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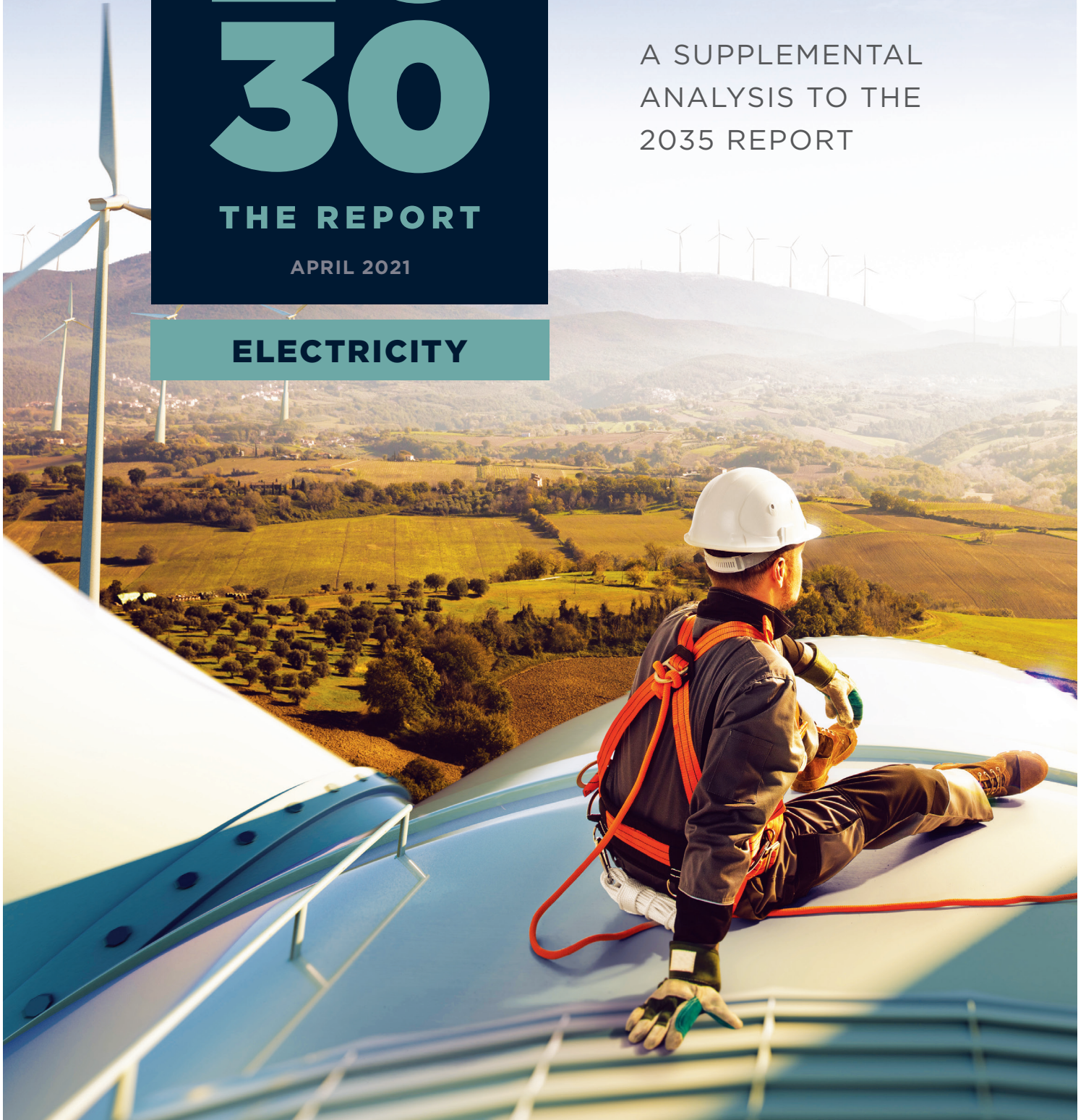
THE REPORT

APRIL 2021

ELECTRICITY

POWERING AMERICA'S CLEAN ECONOMY

A SUPPLEMENTAL
ANALYSIS TO THE
2035 REPORT



2030 REPORT: POWERING AMERICA'S CLEAN ECONOMY

A SUPPLEMENTAL ANALYSIS TO THE 2035 REPORT

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EXECUTIVE SUMMARY

Global carbon emissions must be halved by 2030 to limit warming to 1.5°C and avoid catastrophic climate impacts. As the nation coalesces around 2035 as the target year for power sector decarbonization, rapid progress must be made in the next decade in order for this target to remain in reach. The United States has already committed to reducing its economy-wide greenhouse gas emissions in 2030 by 50-52 percent from 2005 levels. Ambitious power sector decarbonization enables economy-wide decarbonization of the building, industrial, and transportation sectors, setting the United States on a 1.5°C pathway commensurate with international climate goals.

Since the release of the 2035 Report: Plummeting Solar, Wind, and Battery Costs Can Accelerate Our Clean Electricity Future (“2035 Report”), federal legislation, as well as President Joe Biden’s American Jobs Plan and the U.S. Nationally Determined Contribution to the Paris Agreement, have catapulted ambitious clean electricity standards (CES) into the national policy discourse. These policies range in their ambition, but modeling of the U.S. NDC to reduce economy-wide emissions 50 percent from 2005 levels by 2030 converges with the need to reach at least 80 percent clean electricity by 2030.

Several recent studies have analyzed aggressive penetration of renewable energy in the medium- to long-term, including our 2020 release of the 2035 Report. However, very few have assessed the technical and operational feasibility and economic viability of aggressive power sector decarbonization (80 percent or more) in the medium-term (2030 timeframe). Plummeting costs for wind and solar energy have dramatically changed the prospects for rapid, cost-effective expansion of renewable energy. At the same time, battery energy storage has become a viable option to cost-effectively integrate high levels of wind and solar generation into electricity grids.

This report uses the latest renewable energy and battery cost data to demonstrate the technical and economic feasibility of achieving 80 percent clean (carbon-free) electricity in the United States by 2030. Two central cases are simulated using state-of-the-art capacity-expansion and production-cost models: The No New Policy case assumes continuation of current state and federal policies; and the 80% Clean case¹ requires that a national 80 percent clean electricity share is reached by 2030, along with aggressive transportation electrification where electric vehicles (EVs) constitute 100 percent of new U.S. light-duty vehicle sales and 80 percent of medium- and

¹ By 80% Clean, we mean that 80% of total annual US electric power supply comes from zero emission power generators (wind, solar, hydro, nuclear, battery storage (2-10 hour), biomass, and fossil fuel plants with carbon capture and storage).

heavy-duty vehicle sales by 2030 as outlined in the 2035 Report 2.0: Plummeting Costs and Dramatic Improvements in Batteries can Accelerate our Clean Energy Future.

This report uses nearly identical methodology to the original 2035 Report and 2035 Report 2.0, and can be viewed as a supplemental analysis that focuses on the implications of an accelerated interim target, coupled with aggressive end-use electrification.

STRONG POLICIES ARE REQUIRED TO CREATE AN 80% CLEAN GRID BY 2030

The 80% Clean case assumes strong policies drive 80 percent clean electricity by 2030. The No New Policy case achieves only 45 percent clean electricity in 2030 (Figure ES-1). Our modeling shows that without the implementation of a binding national Clean Electricity Standard (CES), rapid near-term power sector decarbonization is not achieved. This outcome would have negative effects on related sectors of the economy (e.g. transportation, industry, and buildings) which must electrify in parallel to support economy-wide decarbonization.

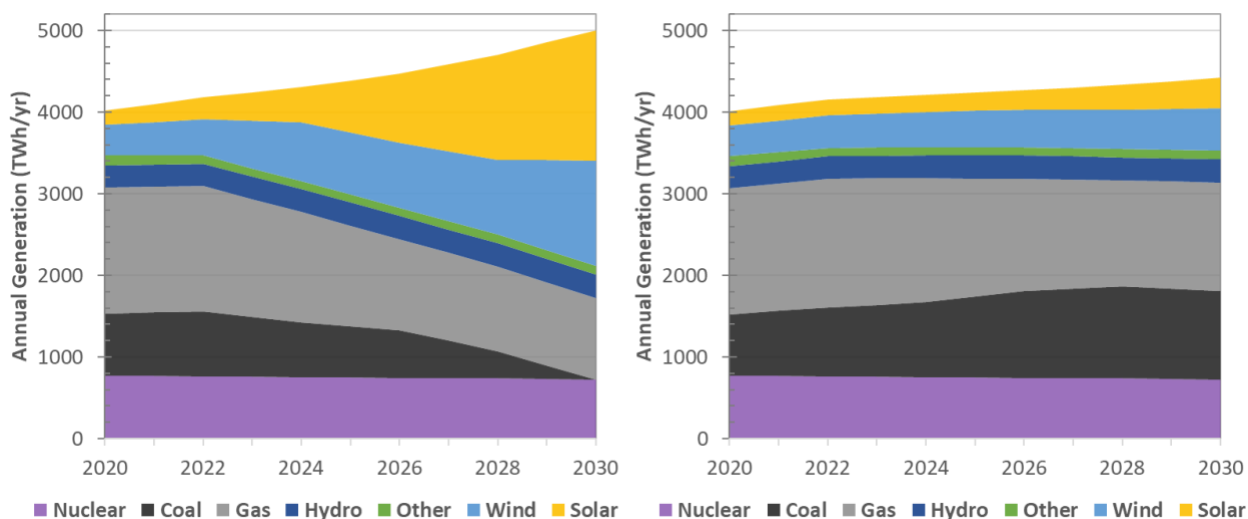


Figure ES-1. Generation mixes for the 80% Clean Case (left) and No New Policy Case (right), 2020–2030.

THE 80 PERCENT CLEAN GRID IS DEPENDABLE WITHOUT COAL PLANTS OR NEW NATURAL GAS PLANTS DESPITE SIGNIFICANT ELECTRICITY DEMAND FROM TRANSPORTATION ELECTRIFICATION

Commensurate with economy-wide decarbonization goals, our modeling assumes rapid transportation electrification targets as outlined in the 2035 Report 2.0 DRIVE Clean case (100 percent electric light-duty vehicle sales and 80 percent electric medium-duty vehicle/heavy-duty truck sales by 2030, which grows to 100 percent electric vehicle sales by 2035). We also assume

significant electrification of buildings and industrial end uses as envisioned in NREL’s Electrification Futures Study (EFS) High Electrification Scenario. As a result, electricity demand increases at an average annual growth rate of 2 percent from 2020-2030 (Figure ES-2).

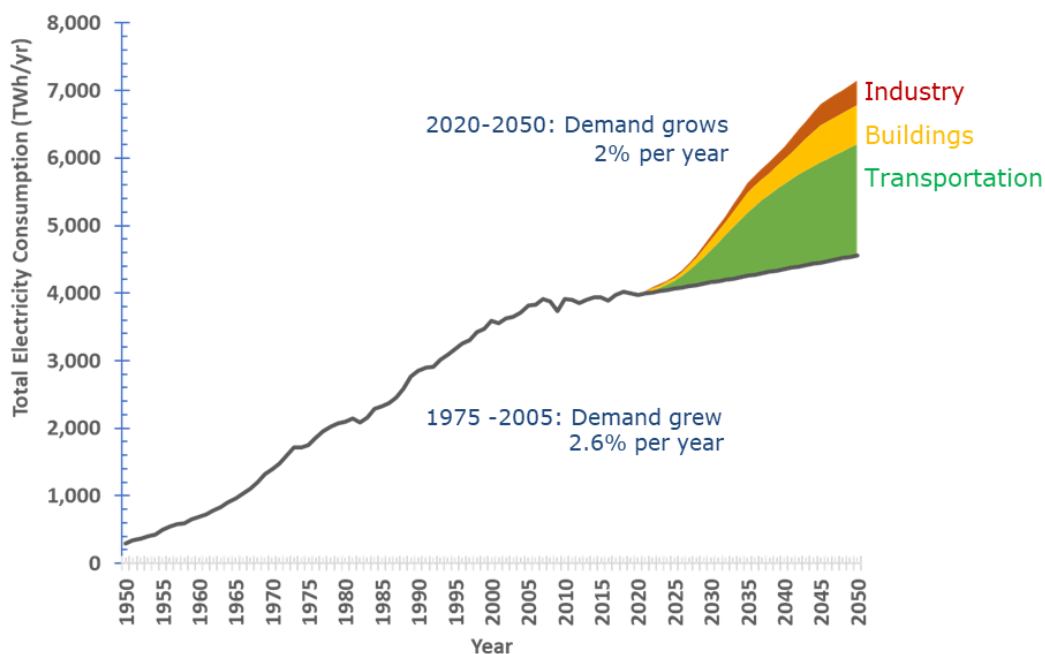


Figure ES-2. Total electricity consumption – historical and with additional electrification

Even accounting for rapid transportation, building, and industrial electrification, the 80 percent clean grid is dependable, providing adequate energy in every hour of the year to meet demand. Wind, solar, and batteries provide about 60 percent of daily generation, while hydropower and nuclear provide 20 percent. Under the 80% Clean case, existing hydropower and nuclear capacity are retained (except for planned retirements), while all existing coal plants are retired by 2030, and no new fossil fuel plants are built. During periods of very high demand or very low renewable generation, existing natural gas, hydropower, and nuclear plants combined with battery storage, cost-effectively compensate for mismatches between demand and wind or solar generation. Generation from natural gas plants would constitute about 20 percent of total annual electricity generation. This is about 30 percent lower than gas generation today.

ELECTRICITY COSTS FROM THE 80 PERCENT CLEAN GRID DO NOT INCREASE FROM TODAY’S COSTS

The cost to generate and deliver electricity in 2030 would be the same as it is today, largely due to low renewable energy and battery storage costs (Figure ES-3). As the electric grid decarbonizes, a large amount of low-cost wind, solar, and battery storage is built to meet the rising clean electricity standard. Relying on natural gas for only 20 percent of generation avoids large investments for infrequently used capacity, helping to avoid major new stranded-asset costs.

