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Offshore Wind Energy Planning

Important new modeling from the University of California at Berkeley and GridLab, led by Energy Innovation, reports the United States can reliably hit 90 percent clean energy by 2035, without increasing customer bills from todayâ€™s levels.

Plummeting costs for wind, solar, and energy storage are the driving force behind this trend. Actual wind and solar costs for 2017-2018 were lower than most modelsâ€™ projected costs for 2030-2035. Utility-scale wind energy has a slightly lower cost than photovoltaic solar energy.
See document uploaded below, The 2035 Report. This clean energy policy will significantly improve public health and generate large-magnitude economic benefits for the CA economy.

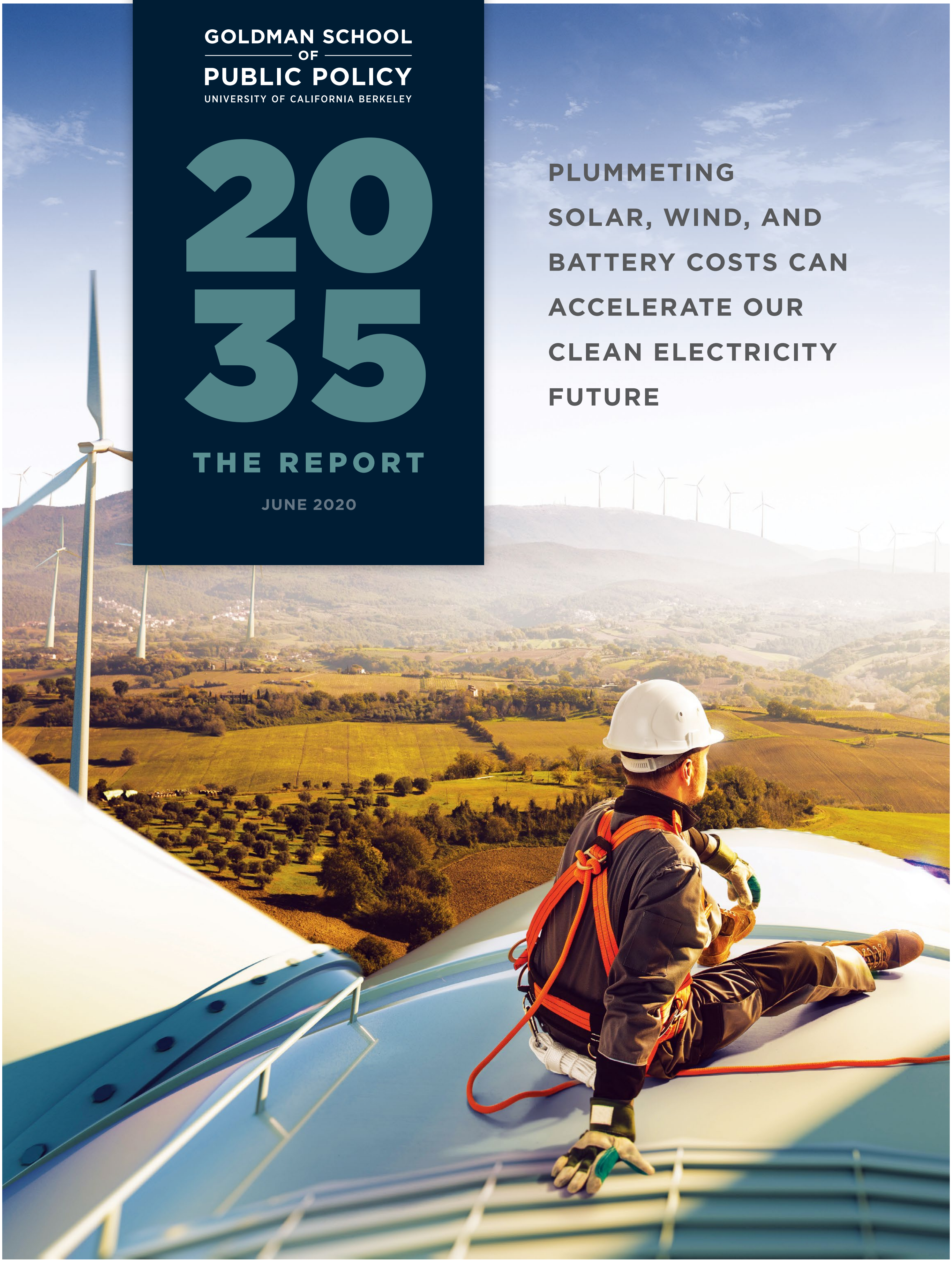
Additional submitted attachment is included below.

