carbon price sends a market signal that favors low carbon technologies and serves as a proxy for an effective pathway to make deep cuts in emissions. We also take account of increased electricity demand due to electrification in other sectors, although we do not explicitly model policies or technology pathways in those other sectors. Because of the long time horizon for this analysis, there is some uncertainty in the evolution of technology costs and performance. To account for this uncertainty, we analyze four different policy scenarios, with different cost assumptions for key technologies including wind, solar and nuclear power, and carbon capture and storage (CCS) technologies.

Our Approach

Our analysis focuses on carbon emissions from the power sector under different policy scenarios. We used the National Renewable Energy Laboratory's Regional Energy Deployment System (ReEDs) model with some revisions to technology and policy assumptions.[1] ReEDS is a electricity generating capacity expansion model that solves for a cost-optimal mix of generating technologies (see Technical Appendix for more information about ReEDS and our approach).

Our Reference case assumes only current policies that were on the books as of the end of 2015. It builds off the EIA's Annual Energy Outlook 2015, but also includes the Environmental Protection Agency's Clean Power Plan and the 2015 federal tax credit extensions for renewable energy from the Consolidated Appropriations Act of 2015 (Bailie et al. 2016a).[2] We have also updated natural gas prices to match the EIA's Annual Energy Outlook 2016.

TABLE 1. **Modeled Scenarios**

Scenarios	Details
Reference Case	Current policies as of December 31, 2015 only
Mid-Cost Case, a middle of the road cost scenario for all technologies	Mid-range technology costs are based primarily on EIA and NREL assumptions, with some limited changes based on project specific data and estimates from recent studies, with a carbon tax*
Optimistic Nuclear Case, an optimistic cost and lifetime scenario for nuclear power	Nuclear capital costs are the same as assumptions in EIA's AEO2015 reference case through 2040, and continue to follow the trend of cost decreases through 2050. Lifetimes of existing nuclear plants are extended from 60 years to 80 years for half of the U.S. nuclear capacity that exists in 2032. This case also has a carbon tax*
Optimistic Carbon Capture and Storage (CCS) Case, an optimistic cost scenario for CCS technologies	CCS costs are the same assumptions as in EIA's AEO2015 reference case through 2034 then decrease more rapidly to reach $40/metric ton of CO_2 captured**, similar to US Department of Energy (DOE) goals for the Carbon Capture program, with a carbon tax*
Optimistic Wind and Solar Case, an optimistic scenario for solar and wind costs	Wind capital costs and capacity factors are from the DOE's Wind Vision high cost reduction case. Solar photovoltaic costs are from the NREL 2016 Annual Technology Baseline low solar cost scenario with a carbon tax*

*The four policy scenarios include a carbon tax of $25/ton CO_2 starting in 2020 and rising at 7 percent per year thereafter to reach $190/ton in 2050.

**The cost of captured CO_2 per ton is a common metric used to describe the onsite costs of capturing CO_2, assuming a 90 percent capture rate. This includes compression but does not include transportation and storage. For retrofits, this would be the cost relative to an existing plant without capture. For more information see DOE 2013 and IEA 2013.

In addition to the Reference case, we ran four policy cases that achieved carbon reductions of 90 percent or more below 2005 levels by 2050. In all the policy cases we use a carbon price on power sector carbon dioxide emissions to drive down those emissions. The carbon price is set at \$25/ton CO_2[3] starting in 2020 and then rising at 7 percent per year thereafter through 2050 to reach \$190/ton in 2050, policy design details chosen to help drive down emissions in line with mid-century deep decarbonization goals.[4,5]

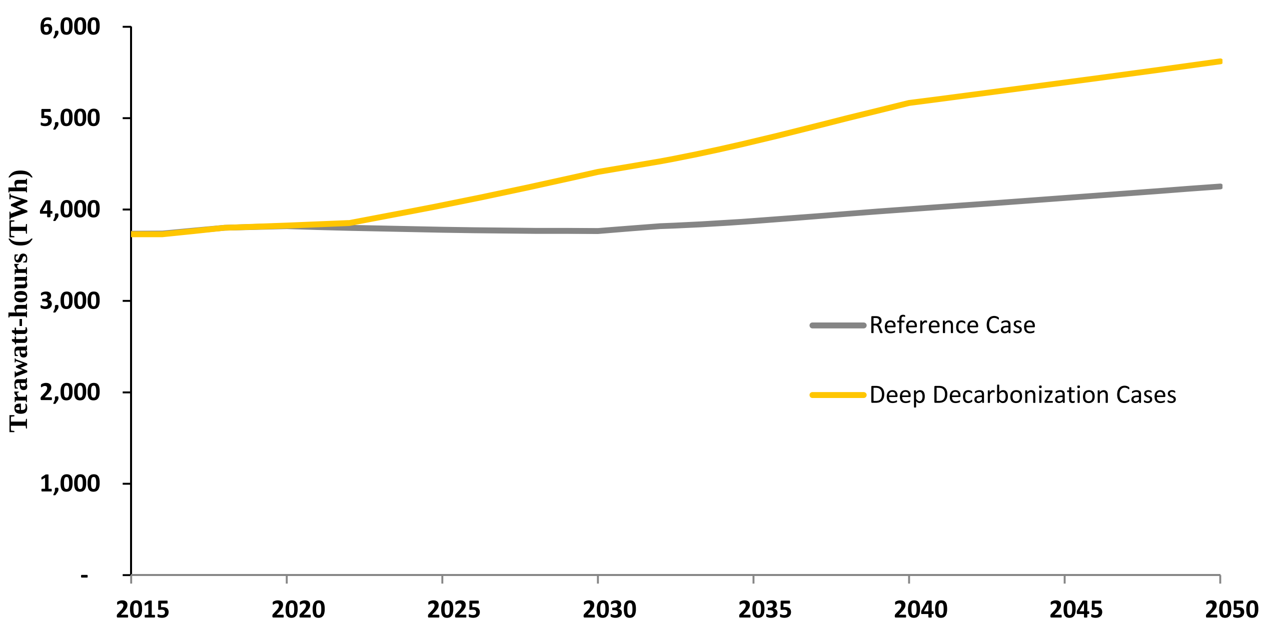
Our four policy cases include: a middle of the road cost scenario for all technologies (Mid-cost case), an optimistic cost and lifetime extension scenario for nuclear power (Optimistic Nuclear case), an optimistic cost scenario for carbon capture and storage (CCS) technologies (Optimistic CCS case), and an optimistic cost scenario for solar and wind costs (Optimistic wind and solar case). Together, these scenarios provide a range of potential pathways and options for cutting power sector emissions.