Retaining some natural gas generation reduces the total amount of renewable energy and long-duration storage capacity needed—helping to achieve 80 percent clean electricity and keep costs down. While still the same as today’s costs, wholesale electricity costs are 6 percent higher under the 80% Clean case than under the No New Policy case in 2030. However, this comparison does not account for large household and business savings from vehicle electrification, nor the value of emissions reductions or avoided health costs under the 80% Clean case. When health and environmental externalities are included, 2030 wholesale electricity prices in the 80% Clean case are 31 percent lower than the No New Policy case.

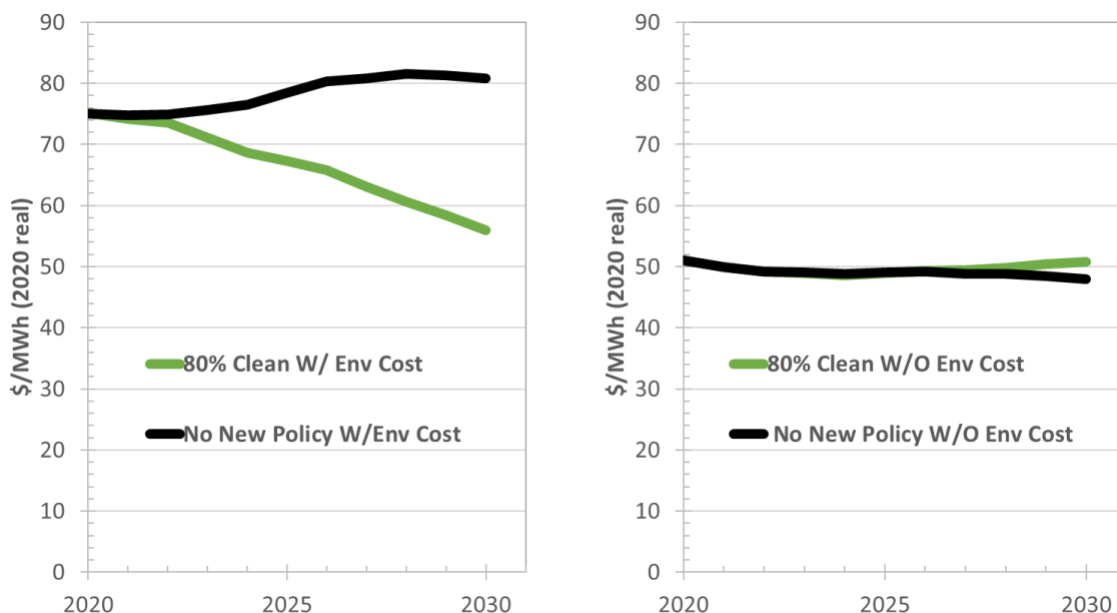


Figure ES-3. Wholesale electricity costs with- and without environmental costs, for the 80% Clean and No New Policy Cases

THE 80 PERCENT CLEAN GRID AVOIDS \$1.7 TRILLION IN HEALTH AND ENVIRONMENTAL DAMAGES, INCLUDING 93,000 PREMATURE DEATHS, THROUGH 2050

The 80% Clean case, coupled with accelerated transportation electrification, results in large environmental and health benefits largely driven by reduced mortality related to electricity generation and vehicular pollution (Figure ES-4). Relative to the 2005 levels, the 80% Clean plus DRIVE Clean case reduces carbon dioxide (CO₂) emissions 84 percent and 33 percent by 2030 from the power sector and transportation sectors, respectively. The combination of these two policies alone results in a 42 percent reduction in economy-wide emissions from 2005 levels by 2030. Coupled with rapid buildings and industrial electrification, economy-wide CO₂ emissions are reduced 50 percent by 2030 from 2005 levels (Figure ES-5). Accelerated power sector decarbonization reduces exposure to fine particulate (PM_{2.5}) matter by reducing nitrogen oxide (NO_x) and sulfur dioxide (SO₂) emissions from the power sector by 90 percent and 98 percent,

respectively relative to 2019 levels and 95 percent and 99 percent, respectively, relative to the 2005 levels (Figure ES-5).² As a result, the 80% Clean case avoids over \$1.7 trillion in health and environmental costs, including 93,000 avoided premature deaths, through 2050 (Figure ES-6). These savings equate to roughly \$25/MWh (or 2.5 cents/kWh) of wholesale electricity costs, which makes the 80% Clean case much lower cost than No New Policy. The environmental benefits of transport electrification are equally significant. Between 2020 and 2050, vehicle electrification avoids over 150,000 additional premature deaths and over \$1.3 trillion in environmental costs. Power sector decarbonization and transportation electrification together avoids over 240,000 premature deaths and \$3 trillion in environmental costs by 2050.

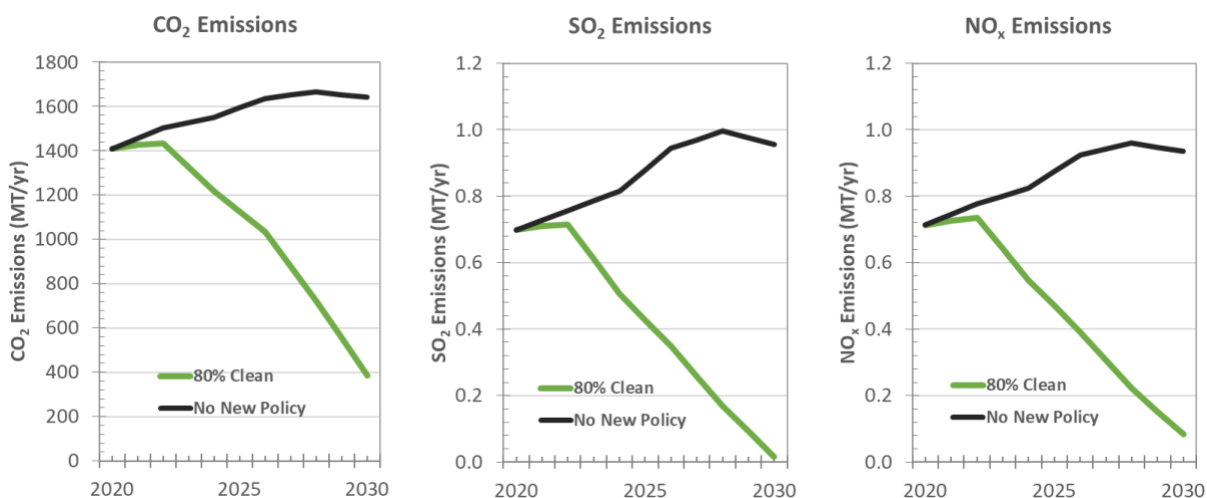


Figure ES-4. Emissions of CO₂, SO₂, and NO_x from power sector in the 80% Clean and No New Policy Cases, 2020–2030

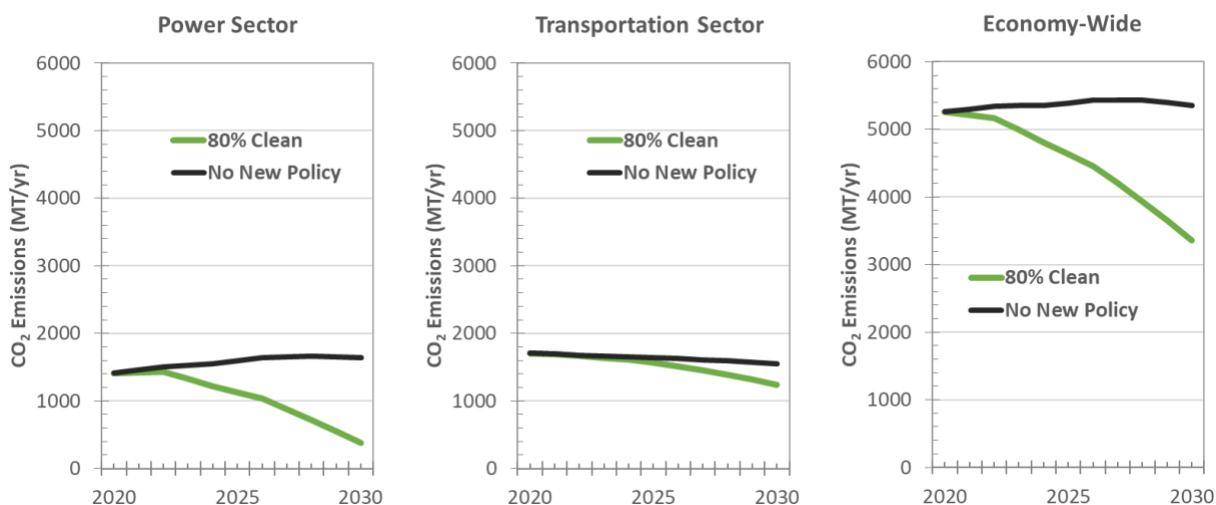


Figure ES-5. Power sector (left), transportation sector (center), and economy-wide (right) CO₂ emissions in the 80% Clean and No New Policy Cases, 2020-2030.

² Primary PM_{2.5} emissions reductions are not estimated by the model, resulting in a conservative estimate of reduced PM_{2.5} exposure.

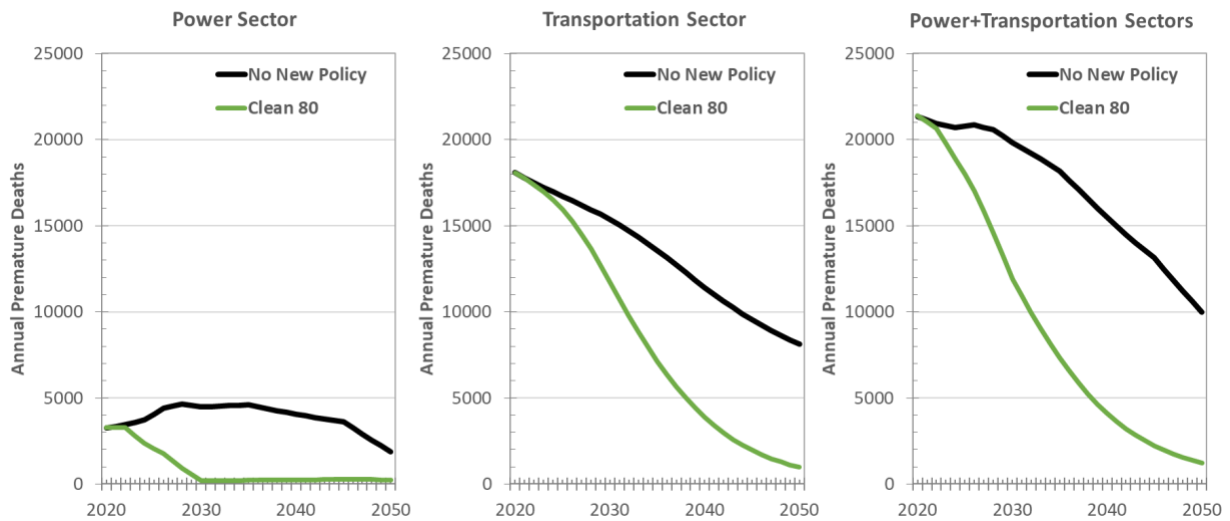


Figure ES-6. Annual premature deaths in the power (left), transportation (center), and combined power and transportation sectors (right) in the 80% Clean and No New Policy Cases, 2020–2050.

SCALING-UP RENEWABLES TO ACHIEVE 80 PERCENT CLEAN ENERGY BY 2030 IS FEASIBLE DESPITE SIGNIFICANT ADDITIONAL ELECTRICITY DEMAND

To achieve a national 80 percent clean electricity share by 2030, 950 GW of new wind and solar generation and over 225 GW of battery storage capacity must be built, averaging about 120 GW of new capacity per year (Figure ES-7). While challenging, domestic and international precedent suggests that strong supporting federal and state policy can help the U.S. achieve this goal. For example, China added 120 GW of new wind and solar capacity in 2020. While once unattainable, new renewable resources can be built cost-effectively in nearly every region of the country, suggesting that such a rapid expansion of new deployments is possible.

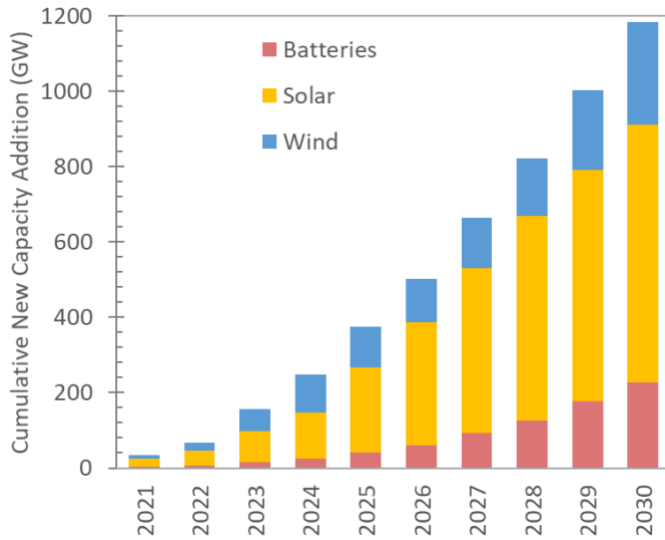


Figure ES-7. Cumulative new capacity additions in the 80% Clean Case, 2020–2030

THE 80 PERCENT CLEAN GRID DRIVES SIGNIFICANT INVESTMENT IN ALL U.S. REGIONS

Achieving 80 percent clean electricity by 2030 requires \$1.5 trillion in clean energy capital investments and \$100 billion in transmission capital investments. Because of the steep decline in renewable energy costs, these new investments are widely spread across the country, including in states traditionally dominated by coal and gas generation (Figure ES-8). The availability of low-cost renewables suggests that the vast majority of the nation can take advantage of new job creation,

local investment, infrastructure spending, and lower electricity costs, all while supporting an ambitious, national clean electricity standard.