GOLDMAN SCHOOL OF PUBLIC POLICY
UNIVERSITY OF CALIFORNIA BERKELEY

2035
THE REPORT

JUNE 2020

PLUMMETING SOLAR, WIND, AND BATTERY COSTS CAN ACCELERATE OUR CLEAN ELECTRICITY FUTURE



EXECUTIVE SUMMARY

Global carbon emissions must be halved by 2030 to limit warming to 1.5°C and avoid catastrophic climate impacts. Most existing studies, however, examine 2050 as the year that deep decarbonization of electric power systems can be achieved—a timeline that would also hinder decarbonization of the buildings, industrial, and transportation sectors.

In light of recent trends, these studies present overly conservative estimates of decarbonization potential. 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 for cost-effectively integrating 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 90% clean (carbon-free) electricity in the United States by 2035. 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 90% Clean case requires that a 90% clean electricity share is reached by 2035.

KEY FINDINGS

Table ES-1 shows the report's findings at a glance, and the following discussion expands on these findings.

	CURRENT GRID (2019)	NO NEW POLICY (2035)	90% CLEAN (2035)
Highly Decarbonized Grid	● (red)	● (red)	● (green)
Dependable Grid	● (green)	● (green)	● (green)
Electricity Cost Reductions	-	● (green)	● (green)
Feasible Scale-Up	-	● (green)	● (green)
Highest Number of Jobs Supported	-	● (red)	● (green)
Largest Environmental Savings	-	● (red)	● (green)

TABLE ES-1.

U.S. Power System Characteristics by Case Modeled in the Report

STRONG POLICIES ARE REQUIRED TO CREATE A 90% CLEAN GRID BY 2035

The 90% Clean case assumes strong policies drive 90% clean electricity by 2035. The No New Policy case achieves only 55% clean electricity in 2035 (Figure ES-1). A companion report from Energy Innovation identifies institutional, market, and regulatory changes needed to facilitate the rapid transformation to a 90% clean power sector in the United States.