The Mid-cost case relies primarily on EIA and NREL assumptions, with some limited changes based on project-specific data and estimates from recent studies (Bailie et al. 2016a; Bailie et al. 2016b). The Optimistic Nuclear case and Optimistic CCS case both draw on assumptions for cost declines in these technologies outlined in a recent NREL report (Cole et al. 2016). Table 2 summarizes our modeling scenarios.

The ReEDS model does not endogenously model electricity sales or efficiency; instead, to account for efficiency, we input assumptions of future electricity demand net of efficiency savings. In our reference case we assume full compliance with state energy efficiency standards that had been established as of end of October 2015 and additional investments in energy efficiency at a level that achieves a reduction in electricity sales of at least 1 percent per year from 2022 to 2030.[6] States with stronger mandatory efficiency policies are assumed to continue meeting their respective targets. We do not vary these efficiency assumptions in our policy cases, although we recognize that there is significant potential to increase efficiency further.

We also assumed that power demand would need to be ramped up to meet the needs of electric vehicles and to take advantage of fuel switching opportunities in the residential, industrial and commercial sectors—all of which helps drive down economy wide emissions. Because ReEDS

FIGURE 1. **Electricity Sales, Differences Due to Additional Electrification and Energy Efficiency in the Deep Decarbonization Cases**



Under the reference case, electricity sales increase between 2020 and 2050. In the deep decarbonization policy cases, end-use electrification combined with energy efficiency contributes to an increase in electricity sales of 17 percent above the reference case in 2030 and 32 percent above the reference case in 2050.

is a power sector-only model, we modeled this cross-sectoral impact by including an estimate for a net increase in electricity demand through 2050. This net electricity demand also takes into account reductions in electricity use due to the adoption of more energy efficient technologies and measures in homes and businesses. We have accounted for emission reductions in the power sector as well as any emission reductions due to electrification in other sectors that drives down fossil fuel use. We did not explicitly model the other sectors, including any technology changes, policy drivers that would be needed to bring about those changes, or the costs of bringing about those changes. We have also not estimated the net cost savings from reduced fossil fuel use in those sectors.

Our estimates for increased net demand are based on the E3 US Deep Decarbonization Pathway analysis, matching their "Delivered electricity (final energy)" values (Williams et al. 2014). By 2050, our assumption is that there will be an approximately 20 percent increase in net power demand (increased electrification net of lowered demand due to energy efficiency) in our policy cases relative to the Reference case. This will require an even more aggressive effort to ramp up renewable energy and other zero carbon technologies to meet the emissions reduction target. We should note that other studies have found net decreases in electricity sales (EPRI 2016; Jacobson 2015); however, we have chosen to go with a more conservative estimate.[7] More details of the net change in power demand that we assumed in our policy cases, relative to the Reference case, is provided in Table 1 and Figure 1.

The ReEDS model only provides information on carbon dioxide emissions from the power sector. Nevertheless, we recognize the importance of also tracking the associated methane emissions arising from the power sector generation mix, including the upstream methane emissions from natural gas operations. We have therefore included an offline calculation of methane emissions from natural gas use in the power sector based on estimates in the literature.

