Halfway to Zero

Progress towards a
Carbon-Free Power Sector

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Halfway to Zero: Progress towards a Carbon-Free Power Sector

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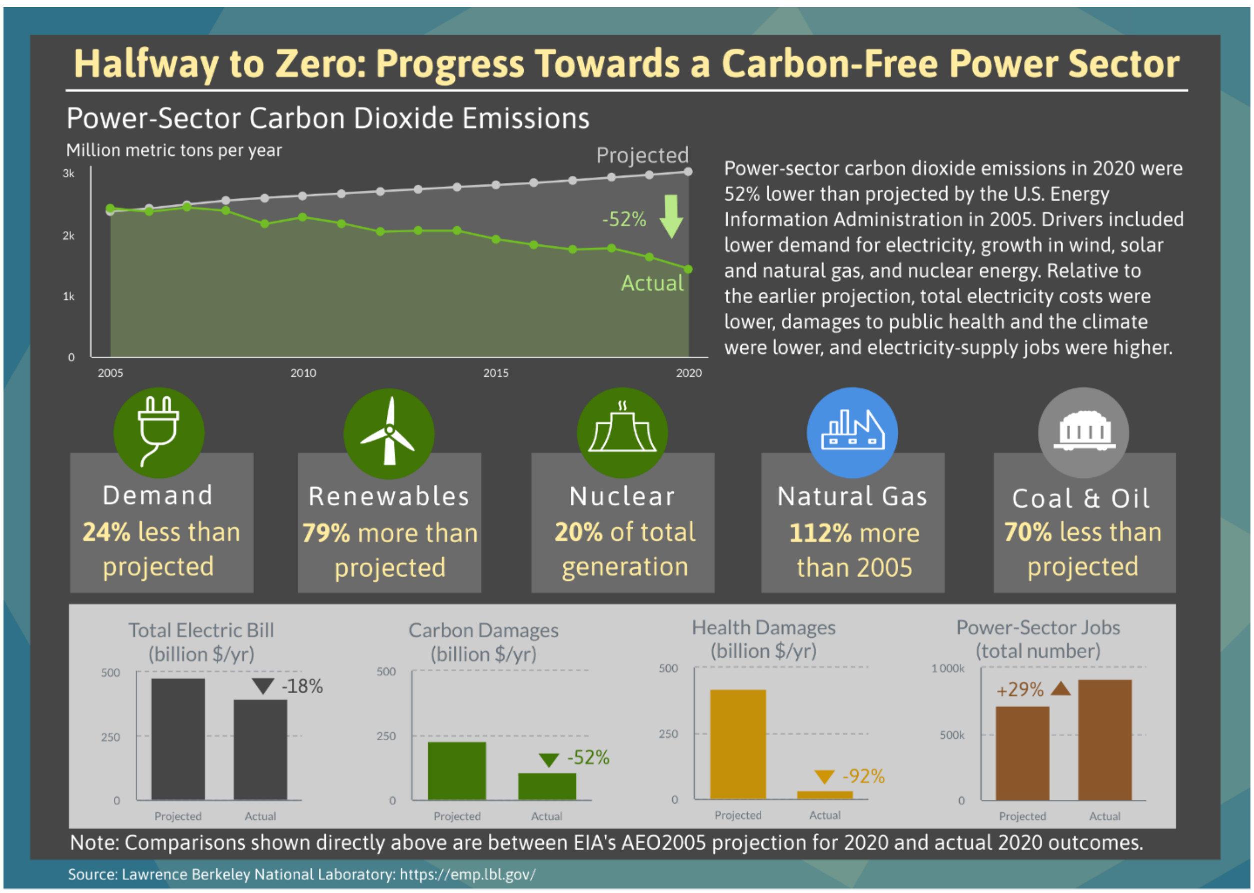
Executive Summary

Sharply reducing carbon emissions is imperative to prevent the worst effects of climate change. Yet even in the power sector—often viewed as the lynchpin to economy-wide decarbonization, and where low-carbon solutions are increasingly plentiful and cost-effective—the pace and scale of the required transformation can be daunting. A review of historical trends, however, shows the progress the power sector has already made in reducing emissions. Fifteen years ago, many business-as-usual projections anticipated that annual carbon dioxide (CO_2) emissions from power supply in the United States would reach 3,000 million metric tons (MMT) in 2020. In fact, direct power-sector CO_2 emissions in 2020 were 1,450 MMT—roughly 50% below the earlier projections. By this metric, in only 15 years the country's power sector has gone halfway to zero emissions. Other metrics also evolved differently than projected: total consumer electricity costs (i.e., bills) were 18% lower; costs to human health and the climate were 92% and 52% lower, respectively; and the number of jobs in electricity generation was 29% higher. Economic, technical, and policy factors contributed to this success, including sectoral changes, energy efficiency, wind and solar, continued operations of the nuclear fleet, and coal-to-gas fuel switching.

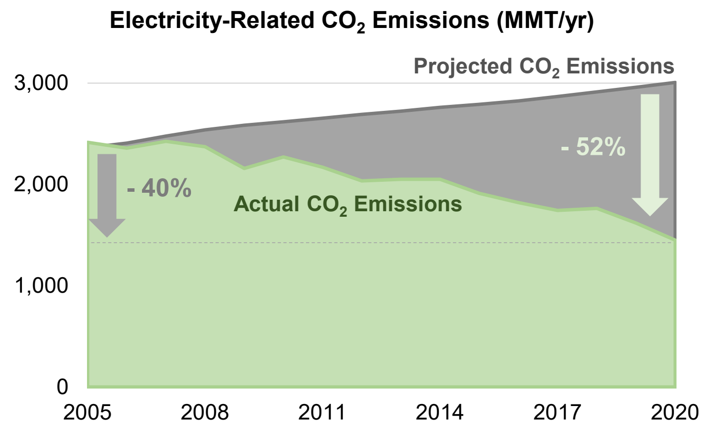


This historical record demonstrates the ability of technological and policy changes to set the power sector on a dramatically different emissions trajectory. Past success, however, does not trivialize the challenges that remain for further decarbonization in the power sector and beyond. Nor does it offer a specific roadmap for how best to achieve additional power-sector emissions reductions. Numerous challenges confront a zero-emissions pathway, and future strategies will likely differ from those of the past. Many recent studies have assessed how to make *further* progress in decarbonizing the power sector on the pathway to decarbonizing the economy as a whole, including a report from the National

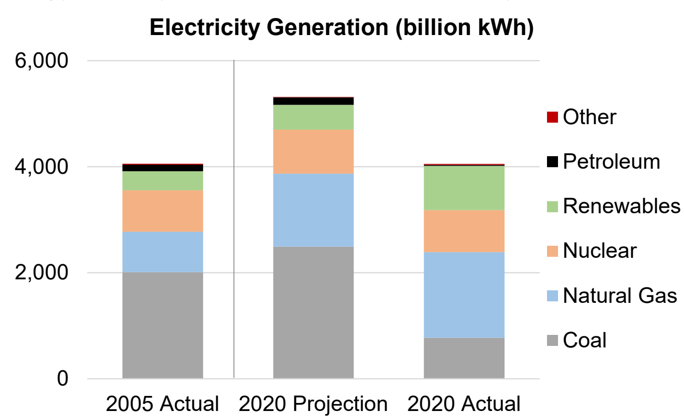
Academies (2021a). We summarize the core results of those studies, but the primary goal of this report is to highlight the progress that has already been made in reducing power-sector emissions. As the country maps out a plan for further decarbonization, experience from the past 15 years offers two central lessons. First, policy and technology advancement are imperative to achieving significant emissions reductions. Second, our ability to predict the future is limited, and so it will be crucial to adapt as we gain policy experience and as technologies advance in unexpected ways.

Key findings on emissions reductions to date

- **Lower Emissions:** The U.S. power sector, in 2020, looks radically different from projections made 15 years earlier. Compared to a range of past business-as-usual projections from the government, private sector, and research communities, in just 15 years the country's power sector has marched halfway to zero emissions. For example, the U.S. Energy Information Administration's (EIA's) 2005 Annual Energy Outlook (AEO) projected that CO_2 emissions from power supply would be 3,008 MMT in 2020. In fact, direct power-sector CO_2 emissions in 2020 were 1,450 MMT, 52% lower than projected. The results for 2020 reflect the impact of COVID-19. Electricity demand in 2020 was 4% lower than in 2019. The 52% reduction in emissions relative to EIA's earlier business-as-usual projection is reduced to 46% if 2019 data are used. Comparing 2020 power-sector CO_2 emissions with 2005 emissions shows a more modest though still sizable 40% reduction. Using pre-COVID data from 2019, the reduction is 33%—on this latter metric, the United States is one third of the way towards zero emissions.

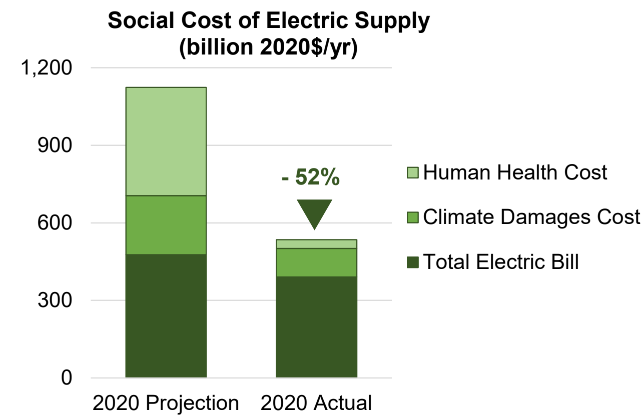


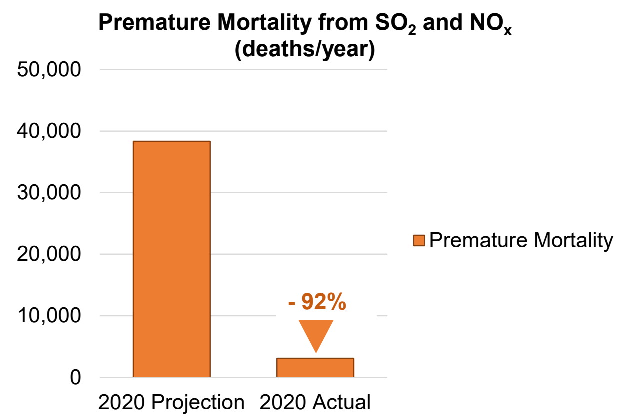
- **Drivers for Progress:** The emissions reductions stem from a diverse array of policy, market, and technology drivers. Electricity demand was 24% lower in 2020 than projected by EIA owing to sectoral and economic changes, and to greater energy efficiency driven by policies and technology advancement. Wind and solar outperformed expectations, delivering 13 times more generation in 2020 than projected, also a result of technology development and state and federal policies. Total renewable electricity supply, also considering hydropower, biomass and geothermal, was 79% higher than projected. Nuclear energy continued to produce 20% of total nationwide electricity generation, carbon free. Finally, coal-to-gas fuel switching played a crucial role, with natural gas generation growing rapidly, driven by the shale gas revolution and the difference between projected and actual fuel prices.