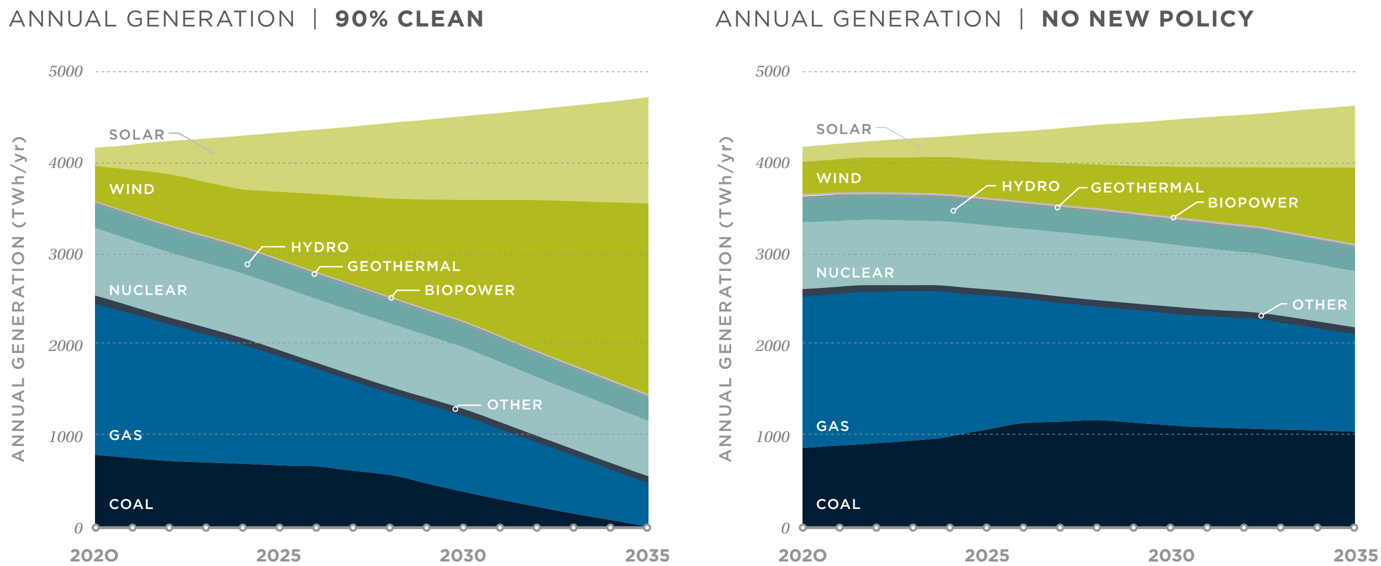


FIGURE ES-1.

Generation Mixes for the 90% Clean Case (left) and No New Policy Case (right), 2020–2035

THE 90% CLEAN GRID IS DEPENDABLE WITHOUT COAL PLANTS OR NEW NATURAL GAS PLANTS

Retaining existing hydropower and nuclear capacity (after accounting for planned retirements), and much of the existing natural gas capacity combined with new battery storage, is sufficient to meet U.S. electricity demand dependably (i.e., every hour of the year) with a 90% clean grid in 2035. Under the 90% Clean case, all existing coal plants are retired by 2035, and no new fossil fuel plants are built. During normal periods of generation and demand, wind, solar, and batteries provide 70% of annual generation, while hydropower and nuclear provide 20%. During periods of very high demand and/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/solar generation. Generation from natural gas plants constitutes about 10% of total annual electricity generation, which is about 70% lower than their generation in 2019.

ELECTRICITY COSTS FROM THE 90% CLEAN GRID ARE LOWER THAN TODAY'S COSTS

Wholesale electricity costs, which include the cost of generation plus incremental transmission investments, are about 10% lower in 2035 under the 90% Clean case than they are today, mainly owing to low renewable energy and battery costs (Figure ES-2). Pervasiveness of low-cost renewable energy and battery storage across the United States requires investment mainly in transmission spurs connecting renewable generation to existing high-capacity transmission lines or load centers. Hence, additional transmission-related costs and siting conflicts are modest. Relying on natural gas for only 10% of generation avoids large investments for infrequently used capacity, helping to avoid major new stranded-asset costs. Retaining natural gas generation averts the need to build excess renewable energy and long-duration storage capacity—helping achieve 90% clean electricity while keeping costs down. While still lower than today's costs, wholesale electricity costs are 12% higher under the 90% Clean case than under the No New Policy case in 2035. However, this comparison does not account for the value of emissions reductions or job creation under the 90% Clean case.