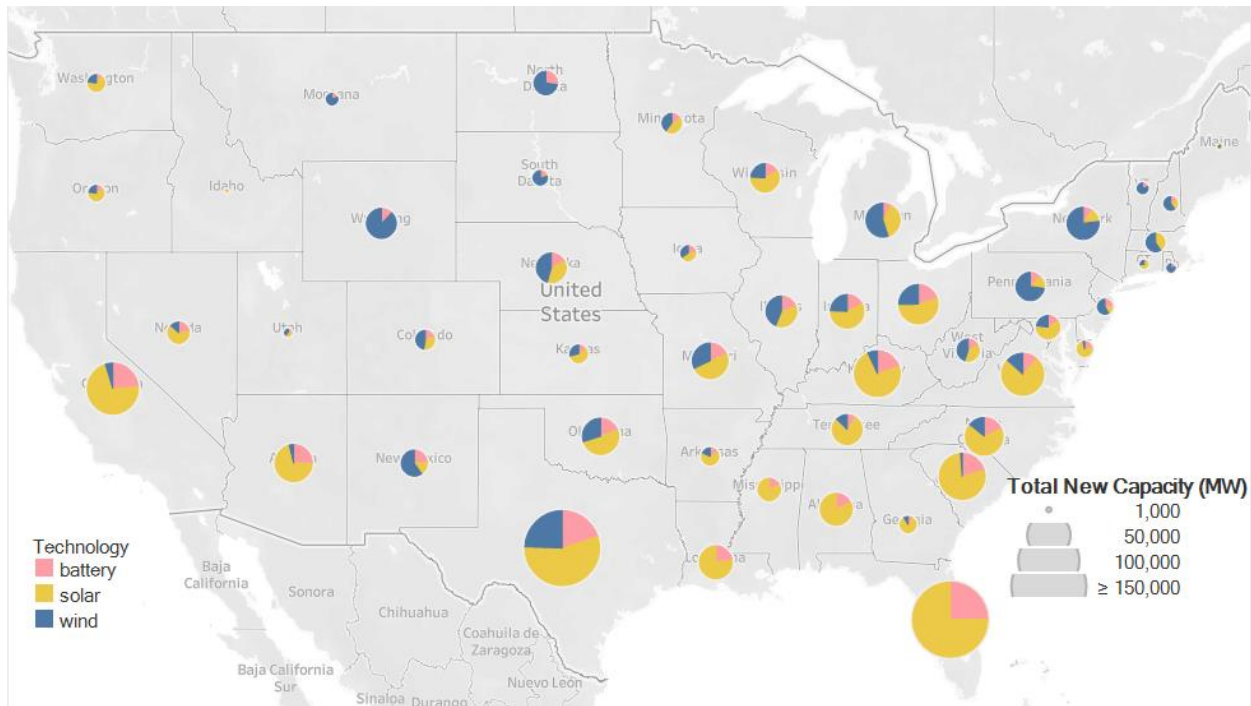


Figure ES-7. New Capacity Additions in the 80% Clean Case by 2030

ACCELERATING THE CLEAN ENERGY FUTURE

The federal government should establish an interim power sector decarbonization target year of 2030 to help align expectations for 100 percent clean electricity and inform the policy dialogue needed to achieve such an ambitious goal. Aiming for 80 percent clean electricity by 2030 is also critical for achieving rapid, cost-effective electrification of other sectors such as transportation, buildings, and industry. By 2030, emerging technologies such as long-duration storage, stationary fuel cells, CCUS, and others should be mature enough to begin to replace the remaining natural gas generation as the nation accelerates toward 100 percent clean electricity. Reaching 80 percent zero-carbon electricity in the U.S. by 2030, coupled with aggressive transportation, buildings, and industrial electrification, would achieve a nearly 50 percent reduction in economy-wide CO₂ emissions from 2005 levels and put the U.S. on a 1.5°C consistent pathway.

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1. INTRODUCTION

Global carbon emissions must be halved by 2030 to limit warming to 1.5°C and avoid catastrophic climate impacts. As the nation coalesces around 2035 as the target year for power sector decarbonization, rapid progress must be made in the next decade in order for this target to remain in reach. The United States has already committed to reducing its economy-wide greenhouse gas emissions in 2030 by 50-52 percent below 2005 levels. Ambitious power sector decarbonization enables economy-wide decarbonization of the building, industrial, and transportation sectors, setting the U.S. on a 1.5°C pathway commensurate with international climate goals.

Since the release of the 2035 Report: Plummeting Solar, Wind, and Battery Costs Can Accelerate Our Clean Electricity Future (“2035 Report”), federal legislation, as well as President Joe Biden’s American Jobs Plan and the U.S. Nationally Determined Contribution to the Paris Agreement, have catapulted ambitious clean electricity standards (CES) into the national policy discourse. These policies range in their ambition, but modeling of the U.S. NDC to reduce economy-wide emissions 50 percent from 2005 levels by 2030 converges with the need to reach at least 80 percent clean electricity by 2030.

Several recent studies have analyzed the impacts of high renewable energy power systems in the medium- to long-term, including our 2020 release of the 2035 Report. However, very few have utilized comprehensive grid modeling to assess the technical and operational feasibility and economic viability of aggressive grid decarbonization (80 percent or more) in the medium-term (2030 timeframe). This report uses nearly identical methodology to the original 2035 Report to investigate the impact of 80 percent CES by 2030, and can be viewed as a supplemental analysis that focuses on the implications of an accelerated interim target.

As the 2035 Report explored, plummeting costs for wind and solar energy have dramatically changed the prospects for rapid, cost-effective expansion of renewable energy. At the same time, battery energy storage has become a viable option to cost-effectively integrate high levels of wind and solar generation into electricity grids and rapidly transition to electric vehicles.

This report uses the latest renewable energy and battery cost data to demonstrate the technical and economic feasibility of achieving 80 percent clean (carbon-free) electricity in the United States by 2030—much more quickly than projected by most recent studies. Two central cases are simulated using state-of-the-art capacity-expansion and production-cost models:

- The No New Policy case assumes continuation of current state and federal policies.
- The 80% Clean case requires that a national 80 percent clean electricity share is reached by 2030, along with aggressive transportation electrification as outlined in the 2035

Report 2.0 (Phadke et al, 2021). Generation from any resource that does not produce direct carbon dioxide (CO₂) emissions is considered clean in this analysis, including generation from nuclear, hydropower, wind, solar, biomass, geothermal, and fossil fuel plants with carbon capture and storage.

Consideration of the accelerated 2030 timeframe helps align expectations for power-sector decarbonization with climate realities while informing the policy dialogue needed to achieve such an ambitious goal. This report's target of 80 percent clean electricity (rather than 100 percent) by 2030 is also important for envisioning decarbonization at a pace more rapid than considered in previous studies. Achieving deep power sector decarbonization in 2030 will likely increase the speed and cost-effectiveness of pervasive, cross-sector decarbonization.

After a brief description of methods and data, the key findings of the 2030 Report are summarized. A companion report from Energy Innovation surveys other credible analyses of rapid electricity sector decarbonization in the U.S., and argues in support of a federal 80 percent by 2030 CES (Energy Innovation 2021).

2. METHODS AND DATA SUMMARY

We performed power sector modeling using nearly identical methods to the original 2035 Report, which benefitted from consultation with a technical review committee consisting of experts from utilities, universities, and think tanks. We employed state-of-the-art models, including NREL's Regional Energy Deployment System (ReEDS) capacity-expansion model and Energy Exemplar's PLEXOS electricity production-cost model, in conjunction with publicly available generation and transmission datasets. Forecasts of renewable energy and battery cost reductions were based on NREL's ATB 2019 (NREL 2019).³ We used these data and methods to analyze two central cases:

- **No New Policy:** Assumes current state and federal policies and forecasted trends in technology costs and electrification.⁴ In regard to transportation electrification, this scenario assumes the continuation of existing (2020) state and federal policies and assumes the extant barriers to EV adoption persist. In this scenario, EVs constitute about 22 percent of new light-duty vehicle (LDV) sales, 10 percent of new medium-duty vehicle (MDV) sales, and 5 percent of new heavy-duty truck (HDT) sales in 2030. The scenario is based on projections from Bloomberg New Energy Finance (BNEF), which suggest that—absent policy intervention—internal combustion engine (ICE) vehicles will constitute 46 percent of the total on-road vehicle population by 2050 (McKerracher 2021).
- **80% Clean:** Requires a national 80 percent clean electricity share by 2030. All coal-fired power plants are assumed to retire by 2030. On the vehicle electrification side, we project that electric vehicles constitute 100 percent of new LDV sales and 80 percent of new MDV and HDT sales in the U.S. by 2030, as modeled in the DRIVE Clean scenario in the 2035 Report 2.0 (Phadke et al, 2021). The DRIVE Clean scenario assumes new policies are adopted and market forces quickly shift to overcome EV-related barriers. By 2050, EVs constitute 97% of all on-road vehicles. We also include electrification of buildings and industries, per NREL's Electrification Futures Study High Electrification Scenario.

We analyzed how the 80% Clean case would respond to periods of extraordinarily low renewable energy generation and/or high demand in order to ensure that a system with 80 percent non-fossil supply meets demand in every hour. To assess system dependability, defined as the ability to meet power demand in every hour of the year, we simulated hourly operation of the U.S. power system over 60,000 hours (each hour in 7 weather years). For each of these hours, we confirmed that electricity demand is met in each of the 134 regional zones (subparts of the U.S. power system represented in the model) while abiding by several technical constraints (such as ramp rates and

³ The cost reductions detailed in this report refer primarily to utility-scale PV, wind, and battery storage. Distributed PV is considered in this analysis, serving as an input to the ReEDS model based on NREL modeling assumptions. In 2030, under the 80% Clean case, there are approximately 48 GW of distributed PV, representing approximately 1.5% of total energy generation.

⁴ ReEDS considers relevant state and federal policies, such as state Renewable Portfolio Standards, as of early 2020.

minimum generation) for more than 15,000 individual generators and 310 transmission lines. Further work is needed to assess issues such as the effect of the 80% Clean case on loss of load probability, system inertia, and alternating-current transmission flows.

We also considered three primary sets of future renewable energy and battery storage cost assumptions (Figure 2):

- Low-Cost: NREL ATB low-case assumptions, assuming 40 percent to 50 percent cost reductions for PV, wind, and storage by 2030 (compared with 2020).
- Base-Cost: modified NREL ATB mid-case assumptions, assuming 2021 costs begin at the ATB low-case assumptions, but post-2021 cost reductions are in line with the ATB mid-case.
- High-Cost: NREL ATB mid-case assumptions, including assumed 2020 costs that are higher than actual 2020 costs.

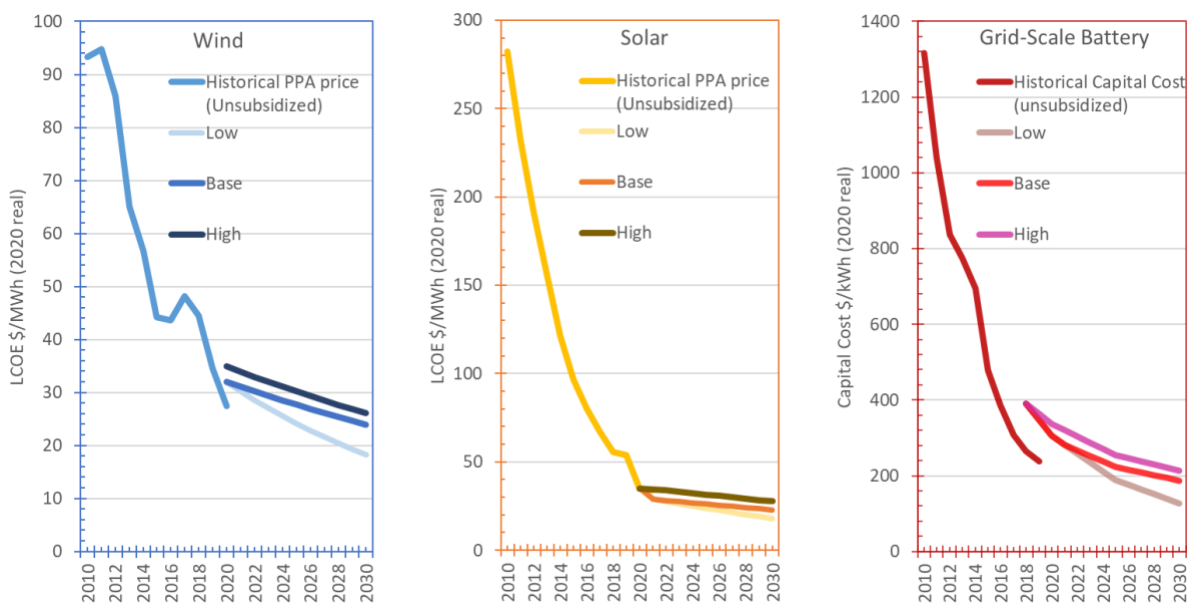


Figure 2. Historical and projected technology cost declines on which our analyses were based. For solar and wind, the historical LCOE was estimated by adjusting historical power-purchase agreement (PPA) prices for subsidies (investment tax credit and production tax credit). PPA price data were obtained from Lawrence Berkeley National Laboratory’s utility-scale solar (Bolinger et al. 2019a, 2019b) and wind (Wiser and Bolinger 2019) reports. For four-hour batteries, historical pack costs were based on Bloomberg New Energy Finance data (Goldie-Scot 2019), and balance-of-system cost data were from NREL (2019). Future cost projections for all three technologies were based on NREL (2019).