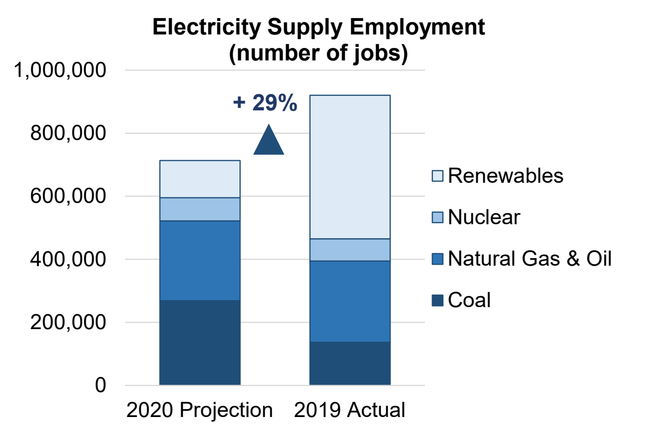
- **Limited National Consumer Electricity-Cost Impacts:** Retail electricity prices in 2020 (10.7 cents per kilowatt-hour [¢/kWh]) were similar to those in 2005 (10.6 ¢/kWh, in real 2020$), but higher than projected for 2020 (9.9 ¢/kWh). Total sales in 2020 were lower than anticipated. Consequently, total customer electricity bills (i.e., costs) in 2005 and 2020 were similar, and 2020 bills—at $391 billion—were 18% lower than the projected $477 billion. These comparisons do not directly capture the cost of carbon reduction and—given the growth of natural gas—are greatly impacted by the decline in gas prices. However, they indicate that national average electricity expenditures are roughly the same today as in 2005, and they are well below previously projected values.

- **Lower Health and Climate Burdens:** The impacts of electricity supply go well beyond consumer electricity bills to include climate damages caused by carbon emissions and human health damages from other pollutants. Climate damages from power-sector carbon emissions in 2020, estimated at $110 billion, were less than half the $229 billion that would have been incurred under the EIA projection. Health costs, at $34 billion, were reduced by more than 90% relative to the $419 billion projected for 2020, owing to reduced coal generation and stronger emissions regulations. Premature deaths from power-sector air pollution in 2020 (3,100 lives lost) were just 8% of what might have been under the business-as-usual trajectory (38,000 lives lost). In total, the calculated social cost of power supply—considering electricity bills, climate damages, and health impacts—in 2020 of $535 billion was 44% lower than in 2005 ($948 billion) and 52% lower than projected for 2020 ($1,124 billion).





- **National Power-Supply Job Gains:** Electricity-supply related employment in 2019 (the most recent year for which comprehensive data are available) was 29% higher than might have been the case under the business-as-usual projection for 2020, because the renewable energy sector is job-intensive, requiring more jobs per unit output than natural gas and coal. As a result, though jobs in the coal sector are considerably lower than might have been the case, natural gas and especially renewable energy jobs boost the overall total to 920,000. Jobs in the nuclear sector largely held steady. Naturally, the regional distribution, required skills, and compensation associated with the employment shifts are also crucial, and these differ across scenarios.



- **Slower Progress in Other Energy Sectors:** Decarbonization in other energy sectors has been slower than in the power sector, which accounts for 53% of total energy-sector emissions reductions.

Nonetheless, trends since 2005 and comparisons to projections for 2020 show broad progress. Total energy-related carbon emissions in 2020 were 39% lower than projected under the EIA's business-as-usual scenario. Relative to emissions in 2005, actual 2020 emissions were 24% lower. These figures drop to 32% and 14%, respectively, if pre-COVID 2019 data are used.

Future pathways and remaining challenges

It is significant that the nation has cut power-sector carbon emissions over the last 15 years. However, if the United States is to progress on a deep-decarbonization pathway, it must absorb the likely near-term rebound in emissions post-COVID, and then once again beat business-as-usual emissions projections. Many challenges confront a zero-emissions pathway, and the strategies of the future will differ from those of the past. Recent literature suggests the following future pathways and challenges:

- **Deep Additional Reductions at Relatively Low Incremental Cost:** Recent literature suggests that solar, wind, and energy storage—along with existing low-carbon resources and energy efficiency—are likely to play important roles in near-term power-sector decarbonization. Given advancements in wind, solar, and battery technologies, decarbonizing the power sector now appears to be more cost-effective than expected just a few years ago. Moreover, more than half of the additional wind and solar capacity needed to approach a zero-carbon power-sector target is already in the development pipeline: about 660 gigawatts (GW) of wind and solar are seeking transmission access (along with about 200 GW of storage), 570 GW of which has requested to come online before the end of 2025. These figures can be compared to the approximately 1,100 GW of new wind and solar capacity that might be required under a 90% clean power scenario for 2035.
- **Challenges Ahead in Scaling Wind, Solar, and Storage:** Dramatically expanding wind, solar, and storage to become major contributors to power supply is not trivial. It would require extensive efforts to ensure electricity delivery and power-system reliability and resilience, significant new transmission infrastructure, enhanced and integrated planning and operations, revised siting processes, focused attention on workforce and supply chain issues, and heightened responsiveness to impacted communities. Aggressive pursuit of energy efficiency and demand response—in part through grid-interactive efficient buildings—can address some of these challenges, but it may create new challenges in system coordination given the increasingly complicated operating environment.
- **Striving for Zero Emissions:** For power systems relying on increasing volumes of wind, solar, and batteries, the incremental cost of carbon reduction begins to rise more steeply as emissions decline and eventually approach zero. Further research, development, and demonstration for the numerous technologies that can fill this gap in the puzzle is needed, to enable technology portfolios that minimize incremental costs. Options include longer-duration storage, hydrogen or synthetic fuels, biofuels, fossil or biomass with carbon capture, nuclear, geothermal, and solar-thermal with storage. Were these additional technology solutions to become available at attractive costs, even faster and more aggressive decarbonization would be feasible, at still-lower power-sector costs and with even-greater health and climate benefits.
- **Moving Beyond the Power Sector:** The power sector is widely viewed as a cornerstone for economy-wide decarbonization, through electrification of other energy end uses. Of course, electrification alone will not yield a zero-carbon economy; many applications cannot be electrified at reasonable cost, given current technology. Though the focus of this report is on the power sector, tackling carbon emissions through other solutions where electrification is not realistic and reducing other greenhouse gases will be essential—in addition to accelerating electrification—if economy-wide net-zero targets are to be achieved. These additional emissions sources are sizable and may prove more challenging to decarbonize, requiring a different set of technologies and policies.

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1. Introduction

This report contrasts power-sector carbon dioxide (CO_2) emissions in 2020 with emissions in 2005 as well as projections of 2020 emissions made in the U.S. Energy Information Administration's (EIA's) 2005 Annual Energy Outlook (AEO). We highlight key differences between each actual and projected period along with drivers for those differences. We quantify a subset of costs and benefits, speaking to electricity-consumer cost impacts, climate damages, human health, and jobs. We then examine trends in CO_2 emissions more broadly, outside just the power sector. Finally, leveraging insight from the extensive literature, we discuss possible implications for further power-sector decarbonization efforts.

For the analysis, we principally draw on data from EIA, and we emphasize EIA's reference-case (business-as-usual) projection from the 2005 AEO (EIA 2005). The comparisons are not intended as a critique of EIA projections but as a means of highlighting progress over the last 15 years. Projecting future outcomes is difficult, and—as has long been known—predictive accuracy is rare (EIA 2020; Craig, Gadgil, and Koomey 2002; Fischer, Herrnstadt, and Morgenstern 2009).

In addition, EIA is explicit about the underlying uncertainties and the fact that its reference case does not assume future policy changes. EIA (2005) expresses this as follows:

The projections in the Annual Energy Outlook 2005 are not statements of what will happen but of what might happen, given the assumptions and methodologies used. The projections are business-as-usual trend forecasts, given known technology, technological and demographic trends, and current laws and regulations. Thus, they provide a policy-neutral reference case that can be used to analyze policy initiatives. EIA does not propose, advocate, or speculate on future legislative and regulatory changes. All laws are assumed to remain as currently enacted; however, the impacts of emerging regulatory changes, when defined, are reflected.

Because energy markets are complex, models are simplified representations of energy production and consumption, regulations, and producer and consumer behavior. Projections are highly dependent on the data, methodologies, model structures, and assumptions used in their development. Behavioral characteristics are indicative of real-world tendencies rather than representations of specific outcomes.

Energy market projections are subject to much uncertainty. Many of the events that shape energy markets are random and cannot be anticipated, including severe weather, political disruptions, strikes, and technological breakthroughs. In addition, future developments in technologies, demographics, and resources cannot be foreseen with any degree of precision. Many key uncertainties in the AEO2005 projections are addressed through alternative cases.

EIA has endeavored to make these projections as objective, reliable, and useful as possible; however, they should serve as an adjunct to, not a substitute for, a complete and focused analysis of public policy initiatives.

Our goal is to convey progress in power-sector decarbonization relative to a "business as usual" projection from 15 years earlier—to highlight headway compared to what might have happened absent new policies and unexpected developments. This approach benefits from a no-new-policy projection, and the EIA reference case is reasonably unique in this respect. Many forecasts do not have that frame, but instead include predictions about future policies. As an official product of the U.S. Government and as a scenario that does not consider new policies, the EIA AEO's reference case offers a useful baseline comparison point from which to judge the combined effect of policy, market, and technological trends.

EIA's reference case from 2005 is also consistent with other business-as-usual projections published at the time (even those that did forecast future policies), both in the amount and mix of electricity generation and in carbon emissions. As shown in Appendix A, EIA's 2005 power-sector projection for carbon emissions is lower than the reference case employed in DOE (2008) and is lower than a simple extrapolation of historical emissions trends from the previous 10 years. The EIA projection for carbon emissions is similar to or slightly higher than five private-sector forecasts from the time (Global Insight, Inc. 2004; Energy Ventures Analysis, Inc. 2004; PIRA Energy Group 2004; Strategic Energy and Economic Research, Inc. 2004; Energy and Environmental Analysis, Inc. 2004). Across all seven of these projections, the maximum deviation from EIA's projection over the 2015–2025 period is +6% to -10%. The general findings presented in this report are therefore robust across a number of past projections.