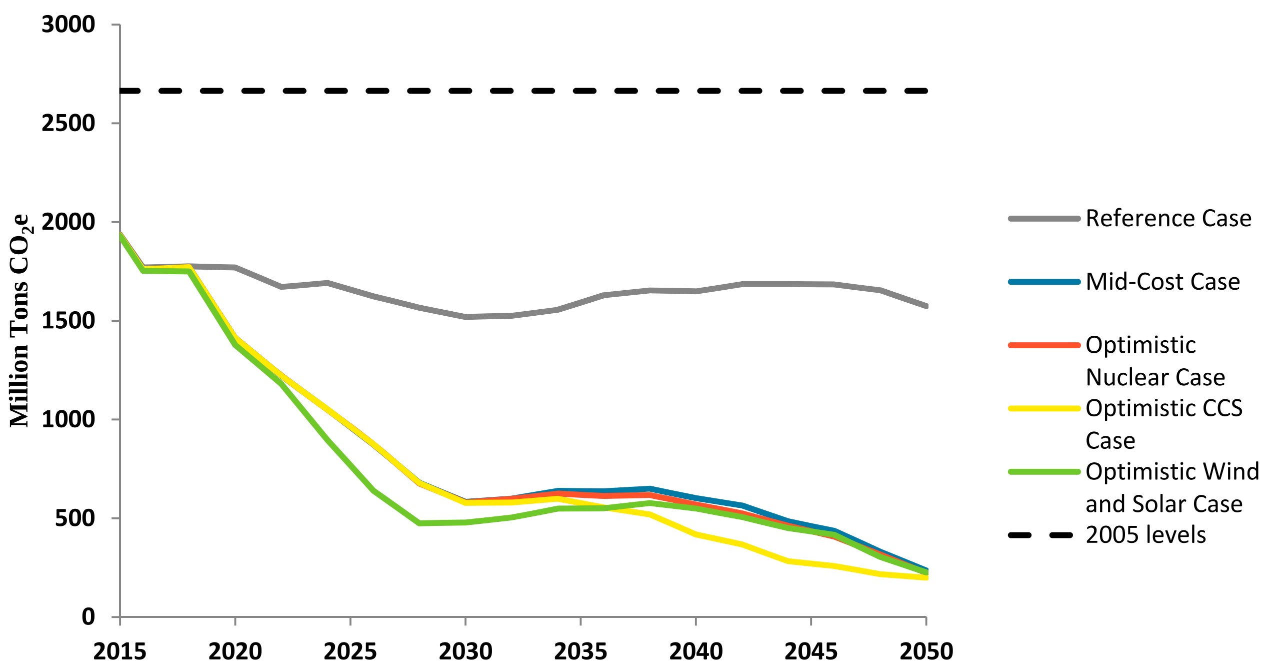
For the upstream emissions, in our Reference case we assume a nationwide average methane emissions leakage rate of 1.5 to 2 percent, based on the current literature, and apply that to the total power sector consumption of natural gas (Littlefield et al. 2016; Alvarez et al. 2012).[8] For the policy cases, we assume that technologies and policies will help drive the upstream leakage rates down to 0.8 to 1 percent by 2050. We have not modeled specific policies but note that the Obama Administration has committed to reducing methane emissions from oil and gas operations by 40 to 45 percent below 2012 levels by 2025 as part of its overall climate action plan and has begun to undertake rulemakings and other actions to help achieve that goal (White House 2015).

In addition, we assumed that baseload natural gas power has emissions of 0.0075 kg CH_4/MWh (7,500 g/GWh), i.e. an emission rate of 0.006 percent at the power plant.[9] We present values in carbon dioxide equivalents (CO_2e), using global warming potential (GWP) values for methane of 86 for a 20 year timeframe and 34 for a100 year timeframe from the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2014). All of these nationally-aggregated assumptions are based on the current literature (Littlefield et al. 2016; Alvarez et al. 2012). There continues to be considerable uncertainty in the overall measurement of methane emissions from the US oil and gas sector, as well as significant variation from site to site as well as based on geography, how a specific plant is getting its gas and on how a plant is run (base load or intermittent peaking). These estimates can be refined as new science and research comes in.[10]

Results

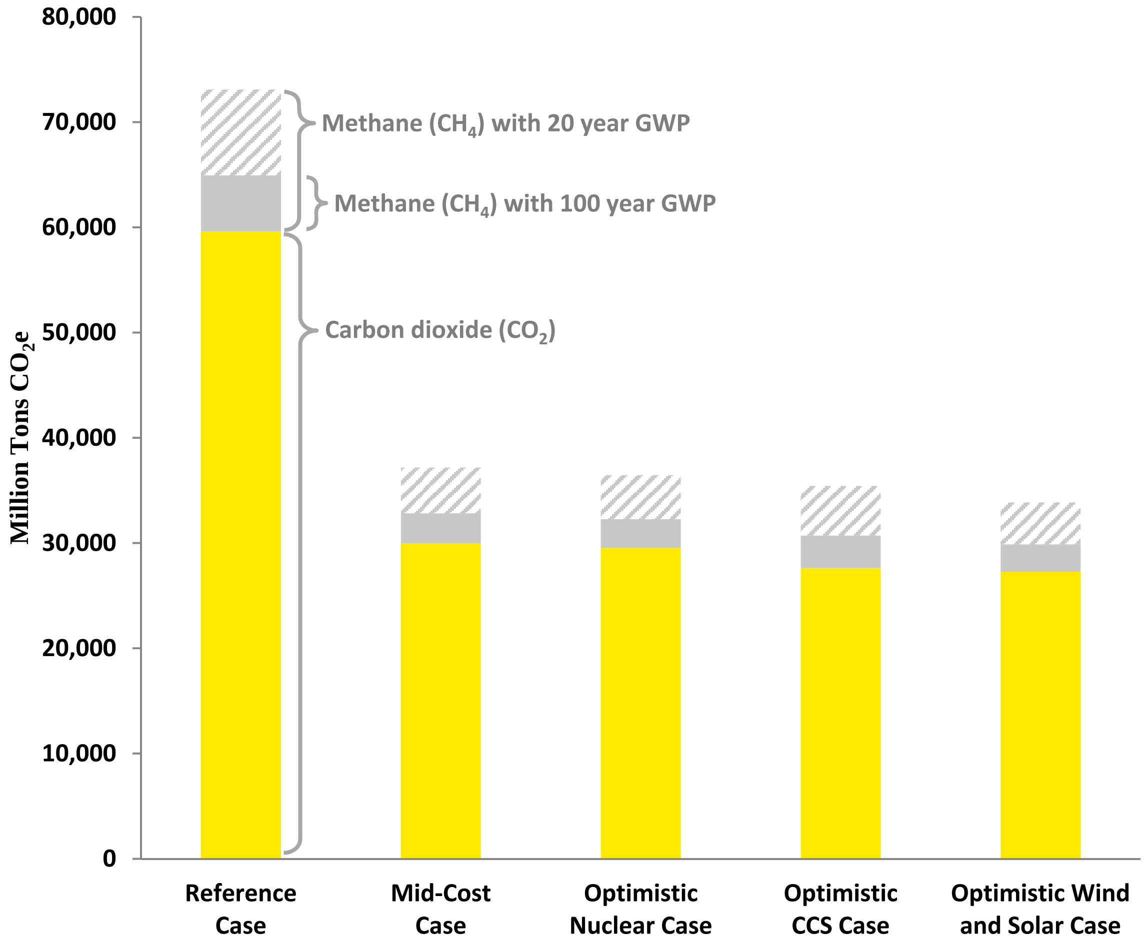
Our results show that deep emission reductions by 2050 are feasible in the power sector under a range of technology cost assumptions, although it will require ambitious actions to ramp up a portfolio of zero carbon technologies and a dramatic transformation of our energy system including investments in the grid. Under the Reference case, economy wide emissions of carbon dioxide decline slightly between 2015 and 2050, going from 5,610 to 5,592 million tons CO_2e, and power sector emissions go from 1,937 million tons CO_2e in 2015 to 1,574 million tons CO_2e in 2050.[11] In contrast, our policy cases show power sector carbon dioxide emissions declining by 90 percent below 2005 levels by 2050 (see Figure 2). In the Mid-cost case power sector emissions decline to 583 million tons CO_2e in 2030 and 236 million tons CO_2e in 2050.Transportation, residential, commercial and industrial emissions decline by 46 percent solely due to switching from fossil fuels to electricity for different end-uses.[12]