We tested the robustness of our findings through sensitivity analyses of the key input assumptions used in this report, including sensitivities around technology costs and fossil gas prices. We considered three primary sets of future renewable energy and battery storage technology costs

(described above) and two sets of fossil gas prices. The base case fossil gas prices are the same as in the reference case in the U.S. Energy Information Administration (EIA) Annual Energy Outlook (EIA 2020a). The low gas prices use New York Mercantile Exchange (NYMEX) future prices until 2022, and beyond 2022 the price of gas is kept constant at \$2.75/MMBtu (2020 real). We evaluate all permutations of these assumptions for the No New Policy and 80% Clean cases (24 cases in total).

We rely on the peer-reviewed literature to estimate the value of environmental and public health impacts. For the transportation sector health impacts, we use national average mortality factors of vehicle-miles traveled from Thakrar et al. (2020) to estimate total premature deaths due to vehicular criteria air pollutant emissions, specifically from primary and secondary particulate matter (PM_{2.5}), in each year. For the power sector health impacts, we use the same methodology used in the 2035 Report. We estimate the change in yearly sulfur dioxide (SO₂) and nitrogen oxide (NO_x) emissions (which contribute to secondary PM_{2.5} formation in the atmosphere) in each of the 134 grid regions based on the ReEDS output. We then apply state-level mortality factors from Thind et al. (2019) to estimate total premature deaths due to SO₂ and NO_x emissions in each state. We estimate the economic benefits of avoided CO₂ and PM_{2.5} emissions using a methodology and values consistent with the 2035 Report. We multiply the value of a statistical life from Holland et al. (2020), \$9.6 million (2020 real), with the avoided premature deaths due to primary and secondary PM_{2.5} emissions reductions. The economic benefit of avoided CO₂ emissions is estimated using a social cost of carbon derived from Baker et al. (2019), Ricke et al. (2018), and Caldeira et al. (2016), which is \$49.6/MT in 2020, increasing at 3 percent per year (\$66.1/MT by 2030). We multiply the social cost of carbon by net carbon dioxide (CO₂) emissions reductions from the transportation and power sectors.

3. KEY FINDINGS

The key findings from our analysis are as follows:

3.1 STRONG POLICIES ARE REQUIRED TO CREATE AN 80 PERCENT CLEAN GRID BY 2030

In the 80% Clean case, we require the model to reach an 80 percent clean electricity system by 2030. In this analysis, clean generation refers to resources that produce no direct CO₂ emissions, including hydropower, nuclear, wind, PV, biomass, fossil generation with 100 percent carbon capture⁵. In the No New Policy case, however, the grid mix is determined by least-cost capacity-expansion modeling based on the current paradigm for electricity-market costs, which does not fully internalize the costs of environmental and health damages from fossil fuel use. As a result, clean resources only supply 45 percent of the electricity in the No New Policy case in 2030. Figure 3 compares the grid mixes in the two cases. The 2030 mix in the No New Policy case is similar to the 2030 grid mix from EIA’s Annual Energy Outlook Reference Case (47 percent clean generation) (EIA 2020a).

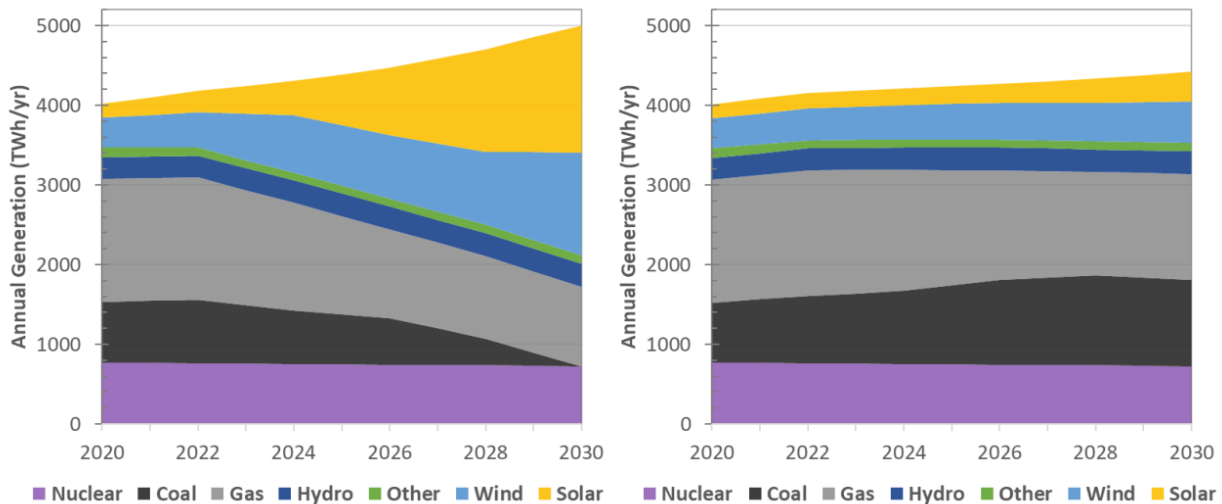


Figure 3. Generation Mixes for the 80% Clean Case (left) and No New Policy Case (right), 2020–2030

The 80% Clean case assumes implementation of policies that promote large-scale renewable energy adoption and yield net societal benefits compared with the business-as-usual approach assumed under the No New Policy case. As detailed in Sections 3.3 and 3.6, the wholesale electricity cost in the 80% Clean case does not increase from today’s level. The nominal cost increase (6 percent) relative to the No New Policy future are more than offset by the societal benefits provided by an 80 percent clean electricity system.

⁵ There is no partial credit for partial carbon capture.

3.2 THE 80 PERCENT CLEAN GRID IS DEPENDABLE WITHOUT COAL PLANTS OR NEW GAS PLANTS

Given the dramatic decline in battery storage prices, we find that significant battery storage is cost-effective and plays a critical role in balancing the grid. We estimate that in 2030 about 1,450 GWh (227 GW of batteries with average duration of about 6 hours⁶) of storage cost-effectively supports grid operations in the 80% Clean case, representing about 11 percent of daily electricity demand. When renewable energy generation exceeds demand, storage can charge using this otherwise-curtailed electricity and then dispatch electricity during periods when renewable generation falls short of demand. Despite the addition of storage, our modeling results show about 8 percent of available renewable energy would be curtailed annually by 2030. Beyond 2030, and perhaps sooner, new long-duration storage technologies might become available to reduce curtailment and gas generation further, but we did not address this potential here.

To estimate the generation capacity required to meet system demand in every hour, even during periods of low renewable energy generation and/or high demand, we simulate hourly operation of the U.S. power system for more than 60,000 hours (each hour in 7 weather years). For each of these hours, we evaluate and confirm how electricity demand is met in each of the 134 regional zones (subparts of the U.S. power system represented in the model) while abiding by several technical constraints (such as ramp rates and minimum generation) for more than 15,000 individual generators and 310 transmission lines.

Over the 7 weather years, we find significant variation in wind and solar generation. During the hour of lowest wind and solar generation, total wind and solar generation is 95 percent below rated capacity (about 46 GW of generation from 1,150 GW of total installed capacity) and 85 percent below the yearly average of wind and solar generation. Solar generation drops to zero in night hours, whereas the lowest hourly period of wind generation is about 88 percent below average. Wind and solar generation perform significantly better compared to average output over days and weeks (Figure 4).

⁶ The model builds 7GW of 2-hour batteries, 32GW of 4-hour batteries, 99GW of 6-hour batteries, 89GW of 8-hour batteries, and 1GW of 10-hr batteries.

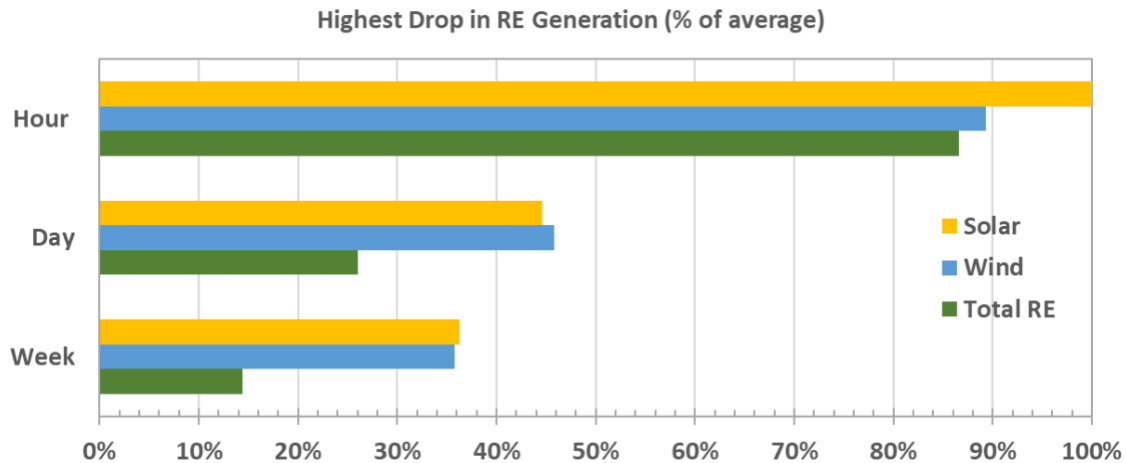


Figure 4. Maximum drop in wind and solar output relative to average wind and solar generation

To highlight the dependability of an 80 percent clean electricity grid and estimate natural gas capacity requirements, we identify the period during the 7 weather years when maximum natural gas generation capacity is dispatched to compensate for the largest gap between clean electricity generation (including battery generation) and load. The maximum natural gas capacity dispatched is 303 GW on August 1 in one of the weather years (2007) (Figure 5). At 8:00 pm Eastern Time on that day, national solar generation declines to 51 GW (70 percent below its annual average), while wind generation (83 GW) is about 50 percent below its annual average, resulting in only about 134 GW of wind and solar production (about 60 percent below the annual average, as indicated in Figures 6 and 7). The total system demand of about 716 GW is met by a combination of other clean resources, such as hydropower and nuclear (totaling 126 GW), approximately 150 GW of battery discharge and 303 GW of gas (Figure 8).

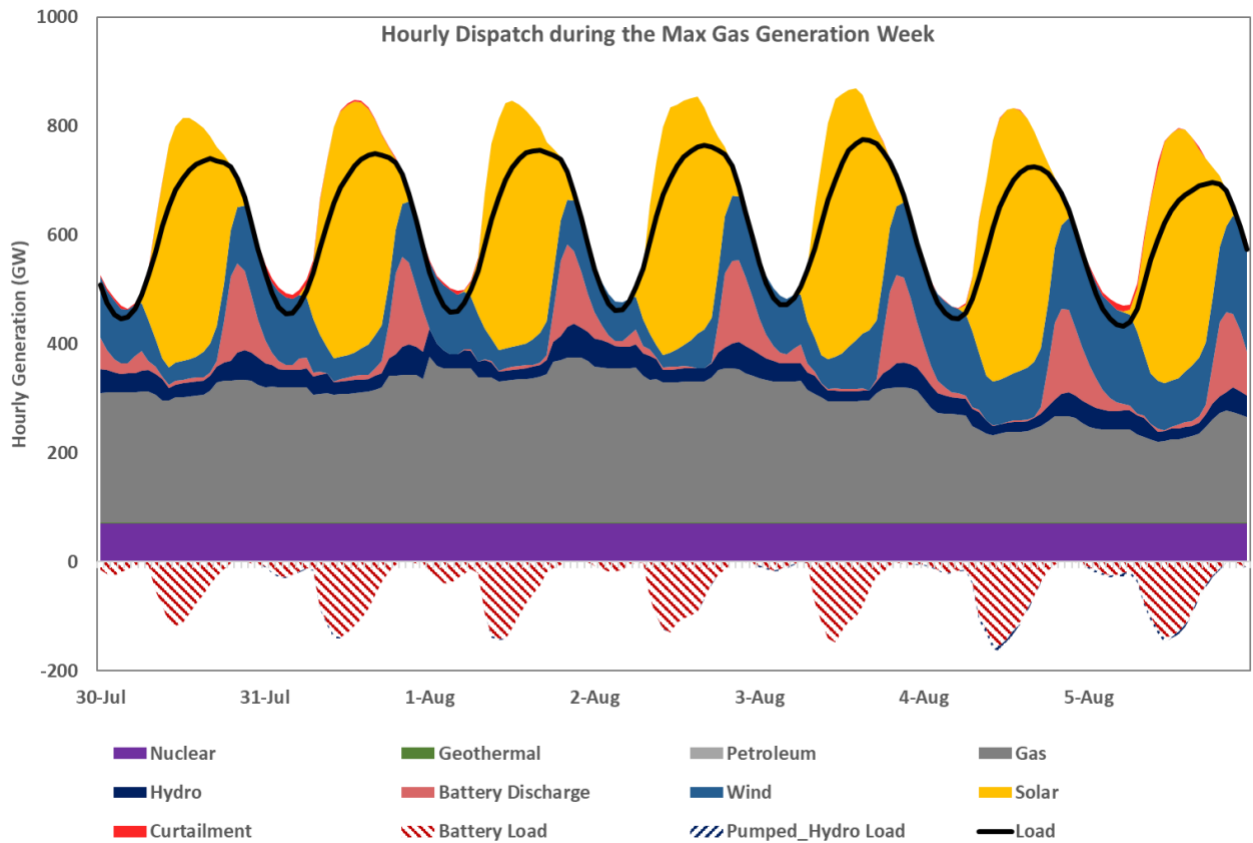


Figure 5. Hourly U.S. power system dispatch for extreme weather days in the 80% Clean case in 2030. Figure 5 details the dispatch for the period of maximum natural gas generation, one week in late July and early August. Approximately 303 GW of natural gas is dispatched to meet demand on August 1, while renewables contribute significantly less generation than normal. Even when wind and solar generation drops to low levels, existing hydropower, nuclear power, and natural gas capacity, as well as new battery storage, are sufficient to maintain dependable system operations.