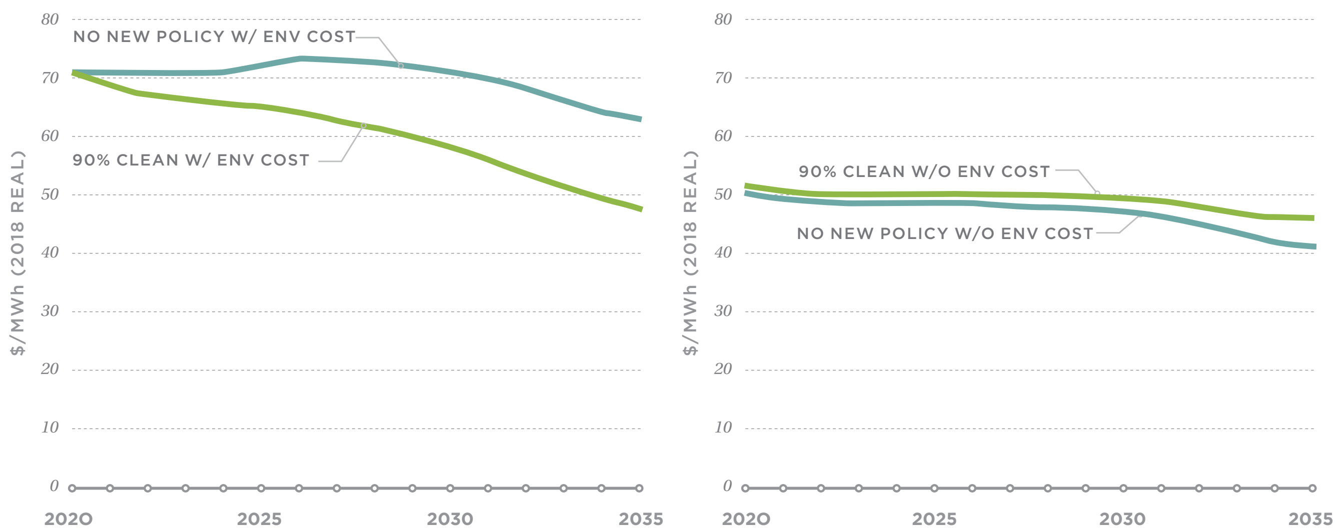


FIGURE ES-2.

Wholesale Electricity Costs with (left) and without (right) Environmental Costs, for the 90% Clean and No New Policy Cases

THE 90% CLEAN GRID AVOIDS $1.2 TRILLION IN HEALTH AND ENVIRONMENTAL DAMAGES, INCLUDING 85,000 PREMATURE DEATHS, THROUGH 2050

The 90% Clean case nearly eliminates emissions from the U.S. power sector by 2035, resulting in environmental and health benefits largely driven by reduced mortality related to electricity generation (Figure ES-3). Compared with the No New Policy case, the 90% Clean case reduces carbon dioxide (CO_2) emissions by 88% by 2035. It also reduces exposure to fine particulate ($PM_{2.5}$) matter by reducing nitrogen oxide (NO_x) and sulfur dioxide (SO_2) emissions by 96% and 99%, respectively.[1] As a result, the 90% Clean case avoids over $1.2 trillion in health and environmental costs, including 85,000 avoided premature deaths, through 2050. These savings equate roughly to 2 cents/kWh of wholesale

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

electricity costs, which makes the 90% Clean case the lowest-net-cost option when environmental and health costs are considered.

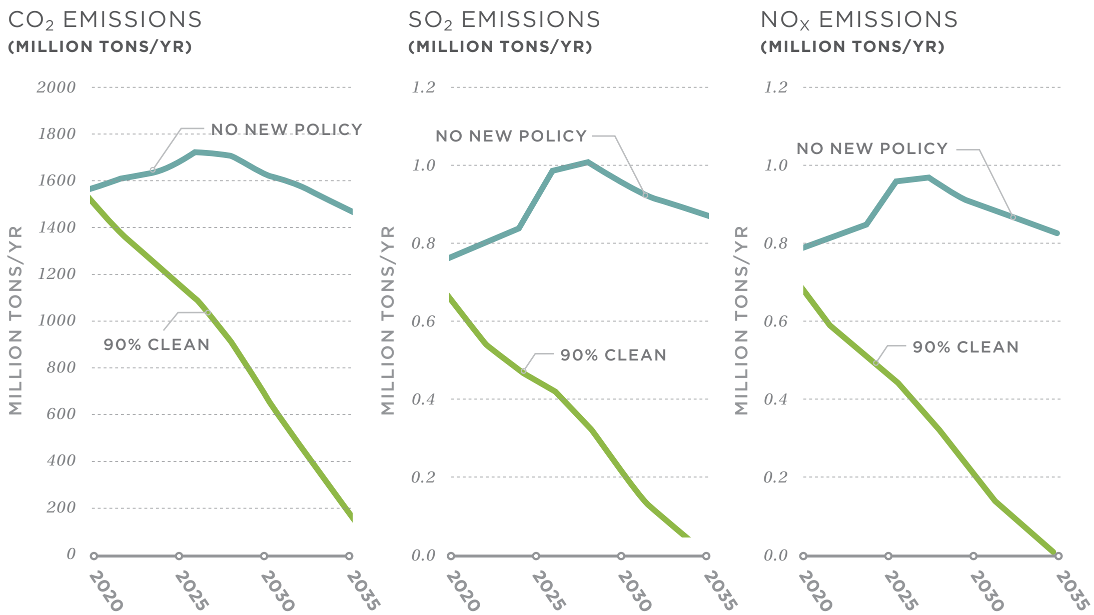


FIGURE ES-3.