FIGURE 2. **Power Sector Carbon Dioxide Emissions**



While the reference case shows power sector carbon dioxide (CO_2) emissions declining only slightly through 2050, all the policy cases show a steep decline in CO_2 emissions, reaching reductions on the order of 90 percent below 2005 levels by 2050. These reductions, which are driven by a carbon price, occur even as net demand for power grows due to a significant economy-wide electrification of energy end uses.

FIGURE 3. **Cumulative Carbon Dioxide and Methane Emissions from the Power Sector, 2015-2050**



All the policy cases show deep carbon dioxide emission reductions, as well as reductions in methane emissions, relative to the reference case. These reductions come from decarbonizing the power sector, electrifying energy end uses in other sectors, and reducing methane leakage from natural gas operations. Methane emissions are shown assuming a 20 year global warming potential (GWP) and a 100 year GWP, based on estimates from the Intergovernmental Panel on Climate Change (IPCC 2014).

Our estimates of power sector-related methane emissions (including upstream methane emissions from natural gas) show those emissions rising. In 2015 methane emissions are estimated to be 111 to 179 million tons, assuming a leakage rate of 1.5 to 2 percent and a GWP of 20 years, or 334 to 538 million tons assuming the same range of leakage rates and a GWP of 100 years. Our mid-cost case shows power sector emissions declining by 56 percent. Assuming a 20 year GWP for methane, overall power sector GHG emissions decline from 111 million tons to 49 million tons by 2050 (see figure 3).

Power Sector Changes in Deep Decarbonization Policy Cases

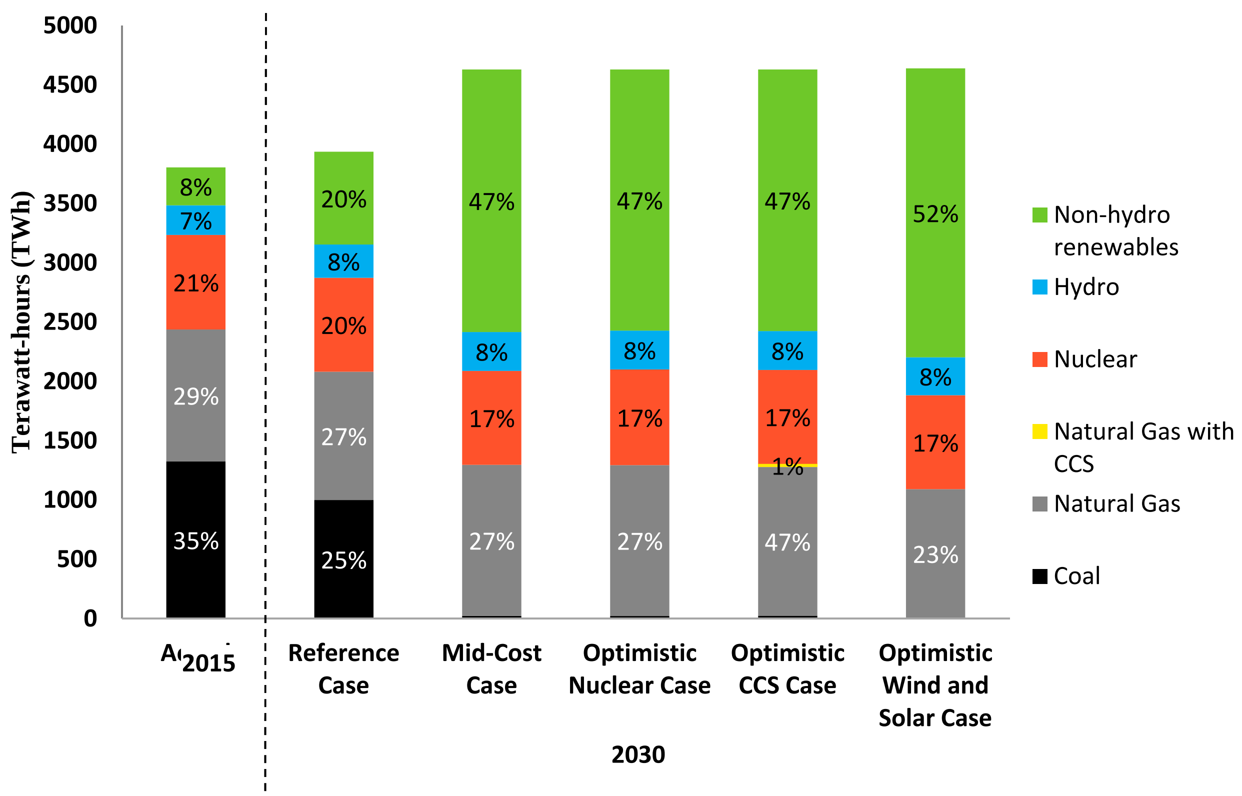
Our analysis shows that achieving deep emission reductions will require a significant, unprecedented level of change in the power sector. The US power generation mix changes considerably between now and 2050 in all our policy cases, shifting toward low and zero carbon resources, even as electricity generation increases by 51 percent above current (2015) levels.