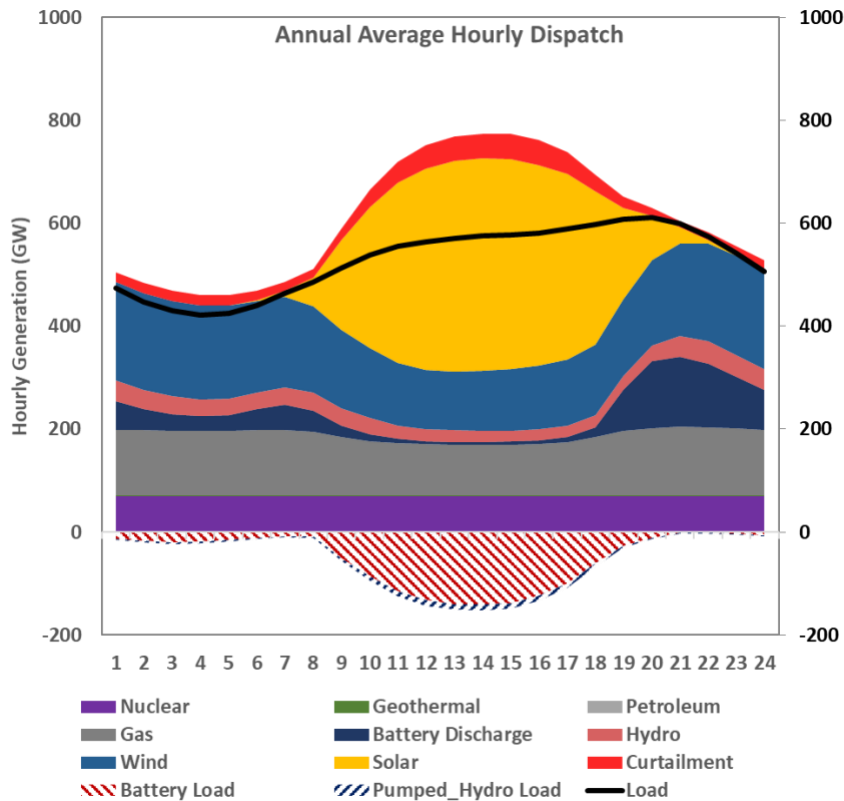


Figure 6. Hourly U.S. Power-System Dispatch for an Average Weather Day in the 80% Clean Case in 2030. Figure 6 details the annual average generation stack for each hour of an average weather day. Wind and solar provide a large share of nighttime and daytime generation, respectively, and broadly complement each other. Battery storage is primarily dispatched during evening hours when solar generation drops, and load remains relatively high.

For all weather years, the natural gas capacity requirements are highest in August, when wind generation falls significantly (Figures 7 and 8). Natural gas generation above 270 GW is required for fewer than 38 hours per year over the 7-weather-year simulation. Of the 303 GW of natural gas capacity that gets dispatched in 2030 under the 80% Clean case, 50 GW has a capacity factor below 1 percent. Other technology alternatives not considered in this analysis, such as demand response or flexible load, may be more cost-effective than gas for system balancing in those hours, and lay the groundwork for further electricity system decarbonization.

We also find that increased electrification of the U.S. economy has little impact on the maximum natural gas capacity required, but it reduces curtailment.

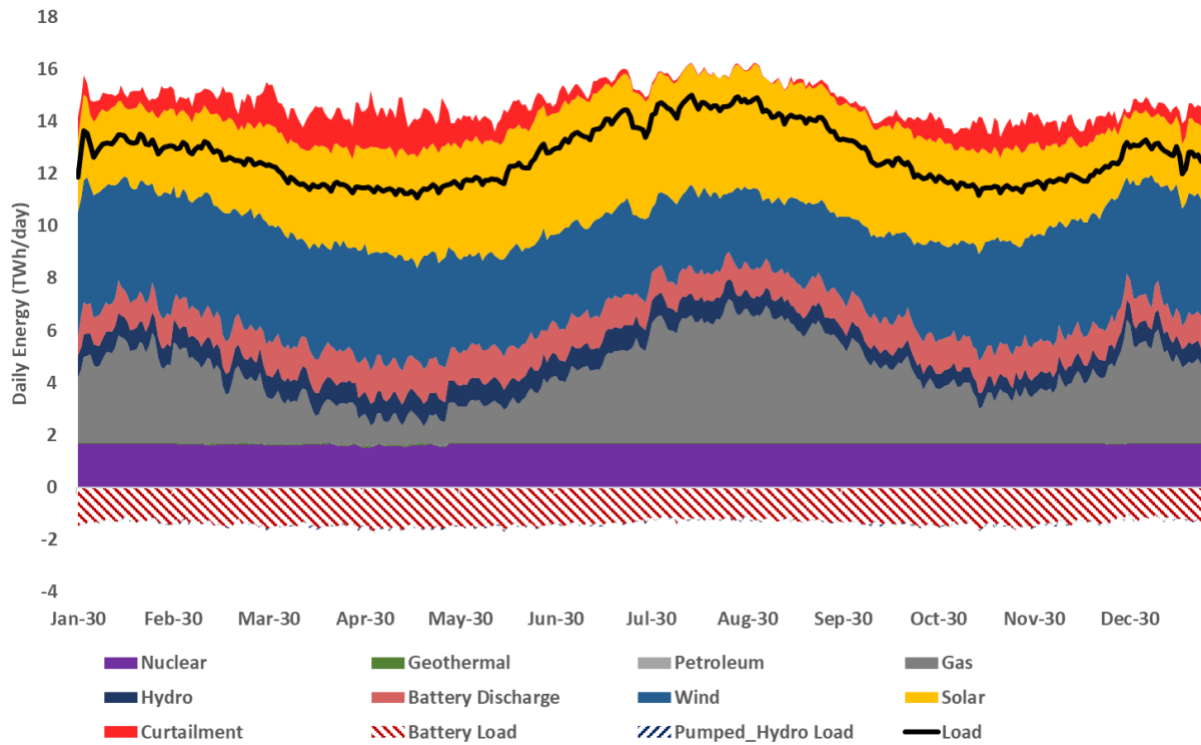


Figure 7. Daily U.S. Power System Dispatch Averaged Over 7 Weather Years in the 80% Clean Case in 2030

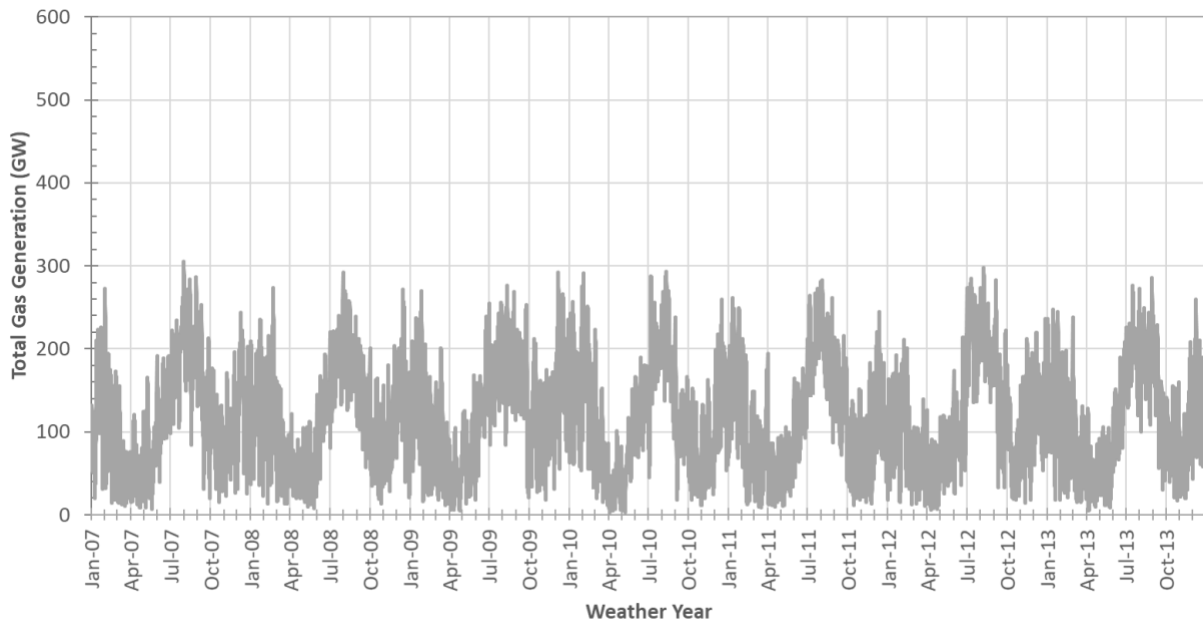


Figure 8. Hourly U.S. Gas Dispatch over 7 Weather Years in the 80% Clean Case in 2030. Figure 8 details the hourly gas generation in 2030 for 7 weather years. The maximum natural gas generation required is 303 GW on August 1 in weather year 2007.

Using 7 years of weather and load data provides a robust picture of grid dependability, however it is not the full universe of possible weather and load combinations. Our analysis does not consider

additional weather years beyond this owing to lack of data. For example, it does not consider increasing extreme weather events, including extreme heat expected as the planet continues to warm from anthropogenic greenhouse gas emissions. Nor does it explore in detail the interaction between drought, heat, and hydropower availability. But renewable energy variation we observe over the 7-year period is similar to the variation observed over a 35-year period by Shaner et al. (2018). Shaner et al. may underestimate the variation in wind generation compared to that seen in our data, as they consider significantly lower spatial resolution than our study. However, our simulation includes adequate gas and battery storage capacity to meet residual load (load minus clean energy generation) up to 100 percent of average load and 80 percent of peak load. Hence, even if a longer period of weather data reveals larger gaps between load and wind/solar generation, additional firm capacity requirements are unlikely to be significant. However, further work is needed to assess this possibility.

In summary, existing hydropower and nuclear power capacity (after accounting for planned retirements combined with about half of existing fossil gas capacity, and 227 GW of new 2- to 10-hour battery storage, is sufficient to meet U.S. electricity demand with an 80 percent clean grid in 2030, even during periods of low renewable energy generation and/or high demand. Under the 80 percent Clean case, all existing coal plants are retired by 2030, and no new fossil fuel plants are built beyond those already under construction. During normal periods of generation and demand, wind, solar, and batteries provide 60 percent of total annual generation, while hydropower and nuclear provide 20 percent. During periods of high demand and/or low renewable generation, existing gas plants (primarily combined-cycle plants) cost-effectively compensate for remaining mismatches between demand and renewables-plus-battery generation—accounting for about 20 percent of total annual electricity generation, which is about 30 percent lower than gas generation in 2019.

Although the capacity-expansion modeling (ReEDS) required that clean resources contribute 80 percent of annual generation in 2030, the hourly operational model (PLEXOS) simulated roughly 79.3 percent clean generation, primarily due to somewhat higher curtailment of wind and solar. PLEXOS model dispatch decisions were based on the variable cost of generation and did not consider the carbon free or non-carbon free nature of the generation source.

In an electricity market with an 80 percent clean energy constraint, as modeled in our 80% Clean Case, clean energy may bid negative prices in certain hours in order to get dispatched and meet the 80 percent constraint. We utilize ReEDS to effectively model this 80 percent clean electricity share, while the main purpose of our simulation in PLEXOS is to evaluate operational feasibility.

For this reason, we did not simulate the same 80 percent clean energy constraint in PLEXOS, which might have required clean energy to bid negative prices in order to get dispatched.⁷

Our modeling approach represents a conservative strategy for achieving 80 percent clean energy. Various complementary approaches could help achieve this deep decarbonization, with potential for even lower system costs and accelerated emissions reductions. In this analysis, we do not consider “managed” or flexible charging of EVs, (see the methodology detailed in 2035 Report 2.0.). However, demand-side approaches, such as “managed” charging, demand response, and other flexible loads could play a large role in grid operations. With proper rate design, flexible load could similarly take advantage of zero or negatively priced electricity that is likely to occur during the hours of curtailment, which will likely increase the overall clean energy share. New supply-side resources, such as firm low-carbon generation or longer-duration storage, could also provide system flexibility. Such alternative approaches to balancing generation and demand could cost less than retaining significant natural gas capacity that is rarely used, if an 80 percent by 2030 CES is pursued.

3.3 ELECTRICITY COSTS FROM THE 80 PERCENT CLEAN GRID ARE THE SAME AS TODAY’S COSTS

Wholesale electricity (generation plus incremental transmission) costs are the same in 2030 under the 80% Clean case as they are today (Figure 9).⁸ The base wholesale electricity cost under the 80% Clean case is 5.1 cents/kWh, which is the same as that in 2020. Wholesale costs in the 80% Clean case in 2030 are 4.7–5.3 cents/kWh across all cost sensitivities. The only sensitivity case in which those costs are marginally (4 percent) higher than costs in 2020 assumes high technology costs. Unchanged wholesale costs between 2020 and 2030 imply no impact on retail electricity prices, assuming electricity distribution costs do not change significantly in the 80% Clean case.⁹

⁷ The fact that PLEXOS curtails more clean energy generation than ReEDS is primarily due to two factors: 1) ReEDS does not have the full set of real system constraints; and 2) we are not modelling a clean energy constraint or negative bid prices in PLEXOS.

⁸ Costs include recovery of capital costs from new and existing generation capacity, fixed operations and maintenance costs, fuel and variable operations and maintenance costs, and new transmission (bulk and spurline) investments. The cost figures referenced throughout this report refer to the total wholesale generation costs plus the cost of additional transmission investments beyond 2020.

⁹ We assume distribution costs do not rise faster than inflation in the next 10 years. Because the 80% Clean case does not rely heavily on distributed energy resources, this is a reasonable assumption. Distributed PV serves as an input to the ReEDS model based on NREL’s distributed generation model. In 2030, under the 80% Clean case, there are approximately 48 GW of distributed PV, representing approximately 1.5 percent of total energy generation. Also, as shown in The 2035 Report 2.0, transport electrification does increase overall distribution investments but does not result in an increase in the average distribution costs since the electricity sales also increase in the same proportion.