Similarly, the findings would not substantially vary were we to use other EIA business-as-usual forecasts from years surrounding 2005. EIA's 2000 AEO, for example, projected power-sector CO_2 emissions in 2020 to be 2,922 million metric tons (MMT), only slightly below the 3,008 MMT projected in the 2005 AEO. EIA's 2007 AEO projected 2020 emissions at 2,832 MMT, only 5.9% lower than the 2005 AEO.

We also judge progress relative to actual power-sector supply, demand, and emissions in 2005, for those uncomfortable with comparisons to business-as-usual projections. The advantage of this approach is that it aligns with actual (as opposed to projected) emissions. The disadvantage is that it fails to fully capture the effects of policy and technology change in bending the carbon-emissions curve away from its expected business-as-usual trajectory. In both comparisons, we select 2005 as the comparison year, in terms of actual emissions and the vintage of the EIA forecast. This is because 2005 is the year to which emissions reductions are linked under the Paris Climate Agreement.

Finally, 2020 was—to put it mildly—a unique year. The impacts of the COVID-19 pandemic were felt in every aspect of human endeavor, including in the energy sector. Within the power sector, however, the impacts of COVID-19 were somewhat less dramatic. Electricity demand in 2020 was 4% lower than in 2019. The 52% reduction in emissions relative to EIA's earlier business-as-usual projection drops to 46% if 2019 data are used. Though the analysis in this report emphasizes 2020, we also report many results for 2019. Broadly, the findings are not substantively different when pre-COVID 2019 data are used.

2. Power-Sector Transformation

2.1 Halfway to Zero in 15 Years

The U.S. power sector in 2020 looked radically different from projections made 15 years earlier. Trends in direct, power-sector CO_2 emissions reflect that transformation (Figure 1).

The EIA business-as-usual projection from 2005 anticipated that CO_2 emissions from power supply would grow to 3,008 MMT in 2020, an increase of 27% over 15 years (EIA 2005). Other business-as-usual projections also showed the long-term historical growth of power-sector emissions continuing largely unabated, due to a predicted increase in electricity demand and the relatively low cost of coal-powered generation relative to other sources.

In fact, direct power-sector CO_2 emissions in 2020 were less than half these predicted amounts, at 1,450 MMT.[1,2] On this metric, in just 15 years, the country's power sector marched halfway to zero emissions.

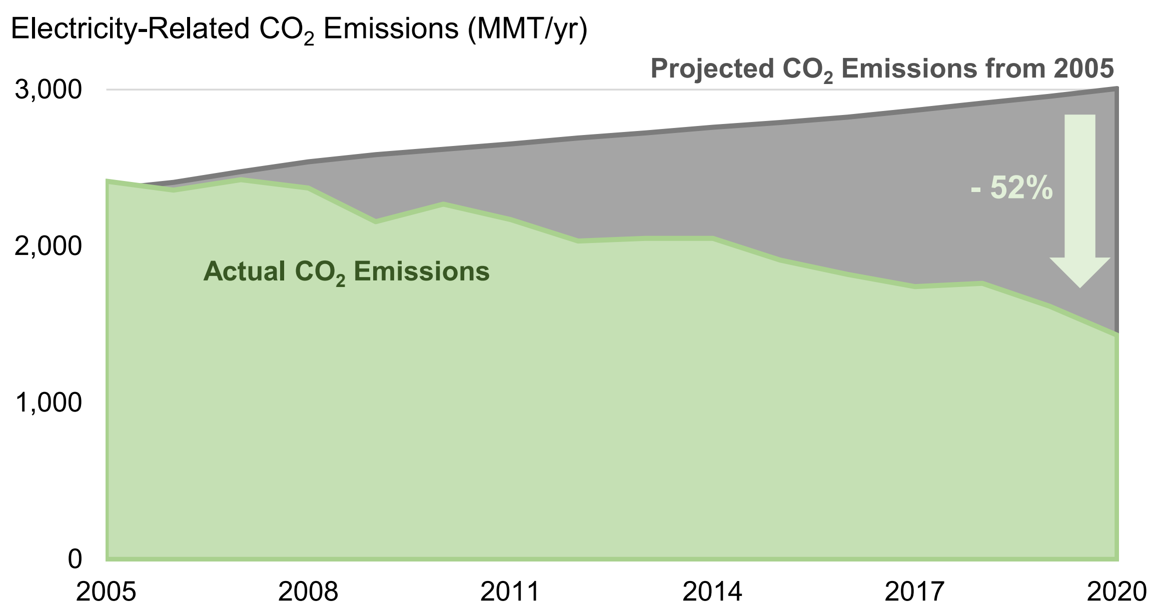

Figure 1. Power-sector CO_2 emissions: business-as-usual projection vs. actual

Using other metrics, the scale of the emissions reductions is more modest yet still notable:

- First, with respect to COVID-19, electricity demand in 2020 was 4% lower than in 2019, a significant decline but not suggestive of an enormous COVID-19 impact. Other work has demonstrated larger energy-related impacts outside the power sector (BloombergNEF 2021; Graves et al. 2020). The 52% emissions reduction in Figure 1 drops to 46% if pre-COVID 2019 data are used.

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[1] Recent data from EIA largely come from EIA's Monthly Energy Review (https://www.eia.gov/totalenergy/data/monthly/) and Electric Power Monthly (https://www.eia.gov/electricity/monthly/).

[2] These data only consider direct, "stack" emissions and do not include upstream carbon emissions or other greenhouse gases (e.g., from natural gas leaks, materials, manufacturing, and construction) (EPA 2020).

- Second, using actual power-sector emissions in 2005 as the comparison point, the reduction through 2020 is 40%. Using pre-COVID 2019 data, the reduction is 33%—on this latter metric, the United States is one third of the way towards zero emissions.
- Third, as presented later, across all energy sectors (not just the power sector, but considering all energy used in the transportation, residential, commercial, and industrial sectors), actual emissions in 2020 were 39% lower than projected under the business-as-usual scenario; this figure falls to 32% if 2019 data are used. Relative to emissions in 2005, actual 2020 emissions were 24% lower, and actual emissions in 2019 were 14% lower.

These comparisons demonstrate that the degree of progress depends on perspective. Nonetheless, it is evident that the United States has made less progress outside the power sector. Within the power sector, emissions reductions calculated relative to past projections are greater than when calculated relative to historical emissions. The results also illustrate the effects of COVID-19 and suggest that a rebound in emissions is possible—perhaps likely—in the very near term. As shown in Figure 1, this occurred around the 2008 financial crisis; a short-term emissions decline was followed by a short-term rebound before reductions continued.

Across all comparison points, the pace and scale of power-sector carbon reductions over the last 15 years remain significant. As discussed below, the reductions stem from a diverse array of policy, market, and technology drivers and actions. With respect to policy, federal and state efforts have played crucial roles, benefiting from experimentation and learning over time. However, these efforts have not been comprehensive and have varied considerably across sectors and states. A concerted, consistent, and comprehensive countrywide effort has been lacking, making progress to date even more notable.

2.2 Drivers for Carbon Reductions

Sectoral changes, energy efficiency, wind and solar deployment, operation of the existing nuclear fleet, and coal-to-gas fuel switching contributed to reducing CO_2 emissions over the past 15 years.

Retail electricity sales in 2020 were 24% lower than projected and nearly unchanged from 2005—despite an increase in GDP and population since 2005 (Figure 2). Reflective of sectoral changes that reduced manufacturing output relative to projections, industrial demand was 25% lower than anticipated. Significant reductions also occurred in the commercial (31% lower than anticipated) and residential (14% lower than anticipated) sectors, in part due to energy efficiency.

Over this timeframe, the country faced two economic crises: the 2008 financial crisis and the COVID-19 pandemic. However, the lower electricity demand was not merely a result of slower population or GDP growth or COVID-19. Actual GDP in 2019 (i.e., pre-COVID) was 13% lower than EIA's reference-case projection—a significant variation but also considerably smaller than the overall reduction in electricity demand. Population in the United States was 1% lower in 2020 than EIA had projected. Finally, the 24% lower sales in 2020 relative to the EIA projection drop to 21% lower if pre-COVID 2019 data are used. As such, in addition to economic and sectoral changes, the demand reductions reflect greater energy efficiency than projected—impacted by equipment, appliance and lighting efficiency standards, building codes, state and utility efficiency policies and programs, and technological advancements such as low-cost efficient lighting (DOE 2017a; Belzer, Bender, and Cort 2017; Goldman, Hoffman, et al. 2020).

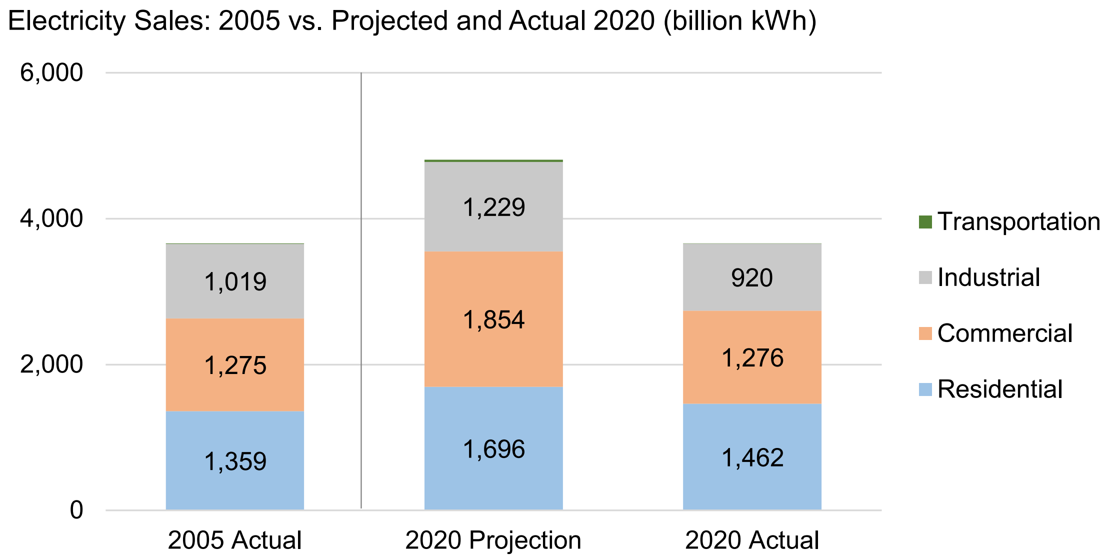


Figure 2. Retail electricity sales: 2005, 2020 projected, and 2020 actual

Trends in the generation mix—related to wind, solar, and nuclear power as well as coal-to-gas fuel switching—also contributed to reduced CO_2 emissions in 2020 relative to the business-as-usual projection and to 2005 (Figure 3).