Conventional fossil-fired generation must be tightly curtailed. By 2030, conventional coal-fired power is nearly phased-out, down from approximately a third of total power generation in 2015. While conventional natural gas is still about a third of the generation mix in 2030 in most of our cases, it declines to 7 percent or lower by 2050. Instead, we see a ramp up of natural gas with CCS (9 percent to 28 percent by 2050 across our policy cases).

Meanwhile renewable energy resources are dramatically ramped up. Renewable energy (hydro plus non-hydro) plays a strong role in all our cases, increasing from 15 percent in 2015 to about 55 to 60 percent of the generation mix by 2030, and 68 to 81 percent by 2050.

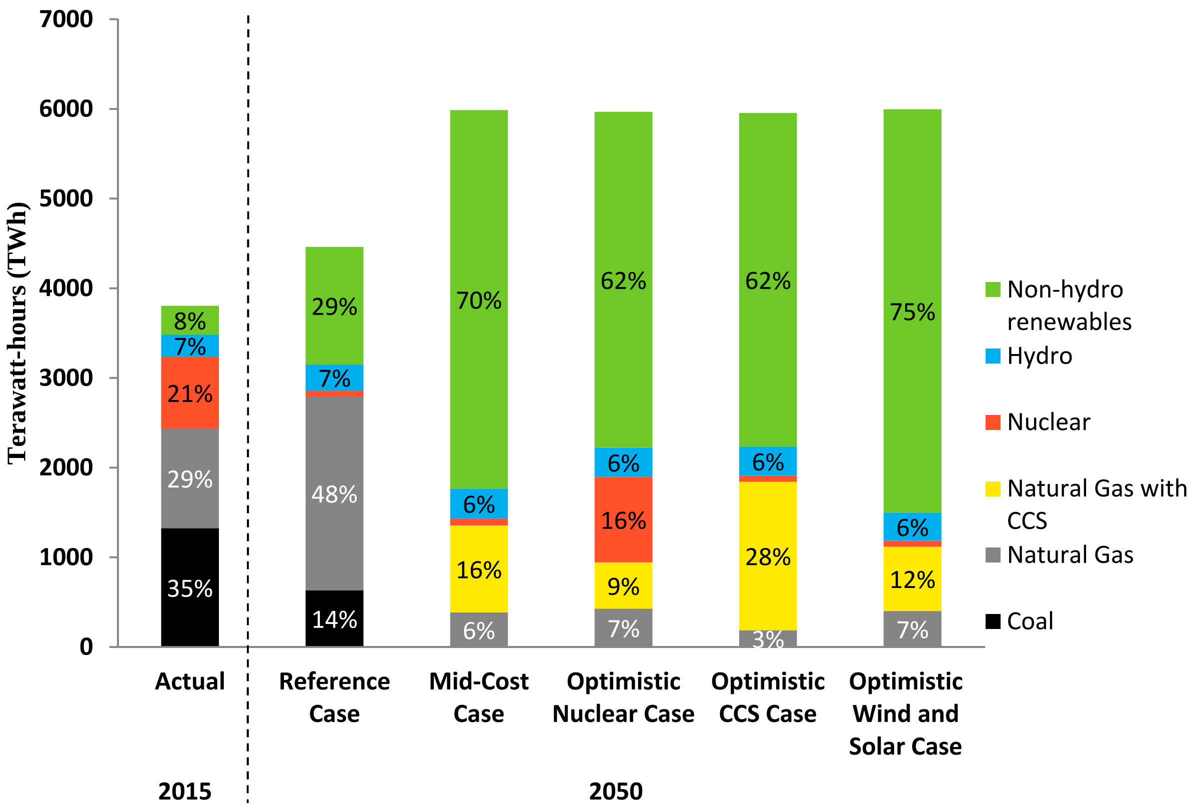
Nuclear generation stays relatively flat through 2030, as the generation from a small number of existing plant retirements are offset with five new reactors that are under construction or recently completed. However, as the demand for electricity increases, nuclear power's share of total generation goes down from 20 percent to 17 percent in 2030[13] and further down to 1 percent by 2050 in most of the cases. This is primarily driven by our assumptions that existing nuclear plants will retire after 60 years and the fact that, in most of the policy cases, new nuclear plants are not able to compete on a cost basis with other resources. The exception is our optimistic nuclear case where nuclear power generation increases 20 percent between 2015 and 2050, accounting for 16 percent of total generation in 2050. In this case, nuclear power replaces some of the natural gas with CCS and non-hydro renewables that are added in the other policy cases. New nuclear plants are responsible for approximately three quarters of the generation increase relative to the mid-cost case while extended lifetimes of existing plants account for the remainder.