These findings are similar to the findings of power system studies conducted in the past one-two years, but the clean power system target date for most of those studies is 15 years later than 2030 (Jayadev et al. 2020, Bogdanov et al. 2019). Our findings contrast sharply with the findings of studies completed more than five years ago, which show future electricity bills rising compared to today’s bills. For example, NREL’s Renewable Electricity Futures Study, published in 2012, projected retail electricity price increases of about 40 percent–70 percent above 2010 prices, for a system with 80 percent renewable electricity penetration in 2050 (NREL 2012). Renewable energy and battery costs have declined much faster than these older studies assumed, which is the main reason their cost results differ so much from ours.

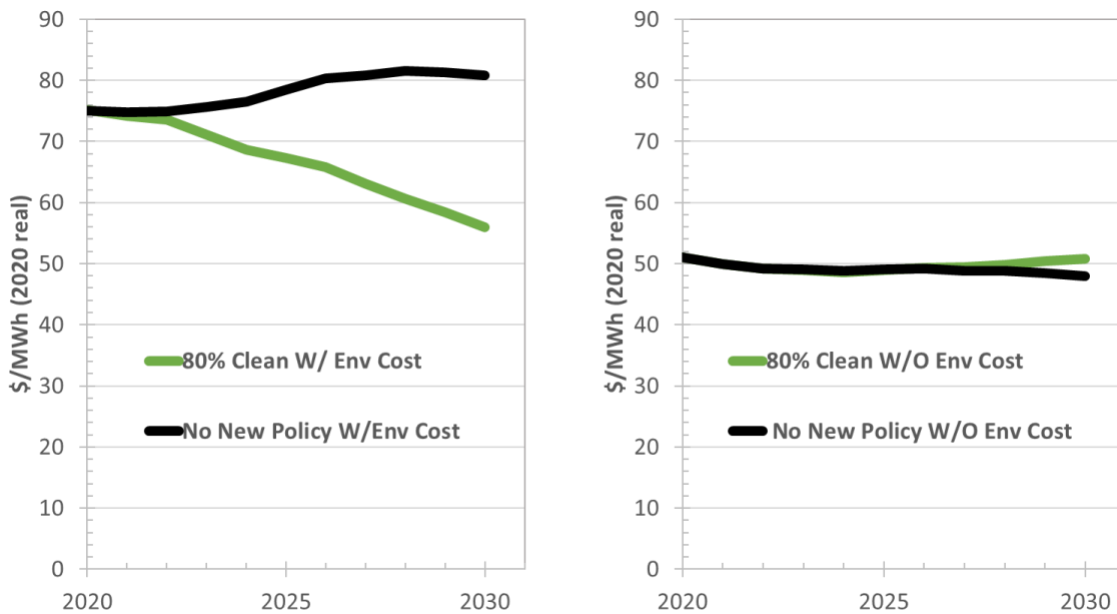


Figure 9. Wholesale Electricity Costs (Costs of Generation and Incremental Transmission) with (left) and without (right) Including Environmental (Air Pollution and Carbon Emissions) Costs, for the 80% Clean and No New Policy Cases. If environmental costs are included, wholesale electricity costs are about 25 percent lower in 2030 under the 80% Clean case than they are in 2020, and they are 31 percent lower in 2030 under the 80% Clean case than they are in 2030 under the No New Policy case. Without considering environmental costs, wholesale electricity costs remain the same in 2030 under the 80% Clean case as they are in 2020. Relative to the no policy case wholesale electricity costs are 6 percent higher in 2030 under the 80% Clean case than they are under the No New Policy case.

Low renewable energy and storage costs are the primary reasons that electricity costs stay the same between 2020 and 2030 under the 80% Clean case. Section 2 shows the dramatic renewable energy and storage cost trends. Figure 10 illustrates that these competitive costs become available throughout the country, even in regions previously considered resource-poor for renewable energy generation. Our estimates align with some of the recent renewable energy bids seen in relatively resource-poor regions.

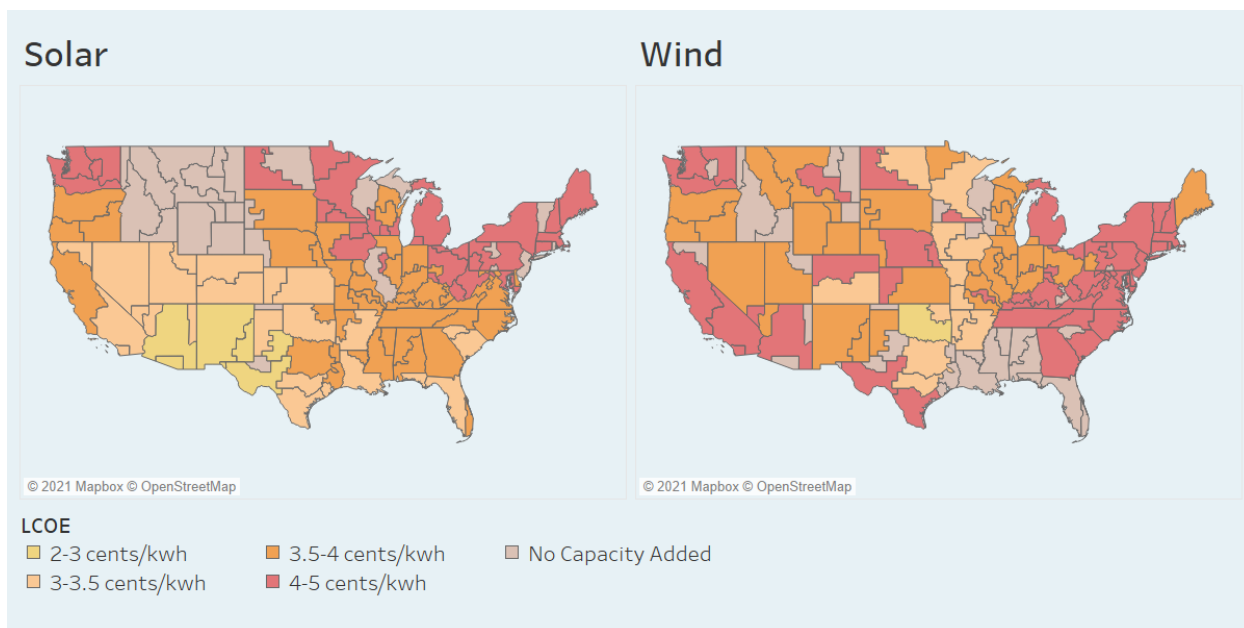


Figure 10. Average Solar (left) and Wind (right) LCOE by Region in the 80% Clean Case in 2030. The maps show capacity-weighted average LCOE for the least-cost portfolio to meet the 80% clean energy target for the 134 balancing areas represented in ReEDS. LCOE includes the current phase-out of the federal renewable energy investment and production tax credits. The LCOE in most zones is lower than 4 cents/kWh. We use NREL’s 2019 ATB Mid-Case (NREL 2019) for cost projections with some modifications, which account for the cost reductions already benchmarked to recent PPA pricing.

Under the 80% Clean case, most transmission investments are in new spurline transmission rather than bulk transmission (Figure 11).¹⁰ Although the 80% Clean case requires about four times more spurline investment than the No New Policy case does, the total new transmission requirements in the 80% Clean case add only 0.15 cents/kWh to total system costs.¹¹ Recent studies that account for low renewable energy and storage costs have similar findings (Jayadev et al. 2020). Studies that assume much higher renewable energy costs or do not consider storage find higher levels of additional bulk transmission required (Clack et al. 2017, NREL 2012).¹² Recent work from Larson et al. (2020) and Clack et al. (2020) find that a least-cost electricity system achieving similar rates of clean energy deployment to our 80% Clean case has far greater levels of interregional transmission. Further work is needed to understand transmission needs more precisely.

¹⁰ Spurline transmission refers to lines needed to connect remote renewable energy generation to the bulk transmission system or load centers. Bulk transmission refers to larger, higher-capacity transmission lines designed to carry electricity across long distances at high voltages, typically above 115 kV.

¹¹ Construction of spurline transmission is likely less complex than construction of bulk transmission, because spurline transmission typically does not cross multiple jurisdictions.

¹² We assessed a scenario with higher renewable energy and storage costs based on NREL ATB 2015 (NREL 2015) and found that significant additional bulk transmission is cost-effective, suggesting that—when renewable energy and battery costs are high—significant new bulk transmission is useful. However, when those costs are low, as modeled in the 80% Clean case, limited new bulk transmission investments are necessary.

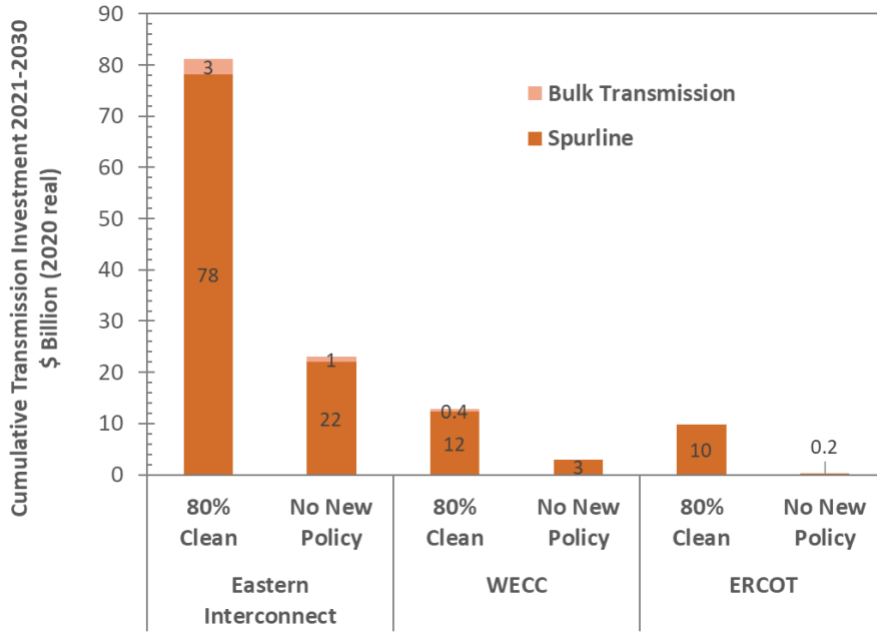


Figure 11. Additional Spurline and Bulk Transmission Investments by Interconnect under the 80% Clean and No New Policy Cases, 2020–2030. The vast majority of transmission investments are spurline investments as opposed to bulk transmission system investments. Total transmission investments add only 0.15 cents/kWh to system costs in the 80% Clean case. ERCOT = Electric Reliability Council of Texas, WECC = Western Electricity Coordinating Council.

Low electricity costs in the 80% Clean case are also facilitated by the limited use of fossil fuel generators; all coal plants are retired by 2030, and no new gas plants are built (see Section 3.2). Thus, the 80% Clean case avoids large amounts of fuel and large investments in generating capacity that is used infrequently. In addition, using a 2030 target year provides sufficient time for existing fossil assets to recover most of their fixed costs and thus avoids significant stranded-asset costs. Of the approximately 800 GW of U.S. fossil fuel generation capacity operating today, 480 GW will be at least 30 years old in 2030 (Figure 12) (Jell 2017). At this time, a high percentage of the coal and older natural gas units will be largely depreciated (given the usual depreciation life of 30 years or less) and can be retired at little or no cost to consumers and minimal stranded costs.¹³ For coal plants with significant undepreciated balances, securitization of these balances through government- or ratepayer-backed bonds can yield significant savings and reduce financial hardship for asset owners (Aggarwal & O’Boyle 2020).

¹³ We define stranded cost as the cost of fossil assets that are not used but have not been fully depreciated, assuming a depreciation life of 30 years. From a market standpoint, this applies only to assets that are built and operated by utilities. Assets that operate under a PPA or are merchant power plants cannot be considered stranded from a market perspective. See the policy report from Energy Innovation accompanying the original 2035 Report for further discussion of stranded assets (Energy Innovation, 2020).

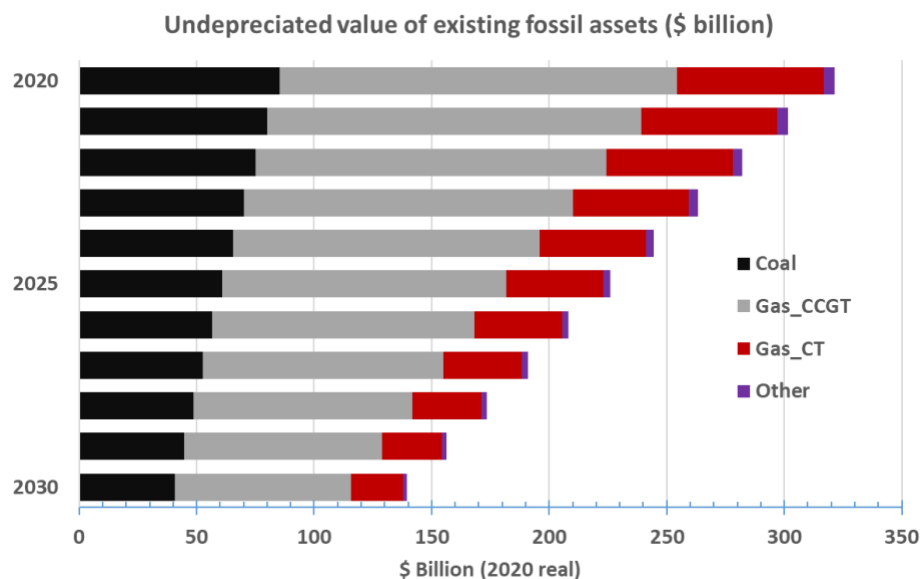


Figure 12. Undepreciated Value of Existing U.S. Fossil Fuel Capacity, 2018–2030. By 2030, the remaining undepreciated value of generating plants is small, suggesting a transition to 80 percent clean energy can be accomplished with minimal stranded assets.¹⁴

Conversely, using existing gas capacity to meet about 20 percent of electricity demand reduces the need amount of new renewable energy and storage capacity needed—helping accelerate the timeline for 80 percent clean electricity while keeping costs down. Further decarbonization could then build on this mostly clean electricity system; several pathways to 100 percent clean electricity have been identified. See, for example our previous work (Phadke et al, 2020b).