Wind and solar widely outperformed business-as-usual expectations. Wind and solar combined were projected to deliver 35 billion kilowatt-hours (kWh) in 2020. Actual generation was more than 13 times greater, at 470 billion kWh. Considering all forms of renewable electricity, supply in 2020 was 834 billion kWh, much higher than projected (465 billion kWh) and much higher than in 2005 (358 billion kWh).[3] In part, these developments reflect the rapid cost reductions experienced by wind (Wiser et al. 2020) and solar (Bolinger et al. 2020). EIA's projected capital cost for utility-scale solar in 2025 was more than twice as high as the capital cost of actual plants built in 2019. In addition, state renewable energy standards, federal tax incentives, regional transmission infrastructure, and other policies have undergirded wind and solar growth (DOE 2017a; Mohlin et al. 2019; Barbose 2021; Carley et al. 2018). Because the earlier projection did not seek to predict policy changes, it naturally excluded many of these policies. Moreover, cost and policy drivers are related, because policies can unleash deployment-oriented learning that helps drive costs lower (Samadi 2018; Junginger and Louwen 2020).

[3] Renewable electricity supply other than wind and solar—inclusive of hydropower, biomass and waste, and geothermal—totaled 364 billion kWh in 2020 (291 billion kWh of hydropower, 56 billion kWh of biomass and waste, and 17 billion kWh of geothermal), lower than the 430 billion kWh projected by EIA (307 billion kWh of hydropower, 101 billion kWh of biomass and waste, and 23 billion kWh of geothermal).

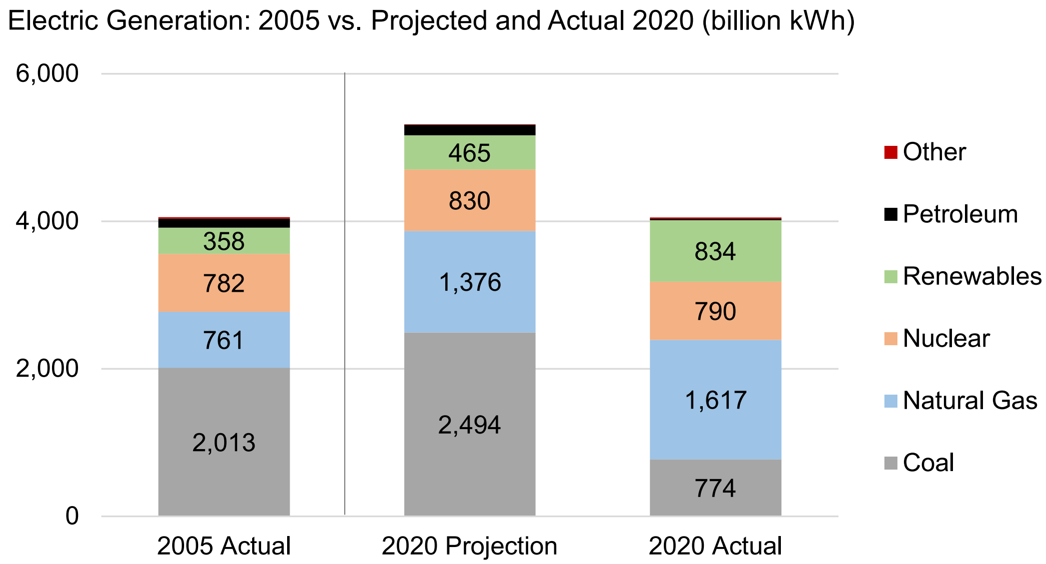


Figure 3. Electricity generation mix: 2005, 2020 projected, and 2020 actual

Nuclear energy has played a longstanding role in reducing carbon emissions. The business-as-usual projection for nuclear power proved to be relatively accurate—actual generation in 2020 was similar to the level in 2005 and only 5% lower than the projected value. The projection from 2005 assumed no retirements or additions through 2020, and it projected that facility upgrades would boost nuclear capacity by 3 gigawatts (GW), to 102.7 GW. Actual nuclear capacity was impacted by retirements, and it totaled 96.6 GW at the end of 2020. On the other hand, operational improvements increased nuclear capacity factors. Earlier, in its AEO 2000, EIA projected that over 40% of nuclear capacity would go out of service by 2020 as operating licenses expired or units were retired early (EIA 1999). Instead, licenses were generally extended. Though some plants retired or announced impending retirement dates (DOE 2017b), most of the nuclear fleet has so far remained online, consistent with the 2005 projection and in part benefiting from recent policy support in a few states. The existing nuclear fleet provided 20% of the nation's electricity supply in 2020, and a sizable fraction of total clean power supply.

Finally, coal-to-gas fuel switching played a crucial role in emissions reductions, driven by the shale gas revolution and the difference between projected and actual fuel prices (DOE 2017a; 2017b; Lu, Salovaara, and McElroy 2012; Mohlin et al. 2019; Fell and Kaffine 2018). Actual 2020 natural gas prices were 67% lower than projected. For coal, prices were 12% higher than projected. As a result, natural gas generation expanded rapidly relative to 2005 and, to a lesser extent, relative to the 2020 projection.

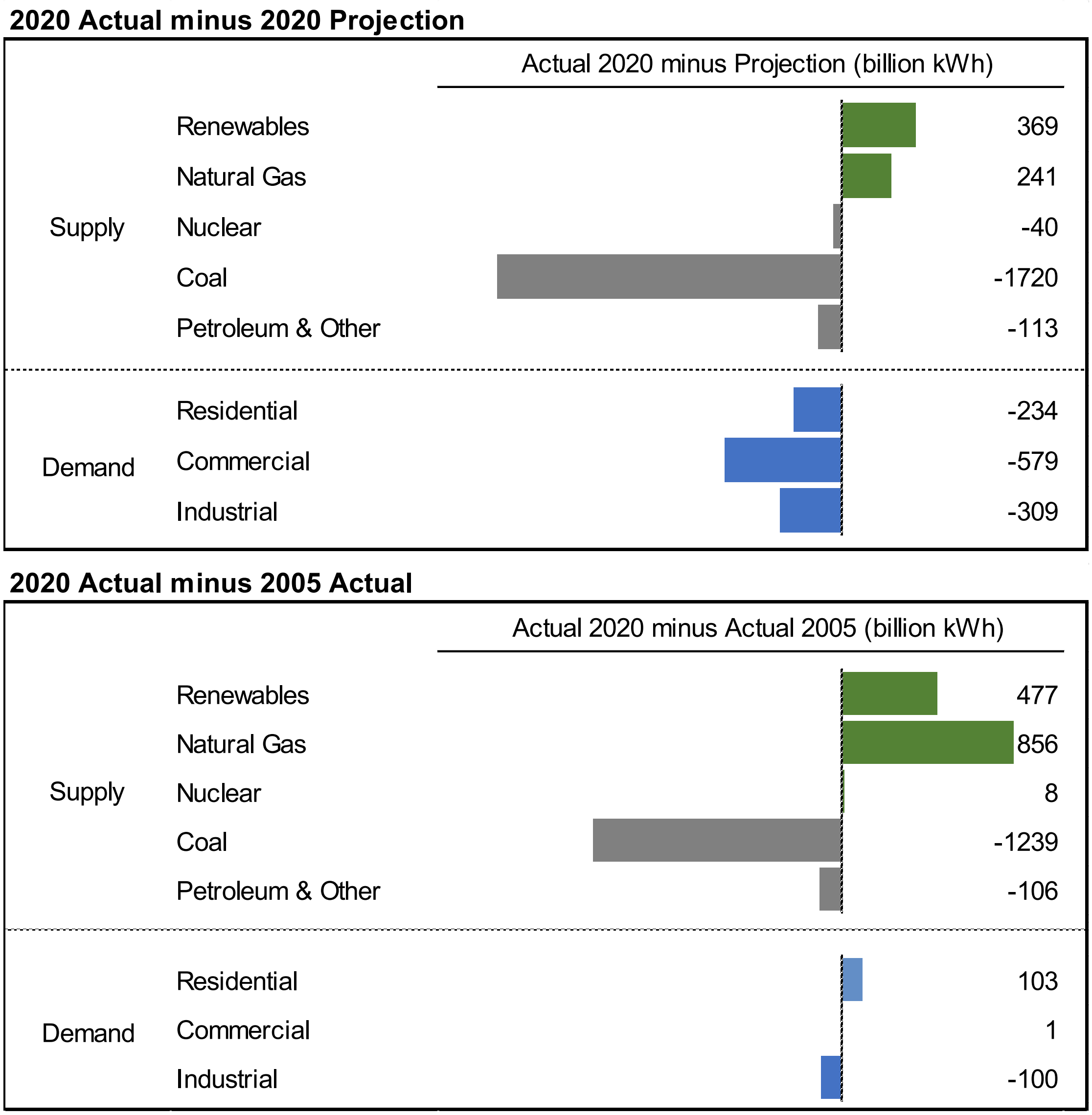
Natural gas generation grew from 761 billion kWh in 2005 to 1,617 billion kWh in 2020. Assuming this growth only displaced coal and considering the relative emissions rates of gas and coal, we estimate that increased natural gas supply reduced 2020 CO_2 emissions by 470 MMT, or 48% of the total emissions reduction since 2005. This value only considers stack emissions; it would be lower were upstream natural gas leaks considered. However, based on stack emissions alone, coal-to-gas fuel switching was a large contributor to power-sector CO_2 emissions reductions from 2005 to 2020.

Though natural gas became a much larger source of electricity supply between 2005 and 2020, the business-as-usual projection only moderately underestimated that growth (1,617 billion kWh in 2020 vs. 1,376 billion kWh projected[4]). Assuming this difference in natural gas generation displaced coal and again considering the relative emissions rates of gas and coal, we estimate that increased natural gas generation relative to the 2020 forecast reduced 2020 CO_2 emissions by 132 MMT, 8% of the total emissions reduction. As such, the degree of contribution varies considerably depending on perspective.

Regardless of the precise attribution of power-sector emissions reductions to various underlying causes, coal generation dropped significantly: the 774 billion kWh delivered in 2020 was well below the 2005 figure (2,013 billion kWh) and the 2020 projection (2,494 billion kWh). Coal-to-gas fuel switching played a prominent role in reducing CO_2 emissions over this period (Mohlin et al. 2019). However, the decline in coal was also a consequence of lower electricity demand, higher wind and solar generation, and the continued operation of most of the nation's nuclear fleet.

Figure 4 summarizes some of these results. It compares actual nationwide supply and demand in 2020 with projections for the same year. It also compares actual 2020 supply and demand with actual supply and demand in 2005. While the relative contribution of the various drivers depends greatly on perspective, all have played important roles in historical power-sector decarbonization.

[4] The level of underestimation is greater if presented in percentage-of-total-generation terms, given that total generation in 2020 was well below projected levels. Specifically, natural gas was projected to provide 26% of electricity supply in 2020; in fact, it contributed 40%.



Note: Positive numbers mean actual 2020 was higher, negative numbers mean actual 2020 was lower.