FIGURE 4. **US Power Generation Mix in 2030**



By 2030, the US power sector undergoes a significant shift away from conventional fossil-fired power, with low and zero carbon resources providing approximately three-fourths of electricity generation in all our policy cases and coal-fired power almost completely phased out.

FIGURE 5. **US Power Generation Mix in 2050**



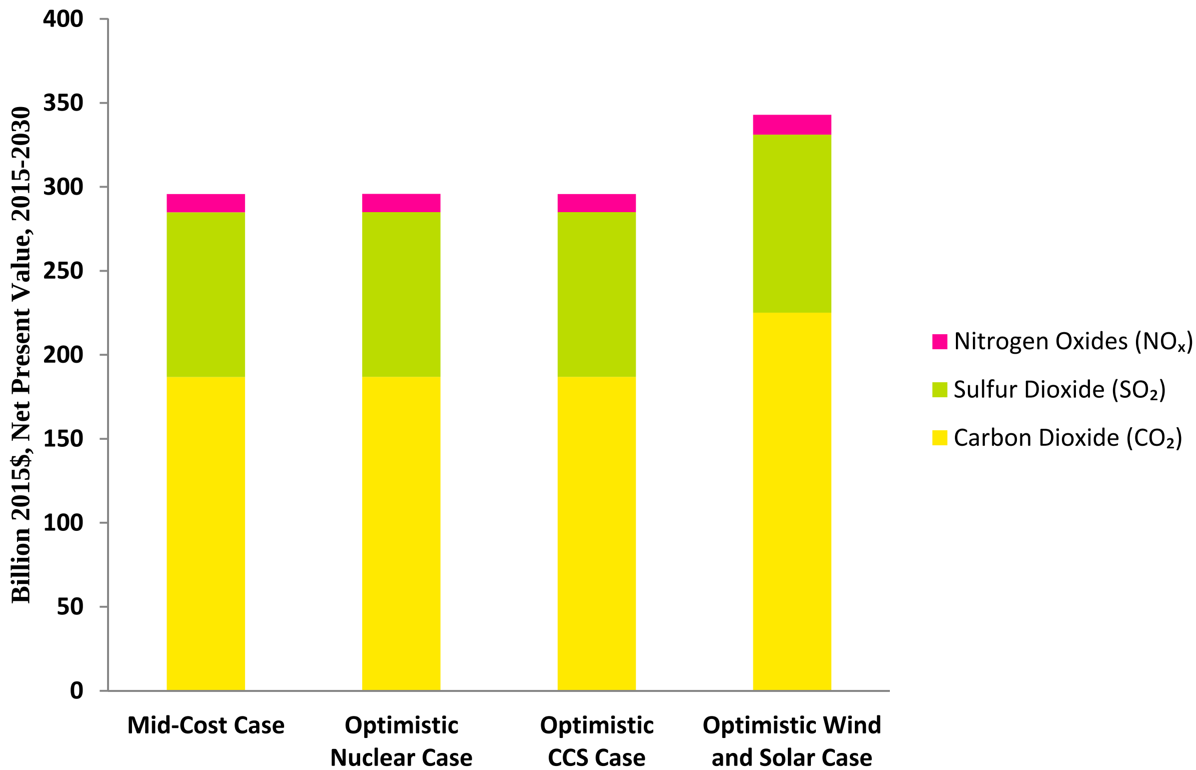
By 2050, all the policy cases show a nearly completely decarbonized power sector. Renewable energy resources provide the majority of generation in all policy cases (68 to 81 percent, depending on the case). Natural gas with CCS is also present in all the policy cases, reaching just over a fourth of the generation share in the optimistic CCS case. The share of nuclear power remains small, except in the optimistic nuclear case where it reaches 16 percent of generation. Conventional natural gas is a small share of power generation, ranging from 3 to 7 percent.

Public Health and Economic Benefits of a Low-Carbon Transition

The shift from fossil fuels to low-carbon electricity will also bring significant public health benefits, in terms of reductions in co-pollutants such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter and toxic pollutants like mercury. We quantified the cumulative monetary benefits of reductions in NO_x and SO_2 emissions in our low-carbon policy cases by 2030, relative to the reference case, using EPA assumptions (EPA 2015). The monetary benefits of CO_2 reductions are estimated, using the central value for the US government's social cost of carbon dioxide (Interagency working group 2016).[14] All the policy cases show cumulative benefits exceeding $270 billion through 2030, relative to the reference case (see Figure 6). The optimistic wind and solar case has the highest cumulative benefits, driven by the higher cumulative CO_2 reductions for that case. Note that we have not estimated the additional public health benefits that would arise due to reduced fossil fuel use in other, non-power sectors driven by electrification of end uses.