Although electricity costs are the same in 2030 under the 80% Clean case as they are today, they are 0.28 cents/kWh (6 percent) higher under the 80% Clean case than they are under the No New Policy case in 2030 (Figure 9). However, this comparison does not account for the value of carbon emissions and air pollutant reductions, which make the societal costs of electricity substantially lower under the 80% Clean case than they are under the No New Policy case (see Section 2.6). Finally, significant natural gas capacity is built under the No New Policy case, which will likely result in future stranded costs, whereas no new fossil fuel capacity is needed under the 80% Clean case.¹⁵

¹⁴ The undepreciated asset numbers are illustrative as they may not include all life-extension or pollution control related capital expenditure.

¹⁵ If there are still a few coal units owned by regulated utilities that, in 2030 (or at time of retirement) have undepreciated life-extension or pollution-control capital costs, those can be retired at low cost using a securitization mechanism. This approach has been used in recent years by large investor-owned and public utilities to create a positive return for shareholders and downward pressure on wholesale and retail electricity prices (Lehr and O’Boyle 2018).

3.4 SCALING-UP RENEWABLES TO ACHIEVE 80 PERCENT CLEAN ENERGY BY 2030 IS FEASIBLE

To achieve the 80% Clean case by 2030, a substantial increase is needed in U.S. renewable energy installations due to the accelerated electrification of the transportation, industry, and buildings sectors. The combined demand growth requires electricity generation to increase approximately 2 percent per year, consistent with the 2.6 percent average historical growth in the electric sector during 1975–2005, when emissions in industry peaked (Figure 13).

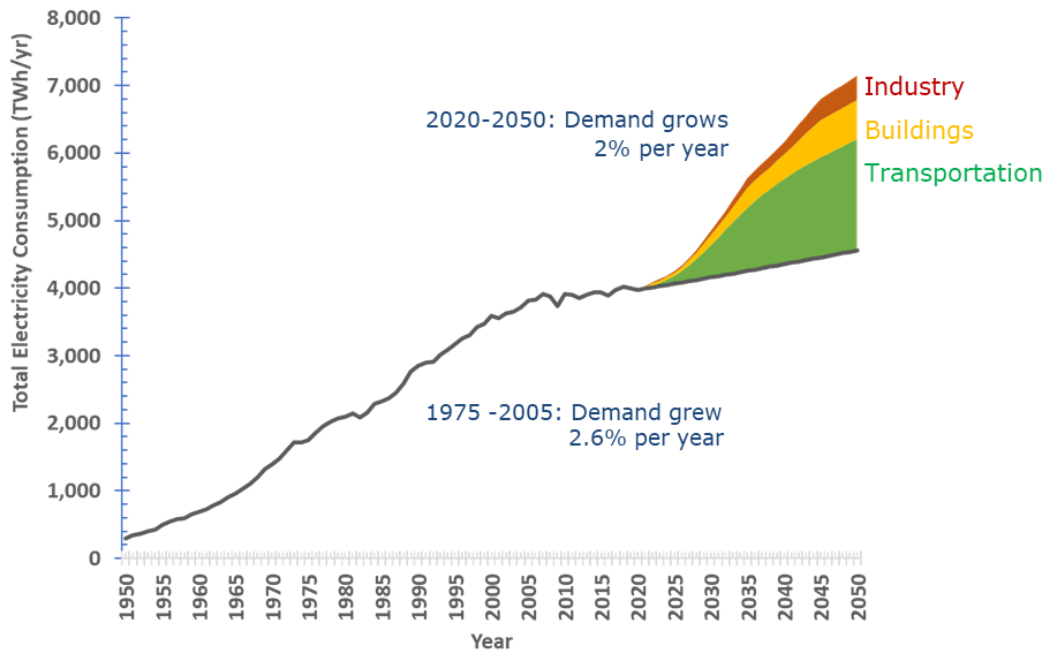


Figure 13. Total electricity consumption – historical and with additional electrification

We find that between 2021 and 2030, 950 GW of new wind and solar generation capacity must be built, averaging about 95 GW per year (Figure 14). In addition, 227 GW of battery storage capacity needs to be built, averaging about 23 GW per year. For comparison, the size of today’s U.S. power sector is approximately 1,000 GW. Although challenging, a renewable energy buildout of this magnitude is feasible with the right supporting policies in place.

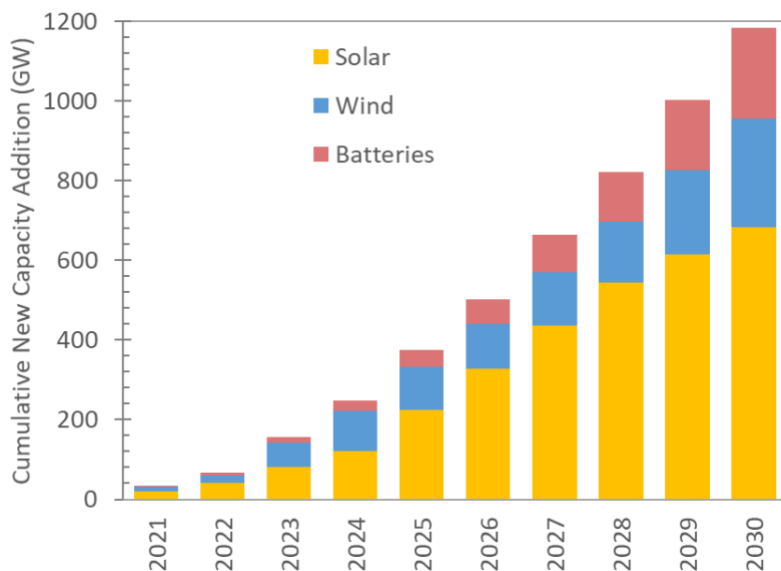


Figure 14. Cumulative New Capacity Additions in the 80% Clean Case, 2020–2030

Historical and planned U.S. generation deployments also suggest that annual deployments of 120 GW (95 GW RE and 25GW of storage) are possible. The US 65 GW of gas generation in 2002 (Ray 2017). In 2020, the U.S. deployed 31 GW of wind and solar capacity (SEIA 2021; ACP 2021). In 2020, China built 120GW of solar and wind capacity in a year. Interconnection queues in the U.S. as of 2019 included 650 GW of wind, solar, hybrid, and standalone battery storage, more than half of the 1,000 GW required (Bolinger et al. 2019a, 2019b) in the 80% Clean case. Storage, onshore wind, and solar generation generally have shorter construction times compared with natural gas plants, and they do not require a gas pipeline connection. Significant policy support is needed to achieve this level of renewable energy deployment (Aggarwal & O’Boyle 2020).

New renewable resources can be built cost-effectively in all regions of the country, as indicated by the proliferation of utility-scale renewables nationwide. The top 10 states for installed utility-scale solar represent at least four distinct regions: New England, the Southeast, the West, and the Southwest. More than 75 percent of U.S. states have one or more utility-scale solar projects (Bolinger et al. 2019a, 2019b). The Midwest, once considered a laggard for utility-scale renewable projects, accounted for the largest percentage of solar added to interconnection queues in 2018 (26 percent).

3.5 THE 80 PERCENT CLEAN GRID DRIVES SIGNIFICANT INVESTMENT ACROSS ALL U.S. REGIONS

Because of the deep reduction in the wind and solar prices, renewable energy investments are found to be cost effective throughout the country, including states with significant existing coal

and gas capacity. This implies significant job gains and opportunities for a just transition from fossil fuels.

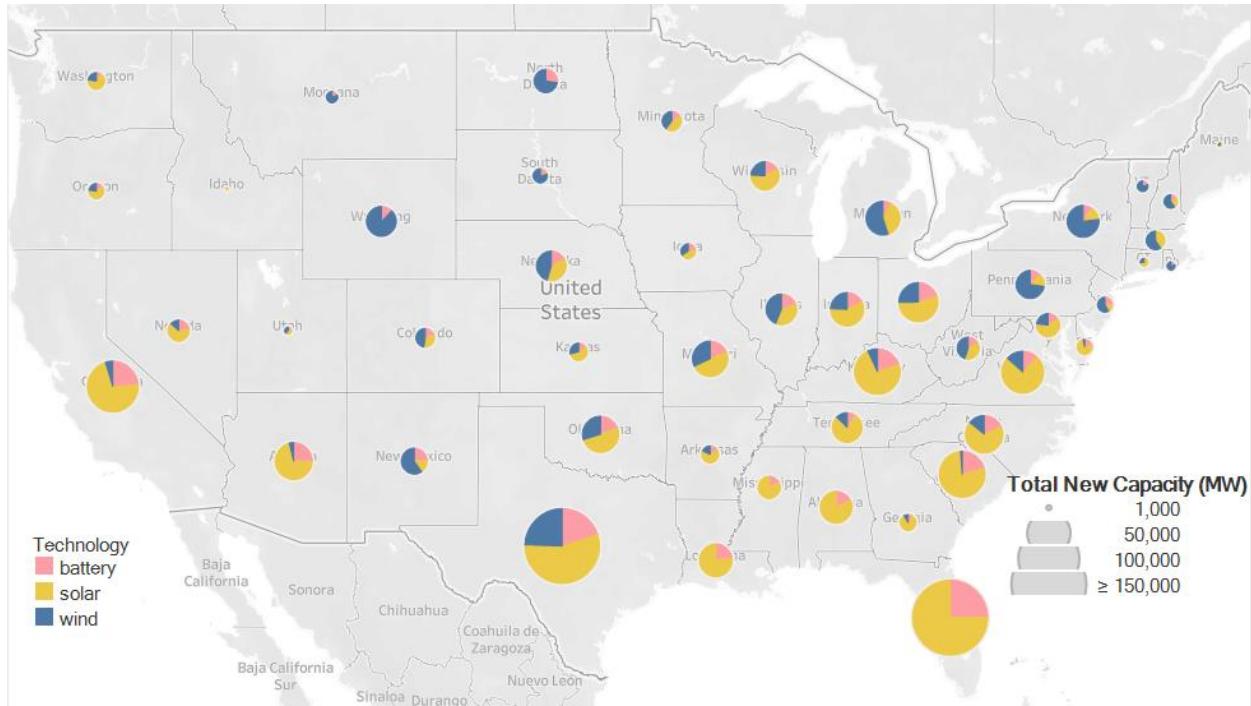


Figure 15: Cumulative New Renewable Energy and Storage Investment (2021-2030) by State

Table 1: Top-15 States by New Clean Energy Investments in the 80% Clean Case (2021-2030 total)

State	New Investments in Wind, Solar, and Storage (GW)	New Investments in Wind, Solar, and Storage (\$ Billion, 2020 real)
Texas	153	190
Florida	153	171
California	70	92
Kentucky	56	65
South Carolina	56	59
Virginia	47	59
Ohio	46	55
New York	27	53
Arizona	37	46
Missouri	34	45
Michigan	34	44

Oklahoma	35	44
North Carolina	38	42
Indiana	32	40
Wyoming	24	38

All regions of the country could experience significant economic activity from local renewable energy generation and storage deployment. However, in some communities, the shift away from fossil fuel generation may disrupt workers and communities that rely on jobs and tax revenue related to fossil fuel production and power generation. Policies implemented to decarbonize the power sector should include explicit measures to support transitions to a lower-carbon economy. Existing research suggests that wind and PV plants can be built close to many retiring coal plants, helping to provide new economic opportunities in the impacted communities (Gimon et al. 2019). Support for economic redevelopment and diversification beyond the clean energy industry can help more generally with an effective transition from fossil fuels. Energy Innovation’s 2035 Report companion policy analysis highlights key policy drivers to support coal community services, health, and employment during the energy transition (Aggarwal & O’Boyle 2020).

3.6 THE 80 PERCENT CLEAN GRID AVOIDS \$1.7 TRILLION IN HEALTH AND ENVIRONMENTAL DAMAGES FROM THE POWER SECTOR, INCLUDING 93,000 PREMATURE DEATHS, THROUGH 2050

The 80% Clean case nearly eliminates emissions from the U.S. power sector by 2030 (Figure 16), resulting in environmental cost savings as well as reduced mortality related to electricity generation. Further, achieving 80 percent clean electricity by 2030 accelerates benefits in ensuing years, because the No New Policy power system continues to be fossil fuel dependent. We estimate climate-related impacts using a social cost of carbon value, and we estimate human health damages due to NO_x, SO₂, and fine particulate matter (PM_{2.5}) emissions using an established method from the literature.¹⁶ Compared to the No New Policy case, in the 80% Clean case, power sector CO₂ emissions are reduced by 1,203 million metric tons (76 percent) through 2030, while NO_x and SO₂ emissions are reduced by 90 percent and 98 percent, respectively relative to the 2019 levels (Figure 16). When compared with 2005 levels, power sector CO₂ emissions are reduced by 2,015 million tons or 84 percent.

¹⁶ Benefits of reduced greenhouse gas emissions are valued at a social cost of carbon of approximately \$50/metric ton (derived from Baker et al. 2019 and Ricke et al. 2018). Avoided air pollution damage estimates for SO₂, NO_x, and PM_{2.5} are based on state-by-state damage factors provided by Maninder Thind based on Thind et al. (2019).