Figure 4. Summary of 2020 supply and demand relative to projected 2020 and actual 2005 values

2.3 Estimating Costs and Benefits

Numerous factors influence consumer electricity costs (i.e., bills): generation capital and operation costs, fuel prices, transmission and distribution expenditures, and policy incentives and mandates.

Figure 5 presents data on average retail electricity prices and total customer electricity bills (i.e., consumer costs)—in 2005, projected for 2020, and actual in 2020.[5] Retail electricity prices in 2020 were similar to those in 2005, but higher than projected. Total retail sales in 2020 were considerably lower than anticipated. Consequently, total customer bills in 2005 and 2020 were similar, and 2020 bills (at $391 billion) were far lower than projected ($477 billion). Electricity consumer costs in 2020 were

[5] All monetary figures are adjusted for inflation and presented in real 2020 U.S. dollars.

impacted by COVID-19. In 2019, the nation's total electricity bill was $406 billion—5% higher than in 2005, but still 15% lower than projected for 2020. Because numerous factors influence electricity costs, these comparisons do not directly capture the cost of CO_2 emissions reductions. However, they highlight that, at least on a national basis, the historical decline in emissions was not accompanied by an obvious, outsized consumer electricity cost burden.

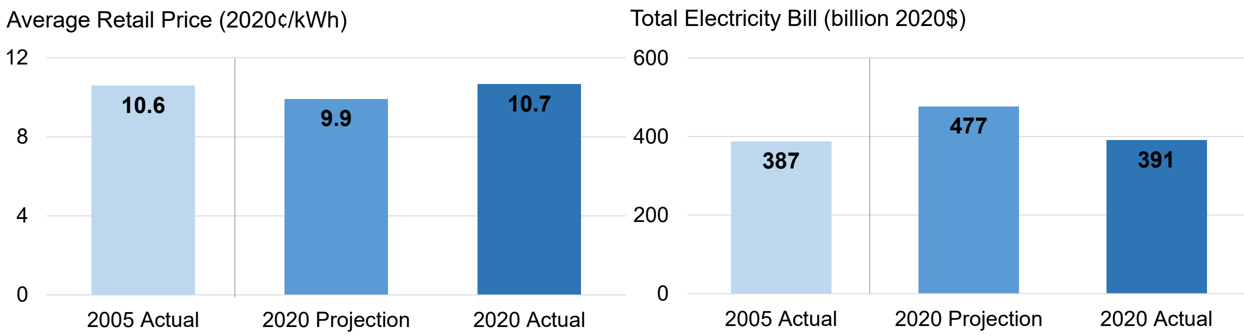


Figure 5. Retail electricity prices and total electricity bills: 2005, 2020 projected, and 2020 actual

More-detailed analyses support the argument that CO_2 emissions reductions have not yet been associated with outsized, nationwide consumer electricity cost impacts. In part this is because natural gas prices have plummeted. The rise of natural gas generation is largely an economic phenomenon, resulting in lower electricity costs (Joskow 2013; Wang et al. 2014; DOE 2017b). Related to renewable energy, one study estimates that compliance costs for state renewables portfolio standards (RPS) may have increased retail rates by 2.6% in 2019, on average across RPS states, albeit with considerably higher impacts in some states and acknowledging that other studies sometimes find larger impacts (Barbose 2021; Upton and Snyder 2017; Tra 2016). Impacts of lower magnitude have generally been estimated for net metering at current penetrations of distributed solar generation, but these are highly dependent on assumptions (Barbose 2017; ICF 2018; Cappers et al. 2019). Energy-efficiency policies and programs may increase retail rates and/or product prices, but they generally are expected to save consumers money over the long term by reducing electricity demand (Goldman, Hoffman, et al. 2020; Brucal and Roberts 2019; Gillingham, Newell, and Palmer 2006; Buskirk et al. 2014; Satchwell, Cappers, and Goldman 2018; Cappers et al. 2020). Others have shown that declining power production costs due to decreasing prices for natural gas, wind, and solar have been offset by increases in sector-wide transmission and distribution costs—a primary reason that retail electricity prices have not declined in recent years (Cappers and Murphy 2019; EIA 2017; CPUC 2021).

To be sure, some costs of CO_2 emissions reductions accrue outside consumer electricity bills. For example, EIA estimated that renewable electricity received $14.4 billion in federal incentives in 2013 and $4.3 billion in 2016 (2020$) (EIA 2018). We do not provide a full accounting of federal incentives here, but such an accounting would ideally be updated to more recent years and include changes in incentives over time for all generation sources and related fuel supply. Regardless, considering just the cost of the renewable energy incentives to the U.S. Treasury, the total cost of electricity (inclusive of tax expenditure) remains broadly similar to 2005, and well below the earlier projection for 2020.

The impacts of electricity supply go well beyond electricity bills and the direct cost of various incentives. Figure 6 estimates the social cost of electricity supply in 2005, projected for 2020, and actual in 2020.

These social costs comprise just three elements and are not all-inclusive.[6] The first is an estimate of total customer electricity bills, presented earlier and derived by multiplying average retail rates by total sales. The second is an estimate of climate damages, calculated by multiplying projected and actual power-sector CO_2 emissions by an estimate of the social cost of carbon emissions (Federal Register 2021; IWG 2016; Stern and Stiglitz 2021; National Academies 2017; IWG 2021).[7] The third is an estimate of human health costs—specifically, the cost of premature death—associated with criteria air pollution, taking data on projected and actual emissions levels and then applying marginal air-quality health impact factors from a reduced-form air-quality impact model (Heo, Adams, and Gao 2016).[8]

Total electricity bills were projected to increase between 2005 and 2020 due in large measure to increased electricity sales—from $387 billion to $477 billion. Climate damages under that trajectory would have also increased ($134 billion to $229 billion), while health costs would have modestly declined but remained sizable ($427 billion to $419 billion). Total social costs, considering just these three factors, would have risen from $948 billion to $1,124 billion, an increase of 19%.

In reality, total electricity bills in 2020 were similar to those from 2005, at $391 billion, and well below the projected $477 billion. Climate damages, at $110 billion, were lower than those in 2005 and less than half the projected $229 billion. Health costs, at $34 billion in 2020, were more than 90% below those in 2005 and also more than 90% lower than projected for 2020; this dramatic improvement was due to reduced coal generation and stronger emissions regulations. Premature deaths from power-

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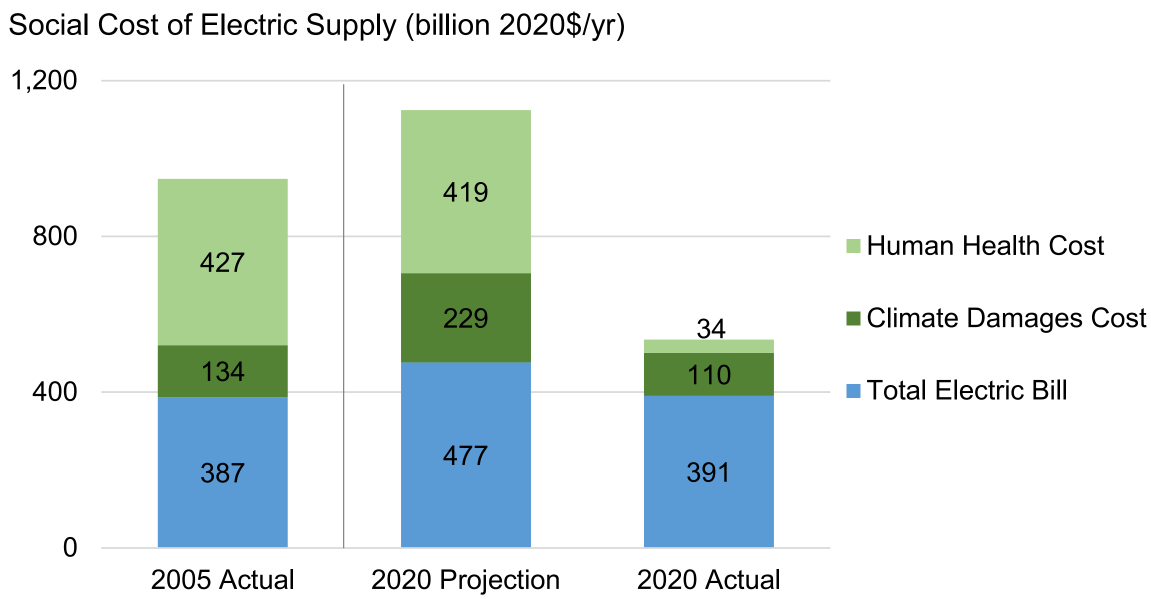
[6] Excluded are subsidies and tax incentives offered by federal, state, and local governments to all forms of generation; other environmental, health, and human impacts associated with electricity supply; and many others.
[7] We use the IWG (2021) estimate for the social cost of carbon under a 2.5% discount rate: $76/MT CO_2 in 2020$, in 2020. The IWG does not provide an estimate for 2005. We back-calculate a $55/MT estimate for 2005, based on annual social cost estimates for 2010 to 2020 (IWG 2016). We use the 2.5% discount rate case because experts—including the IWG—have questioned the use of higher discount rates (National Academies 2017; Stern and Stiglitz 2021; IWG 2021).
[8] We use the EASIUR model to determine premature mortalities associated with power-sector emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x). EASIUR generally performs well compared to other reduced-form models, e.g., AP2, COBRA, and InMAP (Industrial Economics 2019). EASIUR also has similar, but slightly lower, damage estimates than the U.S. Environmental Protection Agency (EPA) has used in regulatory proceedings; see a comparison in Millstein et al. (2017). Another benefit of EASIUR, in comparison to some other reduced-form models, is a relatively high degree of geographic resolution and a stronger connection to full-scale air-quality models. EASIUR provides marginal damages (in dollars and in premature mortalities) per metric ton of emissions, based on the location of the emissions. The marginal damages are based only on increased population exposure to particulate matter, of which SO_2 and NO_x are precursors. Other emissions (e.g., primary particulate matter or mercury) were not evaluated, because SO_2 and NO_x emissions make up the vast majority of air-quality damages from power plants. Two seminal epidemiological studies underpin the damage estimate (Krewski et al. 2009; Lepeule et al. 2012). Results presented here represent an average between these two studies, which fall ±38% on each side of the average. Emissions from EIA's AEOs are provided on a regional basis, and were distributed to specific locations within each region following recorded power-plant emissions in 2005 and 2019 (2020 plant emissions were not available at the time of writing). Estimated 2005 and 2019 emissions from EIA's AEO, and associated damage estimates, roughly match recorded emissions and associated damage estimates. As such, we are comfortable using EIA AEO estimates of emissions for 2005, 2020 (projected from AEO 2005), and 2020 (actual). The dollar value of premature mortality is based on a standard value of mortality risk reduction (often called the value of statistical life). The value used by EASIUR is 8.6 million 2010$ and follows EPA recommendations. This value was adjusted to the population level and income (with a 50% elasticity) of each year in question, and was set to a 2020 dollar year.

sector air pollution in 2020 (3,100 lives lost) were substantially lower than estimated 2005 impacts (43,000 lives lost) and what might have been under the projected 2020 emissions trajectory (38,000 lives lost).