For CO_2 reductions alone, the cumulative benefits for 2015-2050 range from $442 billion in our Mid-cost case to nearly $500 billion in our Optimistic wind and solar case, relative to the reference case (all values are NPV with 3 percent discount rate).

FIGURE 6. **Public Health and Economic Benefits of a Low-Carbon Power System, by 2030, Relative to Reference Case**



The transition to a low-carbon power sector helps reduce carbon dioxide emissions, as well as co-pollutants including nitrogen oxides and sulfur dioxide. Our policy cases show billions of dollars of public health and economic benefits from CO_2, NO_x and SO_2 reductions relative to the reference case. For the benefits from NO_x and SO_2 reductions we used EPA estimates with a 7 percent discount rate. For the CO_2 benefits we used the US government social cost of carbon estimates with a 3 percent discount rate.

Because we used a carbon price as a proxy policy to drive down emissions, we are also able to calculate the carbon revenues that would be generated should such a policy be used. In the policy cases, cumulative carbon revenues through 2050 reach an estimated $434 to $495 billion (in 2015$, net present value assuming a 7 percent discount rate). Through 2030, the estimate for carbon revenues is $214 to $249 billion.

Investments Needed for a Low-Carbon Transition

The decarbonization of the electricity generation mix, and the increased electrification of end-uses, will require significant investments in low carbon power and a transformation of our entire energy system over the next 35 years. In our analysis, we focus solely on the investments needed in the electricity sector.

These investments will need to reach nearly $250 billion per year in our policy cases, three to four times more than the Reference case (Table 2). These costs exclude the investments in research, development and demonstration that may be needed to reach the technology improvements assumed in the cases.

TABLE 2. **Investments and Rate Impacts of a Low-Carbon Transition**

		Reference Case	Mid-Cost Case	Optimistic Nuclear Case	Optimistic Carbon Capture and Storage (CCS) Case	Optimistic Wind and Solar Case
Capital Investment, Average Annual	**Undiscounted Billion 2015$/year**					
2016-2033		58	248	247	249	246
2033-2050		91	315	286	242	300

All of the policy cases require significant investments in low carbon power. These electricity sector investments will need to reach nearly $250 billion per year, three to four times more than the Reference case. These costs exclude the investments in research, development and demonstration that may be needed to reach the technology improvements assumed in the cases.

[CHAPTER 3]

Discussion

The US power mix must change substantially over the next few decades to help achieve our climate goals. Our results show that conventional coal-fired power, long a mainstay of the electricity sector, must quickly be phased out. Under a range of scenarios, we find renewable energy to be the biggest contributor to lowering emissions in the power sector. Depending on technology cost and performance assumptions, natural gas with carbon capture and storage and nuclear power can also make an important contribution. The power sector can also help drive down economy-wide emissions through increased electrification of end-uses in other sectors. Emission reduction pathways with greater cumulative reductions provide additional space for other sectors to develop innovative solutions and our analysis helps identify conditions that support such reductions.

Achieving the ambitious emission reduction goals will require robust policies, a point that numerous studies have emphasized (IEA 2016; NAS 2016; Williams, Haley and Jones 2015). The carbon price we model is simply a proxy; other policies will also be needed to encourage a ramp up of zero carbon energy resources and greater energy efficiency. For example, integration of high levels of renewable energy in the electricity grid requires appropriate investments in expanding the transmission grid, and policies that would drive those investments.[15] Achieving cost reductions and technology breakthroughs in low carbon technologies like wind and solar energy, advanced nuclear reactors, energy storage and carbon capture and storage will require investments in research and deployment. Coordination across sectors, for example electrification of significant portions of the transportation fleet, will also require intentional policies. In addition, policies are needed to help ensure a just transition for workers in the fossil fuel industry and communities currently dependent on these industries. Targeted policies to increase clean energy access in low-income and historically disadvantaged communities are also needed.

The benefits of a low carbon electricity transition will be substantial, including public health, economic and climate benefits. The US power sector's low carbon transition also provides important insights for global efforts to decarbonize the energy sector. Replicating this transition on a global scale can amplify economic and public health benefits, while achieving the global goal of limiting climate change.

Expert opinion may differ on which of the technology cost pathways we modeled aligns with likely future pathways. To have a strong probability of reaching our climate goals, we have to invest in a portfolio of low-carbon technologies rather than putting all our hopes in any one 'magic bullet' solution. Many of the solutions to help decarbonize our power mix are available today and we have to invest in deploying them more rapidly. For others, investments made today can encourage innovation to help bring down costs and improve performance. Different technologies also come with different risk profiles and tradeoffs. Ultimately choices will need to made about the types of tradeoffs that society is willing to accept in the quest to limit climate change.

One way to contextualize our results is to put the price declines assumed in our modeling scenarios in the context of real-world experience today. We have assumed a 22 percent decline in wind costs over the next 20 years and a 50 percent decline in solar photovoltaic costs. In comparison, wind and solar costs have fallen by more than two-thirds just since 2009 (Lazard 2015; Wiser and Bolinger 2015). On the other hand, nuclear power, a mature technology that has been in use for over half a century, has been experiencing significant cost increases and project delays. One new reactor just went on-line and four new reactors are expected to come online by 2020, the first new builds since the 1970s. These new plants have all faced significant delays and cost escalations.