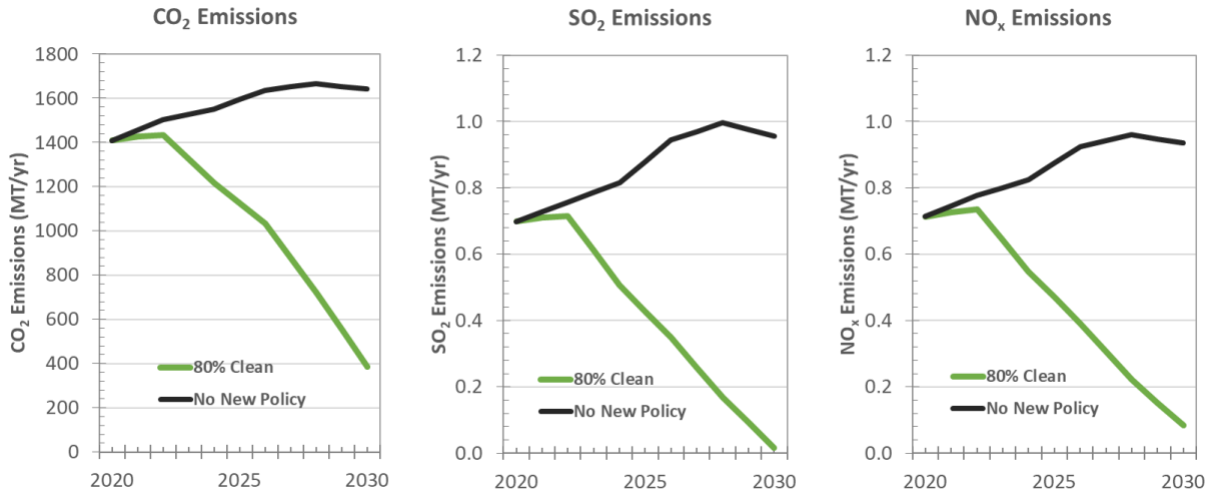


Figure 16. Emissions Reductions of CO₂, SO₂, and NO_x in the 80% Clean and No New Policy Cases, 2020–2030

Transport electrification also results in significant emissions reduction. By 2030, transportation sector CO₂ emissions fall by 522 million tons (30 percent) from 2019 levels and by 612 million tons (33 percent) from 2005 levels. The combined power and transportation sector emissions reductions reduce overall economy-wide energy related CO₂ emissions (excluding land use and agricultural sectors) by 1,723 million tons, or 31 percent relative to the 2019 levels (Figure 17). When compared with 2005 levels, the economy-wide energy related CO₂ emissions are reduced by 42 percent. When combined with electrification of buildings and industries, total economy-wide CO₂ emissions reductions are nearly 50 percent lower relative to the 2005 levels, a target that is critical for limiting the global warming to 1.5°C.

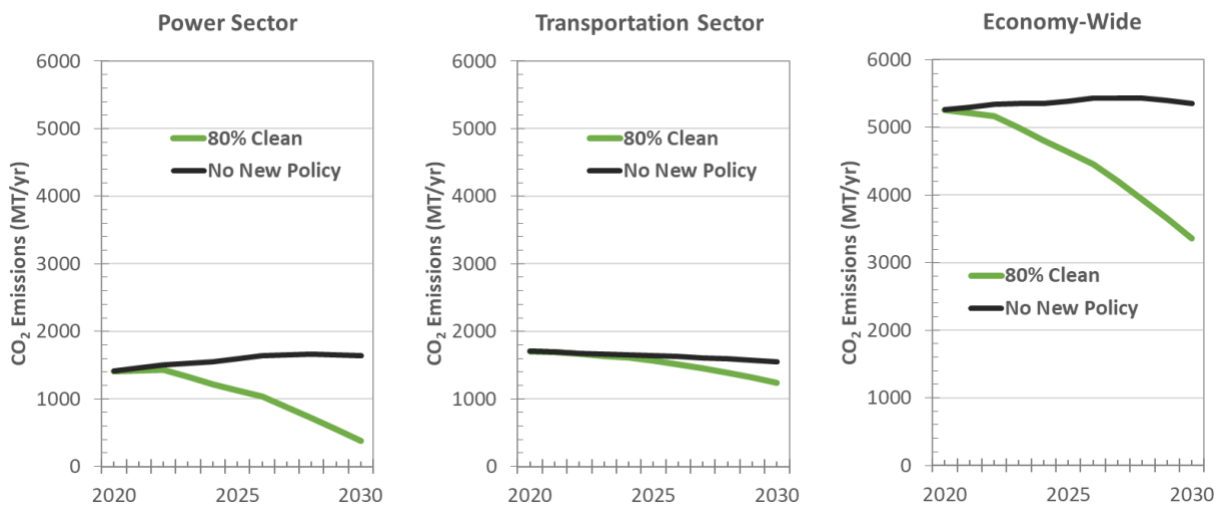


Figure 17. Power sector (left), transportation sector (center), and economy-wide (right) CO₂ emissions in the 80% Clean and No New Policy Cases, 2020-2030.

As a result, the 80% Clean case avoids about \$1.7 trillion (in 2020 dollars) in environmental and health costs through 2050, including approximately 93,000 premature deaths, due to avoided SO₂, NO_x, and CO₂ emissions from power sector (Figure 18).¹⁷ The environmental cost savings in 2030 from power sector alone roughly equate to \$25/MWh (or 2.5 cents/kWh) of wholesale electricity costs. Avoided premature deaths are primarily because of reduced exposure to PM_{2.5}, driven by reductions in SO₂ emissions, a precursor to PM_{2.5}, from coal plants.¹⁸ About 68 percent of the avoided environmental costs are from avoided CO₂ emissions, with the remainder associated with reduced exposure to PM_{2.5}.

The environmental benefits of transport electrification are equally significant. Between 2020 and 2050, vehicle electrification avoids over 150,000 additional premature deaths and over \$1.3 trillion in environmental costs. Power sector decarbonization and transportation electrification together avoid over 240,000 premature deaths and \$3 trillion in environmental costs.

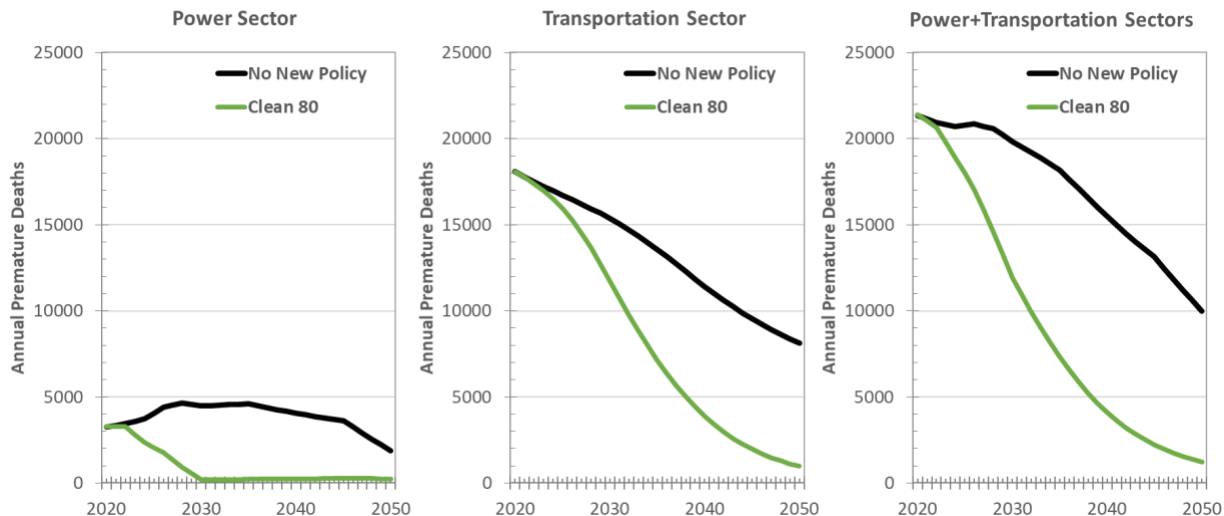


Figure 18. Annual premature deaths due to local air pollution in the power (center), transportation (right), and combined power and transportation (left) sector 2020–2050. The 80% Clean case coupled with transport electrification avoids about 240,000 premature deaths by 2050 relative to the No New Policy case.

These estimates are meant to illustrate the magnitude of some of the societal benefits that may be realized through rapid power-sector decarbonization. However, the environmental and health impacts of electricity use are subject to substantial uncertainties, and differences in input parameters provided by various sources can have large effects on impact calculations (Thind et al.

¹⁷ Coal power generation accounts for about 80% of air pollution related premature deaths and about 70 percent of CO₂ emissions associated with the U.S. power sector in 2019. The marginal environmental damage of coal (which our modeling does not include in our main scenarios) is highly significant (about two times the variable cost of coal).

¹⁸ Primary PM_{2.5} emissions factors are not modeled in ReEDS, and hence our estimate of reduced emissions contributing to reduced PM_{2.5} exposure may be conservative. Based on Thind et al. (2019) and Goodkind et al. (2019), primary PM_{2.5} emissions contribute to roughly 10–15 percent of premature deaths due to PM_{2.5} exposure.

2019). Our estimate of premature deaths due to air pollution from the power sector (about 3,500 per year) for the No New Policy case is approximately half the estimate reported in much of the existing literature, suggesting our analysis presents a conservative estimate of avoided premature deaths.¹⁹ Our assumptions regarding the social cost of carbon are based on the lower range of estimates of national social cost of carbon calculations.

However, our analysis also does not examine local air pollution impacts, and therefore does not adequately address whether an 80 percent clean electricity system will necessarily address longstanding environmental injustices. It may be the case that some communities with gas power plants nearby will see increased air pollution from an 80 percent clean electricity system. Gas power plants may be required to cycle more frequently to provide flexibility in a high-wind and solar system; cycling (ramping, starting, and stopping) of gas plants can lead to increases in NO_x emissions because emissions control technologies are less effective when a plant is cycling (Specht, 2019). However, these same impacts will be in some cases offset by lower fuel use in power plants, cars, and trucks, including reduced exposure to diesel emission from medium and heavy-duty vehicles. More study is needed to understand local air pollution dynamics in a low-carbon electricity system, especially in historically marginalized communities.

3.7 TOWARDS 100 PERCENT GRID DECARBONIZATION

This report's target of 80 percent clean electricity by 2030 is important for envisioning decarbonization at a pace more rapid than considered in conventional policymaking and academic research. It puts us on pathway consistent with a 1.5°C target and to 100 percent electricity decarbonization by 2035. Significant uncertainties surround the economic and operational viability of potential technologies and strategies needed to achieve 100 percent power-sector decarbonization, and these approaches are subject to considerable debate and need additional technology as well as policy research. In our previous work, we have attempted to assess a few illustrative technology pathways for 100 percent grid decarbonization (Phadke et al. 2020).

The major contribution of our report is its demonstration of a feasible power-sector decarbonization pathway that is readily available and cost-effective. However, concerted policy and regulatory action is required to ramp-up affordable clean generation and stop the construction of unnecessary fossil fuel plants. Achieving this rate of power-sector decarbonization by 2030 may ultimately increase the speed and cost-effectiveness of pervasive, cross-sector decarbonization.

¹⁹ Estimates of premature deaths cited in Thind et al. (2019) range between 10,000 and 17,050 premature deaths per year.

CAVEATS AND FUTURE WORK

Although we assess operational feasibility of the U.S. power system using weather-synchronized load and generation data, further work is needed to advance our understanding of other facets of an 80 percent clean power system. First, this report primarily focuses on renewable-specific technology pathways and does not explore the full portfolio of clean technologies that could contribute to future electricity supply. Importantly, our modeling approach represents a conservative strategy to achieve 80 percent clean energy. A number of complementary technologies or approaches could contribute to deep decarbonization, many of which could result in even lower system costs or accelerated emissions reductions.

Additionally, issues such as loss of load probability, system inertia, and alternating-current transmission flows need further assessment. Options to address these issues have been identified elsewhere (e.g. Denholm 2020). Although this analysis does not attempt a full power-system reliability assessment, we perform scenario and sensitivity analysis to ensure that demand is met in all periods, including during extreme weather events and periods of low renewable energy generation. This modeling approach provides confidence that an 80 percent clean electricity grid is operational.

Finally, although this report describes the system characteristics needed to accommodate high levels of renewable generation, it does not address the institutional, market, and regulatory changes that are needed to facilitate such a transformation. A supporting report from Energy Innovation identifies many of these solutions (Aggarwal & O’Boyle 2020).

CONCLUSION

The 2030 Report details how renewable energy and battery storage costs have fallen to such an extent that, with concerted policy efforts, the U.S. power sector can reach 80 percent clean energy by 2030 without increasing consumer bills or impacting the operability of the electric grid. In doing so, the U.S. power sector can inject over \$1.5 trillion in clean energy investments into the U.S. economy, nearly eliminate air pollution emissions from electricity generation, and when coupled with end-use electrification, reduce economy-wide CO₂ emissions 50 percent by 2030. This 80 percent clean electricity grid can provide clean, dependable power without the construction of new fossil fuel plants, despite significant additional electricity demand due to electrification. However, the 80 percent clean grid cannot be achieved without concerted policy action, and business-as-usual could lead to over \$1.7 trillion in cumulative health and environmental damages, including 93,000 premature deaths.

Perhaps most importantly, this report shows that the timeline for near-complete decarbonization of the electric sector can be accelerated to 2030. This is critical, because power-sector

decarbonization can be the catalyst for decarbonization across all economic sectors via electrification of vehicles, buildings, and industry. Owing to the global nature of renewable energy and battery markets, our report indicates the possibility that cost-effective decarbonization can be a near-term reality for other countries. More research is needed to identify the potential for near-complete decarbonization in the 2030 timeframe in other regions of the world. Such rapid decarbonization, if pursued by other high-emitting jurisdictions worldwide, would increase the likelihood of limiting global warming to 1.5°C.

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