In total, the calculated social cost of power supply in 2020 of $535 billion was 44% lower than in 2005 ($948 billion) and 52% lower than had been projected for 2020 ($1,124 billion).



Note: Climate damages and human health costs are calculated by the authors using EIA data on air pollutant emissions and literature-based estimates of the damage cost of those emissions.

Figure 6. Social cost of electricity supply: 2005, 2020 projected, and 2020 actual

Finally, we estimate differences in employment related to electricity supply under the projected 2020 outcome and the actual mix in 2019 (Figure 7). We only estimate employment related to electricity generation and the relevant proportion of fuel production needed to feed the electricity sector. We use resource-specific jobs per megawatt (MW, for generation jobs) and jobs/kWh (for fuel-supply jobs) estimates for 2019, derived from NASEO & EFI (2020) (and EIA), and we apply those to the projected 2020 supply mix. We assume the resource-specific jobs/MW and jobs/kWh estimates derived from 2019 data can be applied, in rough approximation, to the projected mix.[9] For actual jobs, we focus on 2019 as those are the most recent available data from NASEO & EFI (2020).[10] The estimates are inclusive of

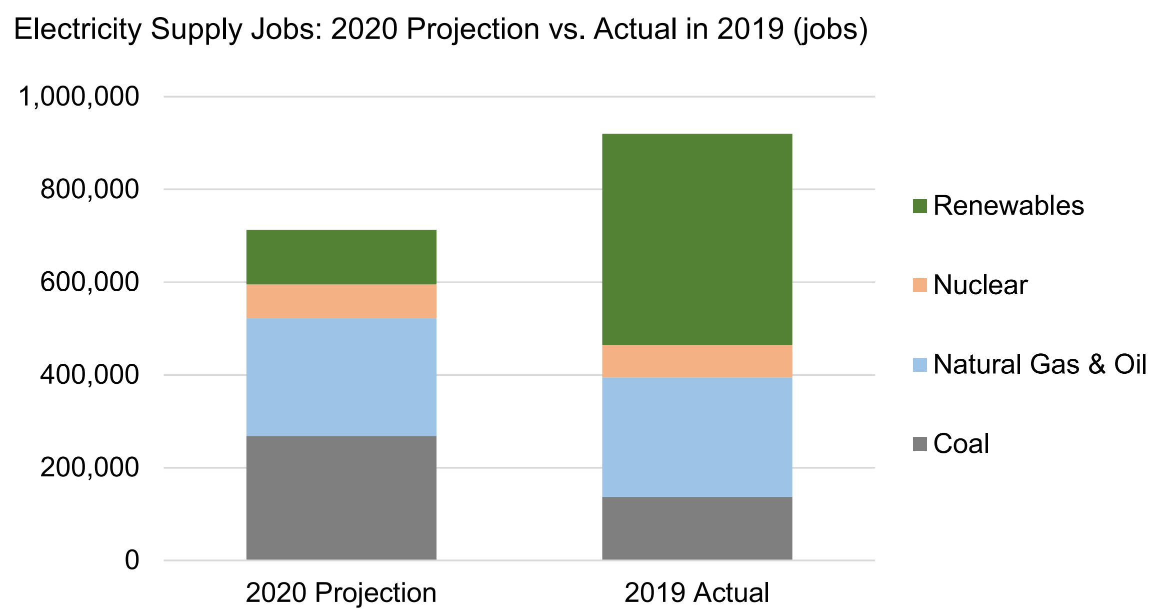
[9] In effect, this approach assumes power-supply jobs scale linearly with total installed capacity in MW for each generation type, and that fuel-supply jobs related to the power sector scale linearly with electricity supply in kWh. In practice, power-supply jobs may scale not only in proportion to total installed capacity, but also in proportion to yearly additions, reflecting construction jobs (or even in proportion to kWh). Additionally, jobs may not scale linearly, especially given the significant differences in supply mix between the projection for 2020 and actual supply in 2019. Given these caveats, we consider the estimates presented for the 2020 projection as first-order approximations.

[10] Though full 2020 data are not yet published, COVID-19 has impacted employment in the power sector. For example, the United States entered 2021 having lost 67,600 renewable energy jobs since the beginning of 2020 (Jordan 2020).

power-supply jobs and the relevant proportion of fuels used in the power system. Owing to methodological challenges, we exclude jobs related to transmission, distribution, and storage, as well as energy efficiency.[11]

With those important caveats in mind, and thereby in recognition that these are rough first-order approximations, we estimate that electricity-supply related employment in 2019 was 29% higher than might have been the case under the business-as-usual projection for 2020. This is because, based on NASEO & EFI (2020), the renewable energy sector is job-intensive, requiring more jobs per unit output than natural gas and coal. As a result, though jobs in the coal sector are considerably lower than might have been the case, natural gas and especially renewable energy jobs boost the overall total to 920,000.

Naturally, the regional distribution, required skills, and compensation associated with these employment shifts are also crucial, and they differ by scenario; we do not analyze those details here. In addition, the job totals depicted in Figure 7 for 2019 relative to earlier projections would likely be higher still if jobs related to electricity distribution, transmission, and energy efficiency were included. NASEO & EFI (2020), for example, estimate that energy-efficiency jobs in 2019 totaled 2.38 million.



Note: Jobs estimates are calculated by the authors using the methods described in the report text.

Figure 7. Employment related to electricity supply: 2020 projected and 2019 actual

[11] NASEO & EFI (2020) present data on transmission, distribution, storage, and energy-efficiency jobs, but we were unable to develop a simple method to estimate employment in these sectors under the EIA projection for 2020. As such, we leave those estimates for possible future research.

3. Headway Across All Energy Sectors

Decarbonization in other U.S. energy sectors has been slower than in the power sector, though trends since 2005 and comparisons to projections for 2020 show progress.

Total energy-related CO_2 emissions consider energy use in transportation, residential and commercial buildings, and industry, and are inclusive of power-sector carbon emissions. In 2020, total energy-related CO_2 emissions were 39% lower than projected under the business-as-usual scenario (Figure 8). Relative to emissions in 2005, actual 2020 emissions were 24% lower. Excluding electricity, all other sources of energy-related CO_2 emissions were 31% lower in 2020 than in the earlier projection. Power-sector emissions reductions represent 53% of total energy-sector emissions reductions.

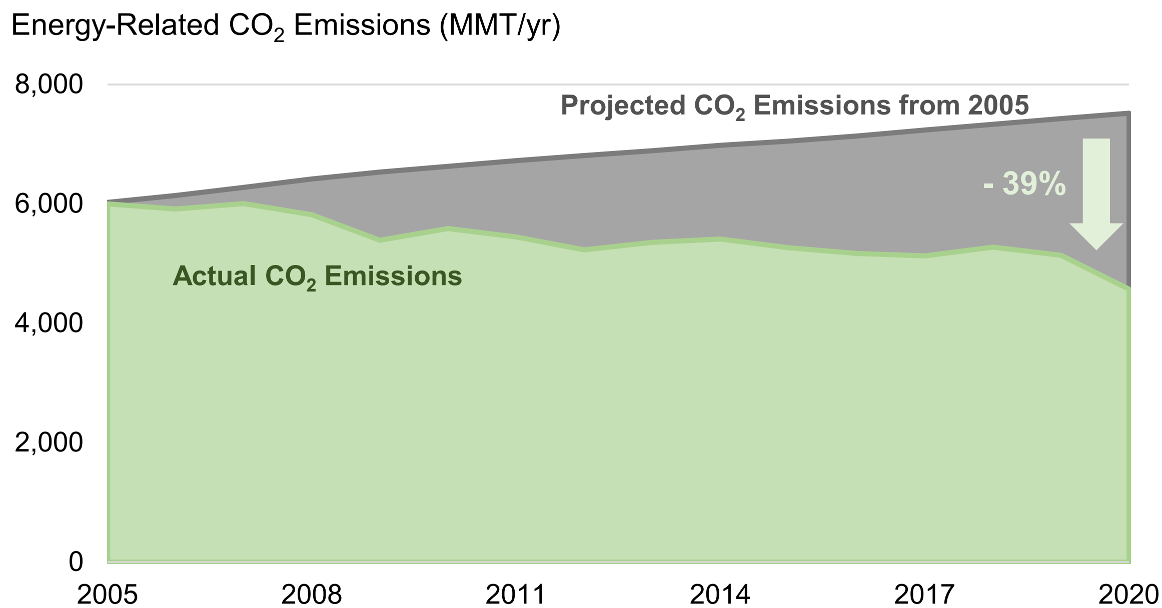


Figure 8. Total energy-sector CO_2 emissions: business as usual vs. actual trajectory

These reductions were magnified in 2020 as a result of COVID-19 (BloombergNEF 2021), but progress is also apparent if 2019 data are used. The 39% reduction shown in Figure 8 falls to 32% if 2019 data are used. Relative to emissions in 2005, the 24% reduction in 2020 falls to 14% if 2019 data are used.

Figure 9 depicts similar comparisons across the various energy subsectors, including both 2020 and 2019 data. The residential, commercial, industrial, and transportation subsectors include emissions related to all energy used, including electricity. Regardless of how the data are sliced, however, it is clear that electricity has outperformed in terms of decarbonization—differentially benefiting the end-use sectors that rely on electricity to a greater extent relative to other fuels.

CO_2 Reductions	2020 actual	2019 actual
Electricity		
Actual vs. 2020 projection	-52%	-46%
Actual change from 2005	-40%	-33%
Residential		
Actual vs. 2020 projection	-40%	-36%
Actual change from 2005	-29%	-24%
Commercial		
Actual vs. 2020 projection	-49%	-42%
Actual change from 2005	-32%	-22%
Industrial		
Actual vs. 2020 projection	-34%	-28%
Actual change from 2005	-22%	-15%
Transportation		
Actual vs. 2020 projection	-38%	-26%
Actual change from 2005	-18%	-3%

Notes: Residential, commercial, industrial, and transportation emissions include embedded emissions associated with electricity use. Negative numbers mean actual 2020/2019 was lower.