Meanwhile, five nuclear power plants have been shut down in the past five years primarily due to safety reasons or because they were no longer cost-competitive compared with other resources, and several more are currently being considered for closure (EIA 2016b). Carbon capture and storage has not yet been demonstrated at scale for a large power plant, although many of the components are well understood and have been in use for many years in other contexts such as enhanced oil recovery. Kemper County, a first of a kind 582 MW coal-with-CCS demonstration project in Kemper, Mississippi has experienced repeated delays and, with a price tag of about $7 billion and rising, is billions of dollars over the initial budget (MIT 2016). The project, which began in June 2010, is not yet fully operational (Mississippi Power 2016).

Clearly, if CCS and nuclear power are to play a major role in a low carbon future, there is considerable work ahead to drive down costs and overcome technical hurdles and safety concerns. There are also challenges to ramping up significant amounts of renewable energy quickly, including siting concerns and inadequacies in the current aging electricity grid. These too, must be confronted, including by investing in a modernized grid specifically designed to integrate high levels of renewables.

Our results also point out the reality that there are path dependencies created by the choices made today in refashioning our electricity mix, which have implications for our 2050 goals. For example, a large build-out of conventional natural gas-fired power plants in the next decade would require either retrofitting these plants with CCS technology, assuming the technology becomes available at scale at a reasonable cost, or abandoning expensive infrastructure and quickly replacing it with other zero carbon resources should CCS not be available by 2030.

[CHAPTER 4]

Conclusion

Continued research on deep carbonization pathways in the context of both developed and developing countries is necessary to help inform future climate and energy policies. These policies must in turn drive the greater ambition in emissions reductions needed to meet the long term deep decarbonization goals of the Paris Agreement.

Our research shows that it is technically feasible to make deep cuts in US power sector carbon emissions, provided we implement strong policies quickly. There are nevertheless significant challenges to achieving ambitious emissions reductions. The choices made in the next decade have significant implications for whether and how much emissions can be reduced. Necessarily, there are also different tradeoffs, costs and risks associated with the various technology pathways available to limit carbon emissions. Societies everywhere, including in the US, will need to grapple with these choices as they embark on a transition to a low carbon economy. Delayed or weak action comes with profound implications. The global carbon budget is severely constrained; to limit some of the worst impacts of climate change, the world must act quickly.

[ENDNOTES]

1 ReEDs is the Regional Energy Deployment System – a model developed by the National Renewable Energy Laboratory. It covers the power sector only; a key strength is its detailed geographic resolution, covering 134 power control authorities in the continental U.S. and 356 wind and solar resource regions, which allows it to address a variety of issues related to integrating renewable energy into the electricity grid. ReEDS does not have foresight. For more information, see *http://www.nrel.gov/analysis/reeds/description.html*

2 For the Clean Power Plan, we use mass-based targets including the new source complement with all states able to participate in a national carbon allowance market i.e. able trade with each other. For more details, see Bailie et al. 2016b

3 Emissions are measured in short (imperial) tons throughout this article.

4 All costs in this article are in real 2015 US dollars.

5 Many recent studies have suggested that a starting value in the range of $20 to $25/ton implemented within the decade would provide an effective initial market signal to help reduce emissions (CBO 2013; Luckow et al.2016; Morris 2016). Some have suggested a higher rate, in line with the US government social cost of carbon (Hafstead et al. 2016). The escalation rate of the tax is also critical to continue to drive down emissions. Our choice of a 7 percent escalation rate is somewhat higher than the 2 to 6 percent rate studies typically adopt; it is specifically designed to help achieve the deep carbon emissions needed in the power sector, in line with a mid-century economy-wide net zero goal.

6 These additional efficiency investments are assumed to be part of the states' compliance strategy for the Clean Power Plan.

7 Another study, the National Renewable Energy Laboratory's Renewable Electricity Futures Study also shows an increase in net demand relative to the reference case under a scenario where end uses are electrified along with increased energy efficiency (NREL 2012).

8 This is based on leakage rates for natural gas delivered to power plants for electricity generation and does not include leakage from the distribution system to households and smaller utilities.

9 This value is based on data from EPA's 2014 version of eGRID. Given that 132 kg of natural gas are combusted per MWh of electricity generated, 0.0075 kg CH4/MWh is equivalent to a CH4 emission rate of 0.006% at the power plant – a much lower emission rate than that for the upstream natural gas supply chain.

10 One avenue for improved estimates, the EPA has issued a draft Information Collection Request as a prelude to issuing standards for methane emissions from the oil and gas industry. (EPA 2016)

11 The ReEDS model excludes some of the smallest units (less than 50 MW) and CHP plants and therefore has a lower level of emissions that the full power sector emissions as estimated by the EIA.

12 Additional emission reductions are possible in these sectors through energy efficiency and other technology and behavior changes but these aspects are excluded from our analysis. See Williams et al 2014 for more information.

13 Generation from nuclear plants is similar in 2015 and 2030, at approximately 800 terawatt-hours (TWh), but total generation increases to meet higher electricity demands, so nuclear plant's contribution to the total decreases.

14 We used the estimates for the social cost of carbon dioxide based on a 3 percent discount rate.

While the ReEDs model we used includes the transmission investments that would be needed for all the cases we analyzed, it does not consider the policies that would be needed to incentivize/approve the transmission.

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