Figure 9. Sector-specific energy-related CO_2 emissions reductions

Beyond energy and considering total economy-wide greenhouse gas emissions, EPA estimates that net emissions declined from 6,577 MMT CO_2 equivalent ($CO_{2\text{-Eq}}$) in 2005 to 5,903 MMT $CO_{2\text{-Eq}}$ in 2018, a 10% reduction (EPA 2020). Others have estimated that emissions in 2020 fell to 5,160 MMT $CO_{2\text{-Eq}}$, partly due to COVID-19, 22% below 2005 levels (Larsen, Pitt, and Rivera 2021). As it relates to economy-wide emissions, we are unable to contrast the 2020 result with an earlier projection, because EIA does not offer an independent projection of economy-wide net greenhouse gas emissions. Clearly, however, accelerated decarbonization is needed to meet a midcentury, economy-wide net-zero emissions target.

4. The Next Half: Review of the Scientific Literature

Notwithstanding the slower pace of U.S. decarbonization outside the power sector, the nation has cut power-sector CO_2 emissions in half in 15 years, relative to earlier expectations—which has played a large role in reducing economy-wide emissions. Using other comparison points, the degree of reduction is more modest. Relative to power-sector CO_2 emissions in 2005, the decline through 2020 was 40% and through 2019 was 33%—on this latter metric, the United States is one third of the way towards zero emissions. Across all comparisons, however, the reductions are notable.

Past success does not trivialize the challenges that remain for further decarbonization in the power sector and beyond. Nor does it offer a specific roadmap for how best to achieve those additional reductions. Many challenges confront a zero-emissions pathway, and future strategies will likely differ from those of the past. For example, perhaps the United States has already picked the low-hanging fruit—the cheapest mitigation options. Coal-to-gas fuel switching cannot be part of the long-term solution set in a zero-carbon future absent carbon capture and storage. On the other hand, a variety of low-carbon technologies have advanced over the last 15 years, with costs dropping at a pace that few anticipated. Research, development, and demonstration may yield even more options in the future. In addition, the historical reductions have occurred without a consistent, comprehensive, and coordinated state and federal policy impetus. This is not to minimize the role of past or present policies—efficiency standards, building codes, ratepayer-funded efficiency programs, federal tax incentives, state renewable energy standards, and myriad other policies have been vital. However, these efforts have not been comprehensive and have varied considerably across sectors and states. A comprehensive array of coordinated national and state efforts would presumably have yielded even further reductions.

One thing is clear: If the United States is to complete the remaining power-sector decarbonization puzzle, it must once again beat business-as-usual projections. Figure 10 contrasts EIA's latest projection for power-sector emissions out to 2035 (EIA 2021) with a 2035 carbon-free target—in the latter case, presuming a linear trajectory for emissions reductions. EIA's reference-case scenario no longer features increased emissions, at least after a near-term post-COVID expected uptick, but neither does it approach deep decarbonization—reaching 1,180 MMT of CO_2 emissions in 2035. Other recent forecasts bracket the EIA projection: the latest National Renewable Energy Laboratory mid-case forecast shows higher emissions in 2035 (1,350 MMT), whereas a BloombergNEF forecast shows lower emissions (930 MMT) (Cole et al. 2020; BloombergNEF 2020). Achieving further deep reductions in power-sector emissions therefore means, first, absorbing the likely near-term rebound in emissions post-COVID, and then beating projected business-as-usual trajectories.

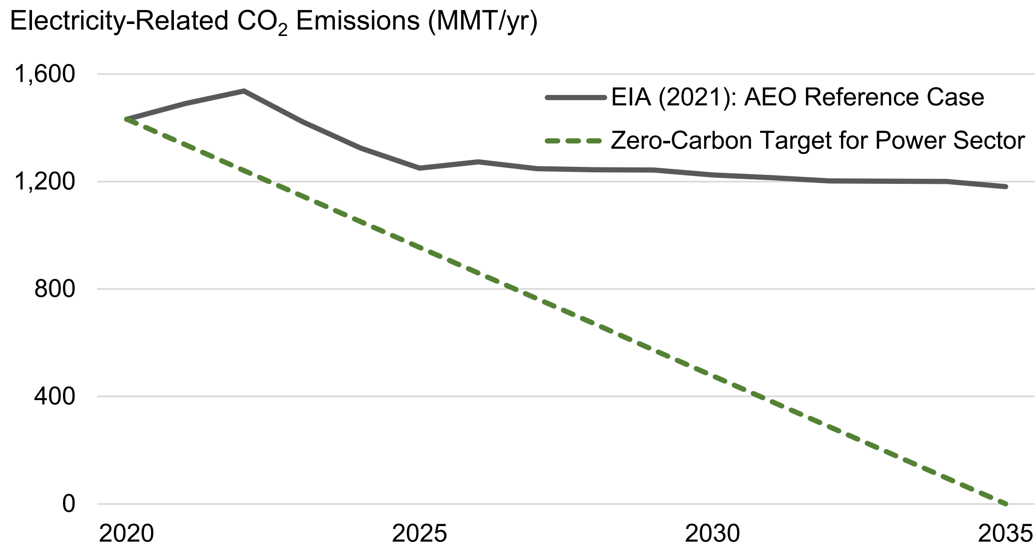


Figure 10. Projected power-sector CO_2 emissions vs. a zero-carbon target

Progress over the last 15 years suggests that concerted efforts could enable further deep emissions reductions—consistent with the scientific imperative (IPCC 2018; USGCRP 2018) and the growing number of state, municipal, utility, and corporate clean energy and carbon-reduction targets.[12] Meanwhile, the burgeoning literature on power-sector decarbonization, clean power growth, and net-zero emissions provides a possible roadmap for the remaining journey towards decarbonizing the power sector on a pathway to decarbonizing the economy as a whole.

To start, with the declining cost of solar, wind, and battery storage (Wiser et al. 2020; Bolinger et al. 2020; Schmidt et al. 2017; Mongird et al. 2020), the most recent analyses suggest that all three technologies are likely to play important roles in near-term efforts towards power-sector decarbonization (Jayadev, Leibowicz, and Kutanoglu 2020; Larsen et al. 2020; Phadke, Paliwal, et al. 2020; National Academies 2021a; Bistline et al. 2018; Williams et al. 2021; Jacobson 2020; IEA 2020; DNV GL 2020; E3 2020; DOE 2017a; Luderer et al. 2017; Pietzcker et al. 2017; Cole et al. 2020). More specifically, recent studies show that the combination of rapid deployment of these three resources along with existing low-carbon resources (nuclear, hydropower, geothermal, and other renewables) and energy efficiency can yield deep and relatively low-cost reductions in power-sector emissions (Jayadev, Leibowicz, and Kutanoglu 2020; Larsen et al. 2020; Phadke, Paliwal, et al. 2020; Williams et al. 2021; National Academies 2021a; E3 2020). Given advancements in wind, solar, and battery technologies, decarbonizing the power sector now appears to be more cost-effective than expected just a few years ago. The studies also find that electric grid reliability need not be sacrificed, assuming the myriad significant challenges noted below are overcome. Many of the studies suggest that, collectively, these low-carbon resources could reliably meet as much as 70%–90% of power supply needs at low

[12] See, for example: https://www.ncsl.org/research/energy/greenhouse-gas-emissions-reduction-targets-and-market-based-policies.aspx; https://www.c2es.org/document/greenhouse-gas-emissions-targets/; https://www.cesa.org/projects/100-clean-energy-collaborative/; https://www.brookings.edu/research/pledges-and-progress-steps-toward-greenhouse-gas-emissions-reductions-in-the-100-largest-cities-across-the-united-states/; https://sepapower.org/utility-transformation-challenge/utility-carbon-reduction-tracker; https://rebuyers.org/deal-tracker/.

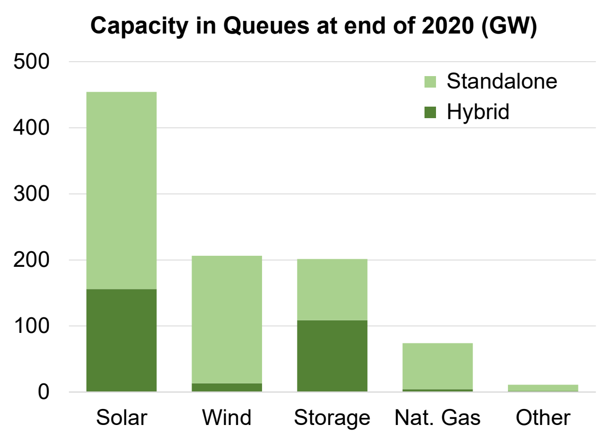
incremental cost. The expected incremental costs can also be viewed within the context of the offsetting benefits of reduced climate damages and reduced premature deaths and sickness from air pollution (Phadke, Paliwal, et al. 2020; Millstein et al. 2017; Buonocore et al. 2019).

Queued Up: Can Renewables Deploy at the Pace Suggested by Recent Research?

Research focused on a 90% clean electricity scenario calls for the addition of 1,100 GW of wind and solar by 2035, along with 150 GW of 4-hour batteries (Phadke, Paliwal, et al. 2020). Other recent research exploring net-zero economy-wide emissions pathways by mid-century identifies similar levels of wind and solar buildout by 2035, with deployment expanding even faster through 2050 as the electrification of other energy uses proliferates (Williams et al. 2021; Larsen et al. 2020).

These figures imply an average combined wind-plus-solar build rate over the next 15 years of about 70 GW/year. This is roughly double the 34 GW brought online in 2020 (BloombergNEF 2021) and would require careful land-use planning, supply-chain management, expanded transmission infrastructure, and more. However, past experience and current commercial interest suggests a buildout of this magnitude may be feasible. From 2017 to 2019, for example, wind and solar were added to the U.S. grid at an average pace of 17 GW per year. In 2020, that figure doubled—to 34 GW. From that narrow historical perspective, another doubling seems plausible.

In addition, at the end of 2020, about 660 GW of proposed wind (207 GW) and solar (454 GW) projects were seeking transmission interconnection, more than half of what would be needed to meet the 2035 deployment figures reported above. Approximately 570 GW of this proposed capacity has requested to interconnect and come online before the end of 2025. Storage capacity in the queues—both standalone and as part of hybrid projects in which storage is combined with other generation sources such as solar—totaled about 200 GW, consistent with what might be needed under a power-sector deep-decarbonization pathway.



As such, more than half of the clean energy resources needed to approach a zero-carbon power-sector target for 2035 are already in the development pipeline. To be fair, many of these specific projects are unlikely to move forward, because cancellation rates are high under current transmission interconnection procedures. Revised interconnection and transmission planning approaches are likely needed to cost-effectively deploy a sizable fraction of the wind and solar in the queues (Caspary et al. 2021). At a minimum, however, these data demonstrate the high level of current commercial interest among solar and wind developers, and they illustrate how rapidly these industries have been able to scale historically in the United Sates.

Quickly and dramatically expanding wind, solar, and storage to become major contributors in the power system requires significant upscaling of past deployment levels. This effort will not be easy, and entails numerous challenges and potential solutions, such as the following:

- As weather-dependent, inverter-based resources including solar and wind progressively deploy, extensive attention to grid infrastructure and operations is required to ensure power system flexibility, reliability, resilience, stability, and security (DOE 2017a; 2017b; Holttinen et al. 2020; Frew et al. 2019; National Academies 2021b).

- Battery storage is likely to be a core response to these concerns in the near term, but many forms of flexibility can be leveraged—not only other forms of storage, but also load responsiveness and supply flexibility (Williams et al. 2021; Jenkins, Luke, and Thernstrom 2018; Jacobson 2020; Gorman et al. 2020; Strbac et al. 2020).
- Significant new transmission infrastructure (and more-efficient use of existing assets) may be needed to integrate growing shares of wind and solar; interconnection processes may need to be reformed (Williams et al. 2021; Joskow 2020; Brown and Botterud 2020; MacDonald et al. 2016; Bloom et al. 2020; National Academies 2021b; ESIG 2021; Caspary et al. 2021).
- Wholesale power markets may need to transform to accommodate the changing supply and demand conditions; new technology standards and capabilities as well as planning and operating models and procedures would be needed (Ela et al. 2021; Holttinen et al. 2020; Frew et al. 2019; DOE 2017a; EPRI 2021).
- Siting and permitting innovation, streamlining, and procedures—at the local, state, and national levels—will be needed to manage a step-change increase in new supply and delivery infrastructure (Williams et al. 2021; Larsen et al. 2020; Mai et al. 2021). Human use and ecological conflicts must be mitigated and managed (National Academies 2021a; Rand and Hoen 2017).
- Challenging issues related to energy and environmental justice, the workforce, and supply-chain development must be managed (Carley and Konisky 2020; Hertwich et al. 2015; Eisen and Welton 2019; National Academies 2021a; Larsen et al. 2020; National Academies 2021b; Brown et al. 2020).
- Aggressively pursuing energy efficiency and demand flexibility—in part through grid-interactive efficient buildings—can address some of these challenges by reducing the need for new supply and delivery infrastructure and providing another form of flexibility (Williams et al. 2021; DOE 2017a; Langevin, Harris, and Reyna 2019; Goldman, Murphy, et al. 2020; Neukomm, Nubbe, and Fares 2019).

Even if these challenges are overcome, for power systems relying on increasing volumes of wind, solar, and batteries, the incremental cost of carbon reduction begins to rise more steeply as emissions decline and eventually approach zero (Jayadev, Leibowicz, and Kutanoglu 2020; Dowling et al. 2020; Williams et al. 2021; Larsen et al. 2020; Jenkins, Luke, and Thernstrom 2018; Sepulveda et al. 2018).[13] The precise point at which the cost inflection occurs varies based on study assumptions and context. Transmission and demand flexibility can delay increases in the cost of carbon reduction, as can over-building renewable energy and maximizing inter-sectoral energy linkages (Williams et al. 2021). However, the condition remains: As weather-dependent resources, wind and solar require complementary flexible resources that are available on demand during prolonged periods of low wind and solar output.

That residual need is not fully served by current battery technology, but it could in principle be met with any number of technologies—such as longer-duration storage, hydrogen or synthetic fuels, biofuels, fossil or biomass with CO_2 capture and sequestration or use, nuclear, geothermal, and concentrating solar-thermal power with storage (Dowling et al. 2020; Williams et al. 2021; Jenkins, Luke, and Thernstrom 2018; Jacobson 2020; Larsen et al. 2020; E3 2020; Sepulveda et al. 2018; J. Guerra et al.

[13] To be fair, this concept of rising marginal costs as emissions approach zero is not solely applicable to power systems that rely heavily on wind and solar.

2020; Quarton et al. 2019; Sepulveda et al. 2021). Many of these options have a relatively high cost, especially if run infrequently and primarily to fill in for periods of low solar and wind output. However, if used to serve only a portion of electricity demand, even high per-unit-output costs need not dramatically raise customer bills (Phadke, Aggarwal, et al. 2020; Larsen et al. 2020; Williams et al. 2021). Moreover, depending on how these technologies advance, direct-air capture of CO_2, other net-negative-emissions options, or even decarbonization options outside the power sector may serve as a backstop for jurisdictions seeking zero-carbon power systems (Williams et al. 2021; Larsen et al. 2020; National Academies 2021a). Further research, development, and demonstration are needed in relation to the numerous technologies that might provide on-demand zero-carbon power as well as negative-emissions technologies, to enable technology portfolios that minimize incremental costs (Jenkins, Luke, and Thernstrom 2018; Sepulveda et al. 2018; National Academies 2021a; 2021b). Were these additional technology solutions to become available at attractive costs, even faster and more aggressive decarbonization would be feasible, at still-lower power-sector costs and with even-greater health and climate benefits (Dowling et al. 2020; Bistline and Blanford 2020; Budinis et al. 2018; Bui et al. 2018; NEI 2020; Sepulveda et al. 2021).

The critical role of the electricity delivery system also should not be overlooked. The electric grid is undergoing its own transformation, from a passive, more-centralized traditional system to one that is increasingly dynamic, flexible, and able to integrate a large number of inverter-based resources. Without investments in new grid technologies, infrastructure improvements, and operational changes that will facilitate this transition, the grid itself could constrain the potential for future carbon reductions (DOE 2017a; National Academies 2021b; 2021a).

The power sector is widely viewed as the cornerstone for economy-wide decarbonization, in part because key technologies for power-sector decarbonization are already available at increasingly low cost (DOE 2017a; Wiser et al. 2020; Bolinger et al. 2020; Mongird et al. 2020). It is also because low-carbon power systems can enable broader carbon reductions though electrification of other energy end uses, most prominently through electrified transport, residential and commercial heating, and industry (National Academies 2021a; Larsen et al. 2020; Williams et al. 2021; Murphy et al. 2020; Jacobson 2020; IEA 2020). Of course, electrification alone will not yield a zero-carbon economy; many applications simply cannot be electrified at reasonable cost, given current technology. Though the focus of this report is on the power sector, tackling carbon emissions through other solutions where electrification is not realistic and reducing other greenhouse gases will be essential—in addition to accelerating electrification—if economy-wide net-zero targets are to be achieved (Williams et al. 2021; Larsen et al. 2020; National Academies 2021a; E3 2020; Clack et al. 2020). These additional emissions sources are sizable and may prove more challenging to decarbonize. They will require a different set of technologies, policies, and conditions than those covered in this report.

To conclude, though this basic literature-informed roadmap for the power sector appears clear, at least in broad terms and in the very near term, the devil is in the details and the challenges are substantial. Moreover, if the past 15 years of power-sector decarbonization provide a guide, then two central lessons emerge. First, policy and technology advancement are imperative to achieving significant emissions reductions. Second, our ability to predict the future is limited, and so it will be crucial to adapt as we gain policy experience and as technologies advance in unexpected ways.

Acknowledgments

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Appendix A: Comparison of Past Carbon Emission Projections

Figure A-1 contrasts the EIA AEO 2005 reference-case projection for power-sector CO_2 emissions with other projections from the same period. For the U.S. Department of Energy, we show the "no new wind" reference case from DOE (2008). For the historical extrapolation, we estimate the average rate of growth in power-sector emissions from 1995 to 2005 and use that growth rate to project emissions to 2025. Results for the other five forecasts are summarized in EIA (2005), for 2015 and/or 2025 (Global Insight, Inc. 2004; Energy Ventures Analysis, Inc. 2004; PIRA Energy Group 2004; Strategic Energy and Economic Research, Inc. 2004; 2004; Energy and Environmental Analysis, Inc. 2004). That summary does not include CO_2 emissions but does include projections for generation amounts for coal, petroleum, and natural gas. We estimate CO_2 emissions by applying emissions rates (MMT per billion kWh) from EIA (2005) to the generation amounts from each of these five forecasts. We then add a small amount of "other" emissions as projected by EIA, to enable apples-to-apples comparisons.

Across all seven of these projections, the maximum deviation from the EIA AEO 2005 reference case over the 2015–2025 period is +6% to -10%.

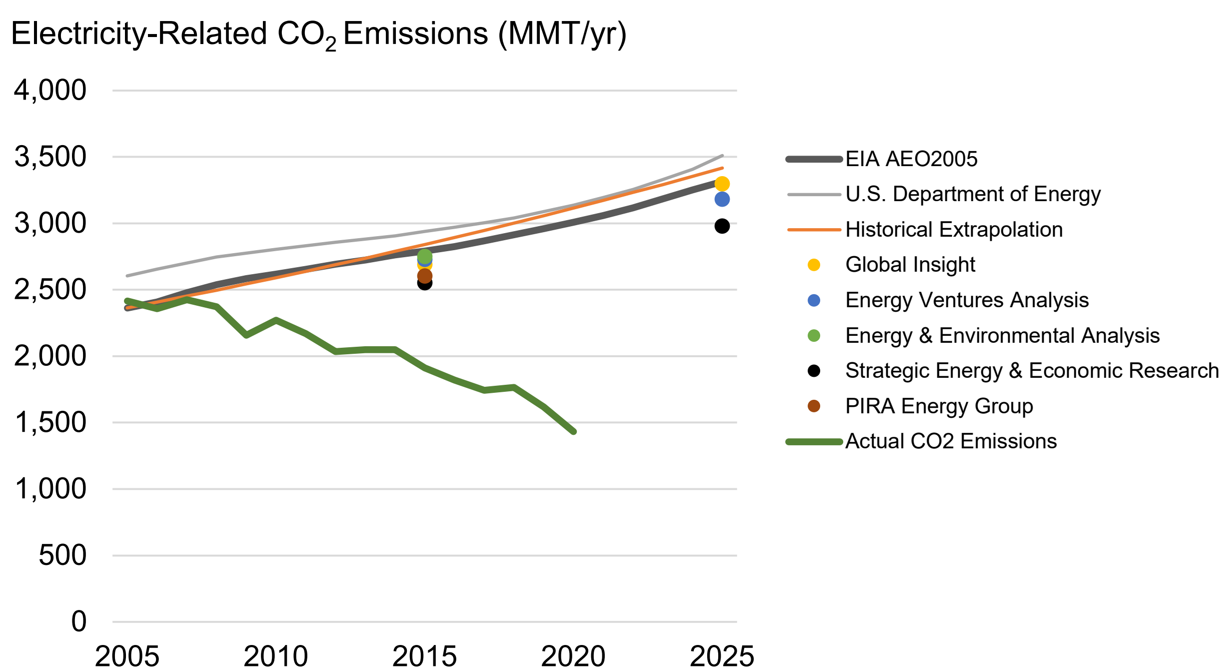

Figure A-1. Projected power-sector CO_2 emissions from the mid-2000s