Emissions of CO_2, SO_2, and NO_x in the 90% Clean and No New Policy Cases, 2020–2035

SCALING-UP RENEWABLES TO ACHIEVE 90% CLEAN ENERGY BY 2035 IS FEASIBLE

To achieve the 90% Clean case by 2035, 1,100 GW of new wind and solar generation must be built, averaging about 70 GW per year (Figure ES-4). Recent U.S. precedents for natural gas and wind/solar expansion suggest that a renewable energy buildout of this magnitude is challenging but feasible. New renewable resources can be built cost-effectively in all regions of the country.

CUMULATIVE NEW CAPACITY ADDITIONS

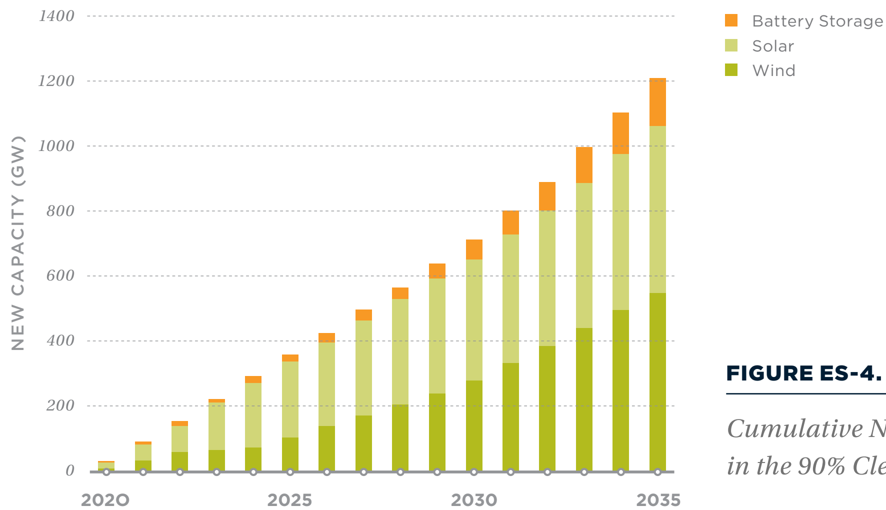


FIGURE ES-4.

Cumulative New Capacity Additions in the 90% Clean Case, 2020–2035

THE 90% CLEAN GRID CAN SIGNIFICANTLY INCREASE ENERGY-SECTOR EMPLOYMENT

The 90% Clean case supports a total of 29 million job-years cumulatively during 2020–2035. Employment related to the energy sector increases by approximately 8.5 million net job-years, as increased employment from expanding renewable energy and battery storage more than replaces lost employment related to declining fossil fuel generation. The No New Policy case requires one-third fewer jobs, for a total of 20 million job-years over the study period. These jobs include direct, indirect, and induced jobs related to construction, manufacturing, operations and maintenance, and the supply chain. Overall, the 90% Clean case supports over 500,000 more jobs each year compared to the No New Policy case.

ACCELERATING THE CLEAN ENERGY FUTURE

Establishing a target year of 2035, rather than the typical 2050 target, helps align expectations for power-sector decarbonization with climate realities while informing the policy dialogue needed to achieve such an ambitious goal. Aiming for 90% clean electricity—rather than 100%—by 2035 is also important for envisioning rapid, cost-effective decarbonization. By 2035, emerging technologies such as firm, low-carbon power should be mature enough to begin to replace the remaining natural gas generation as the nation accelerates toward 100%, cross-sector decarbonization. Reaching 90% zero-carbon electricity in the United States by 2035 would contribute a 27% reduction in economy-wide carbon emissions from 2010 levels.

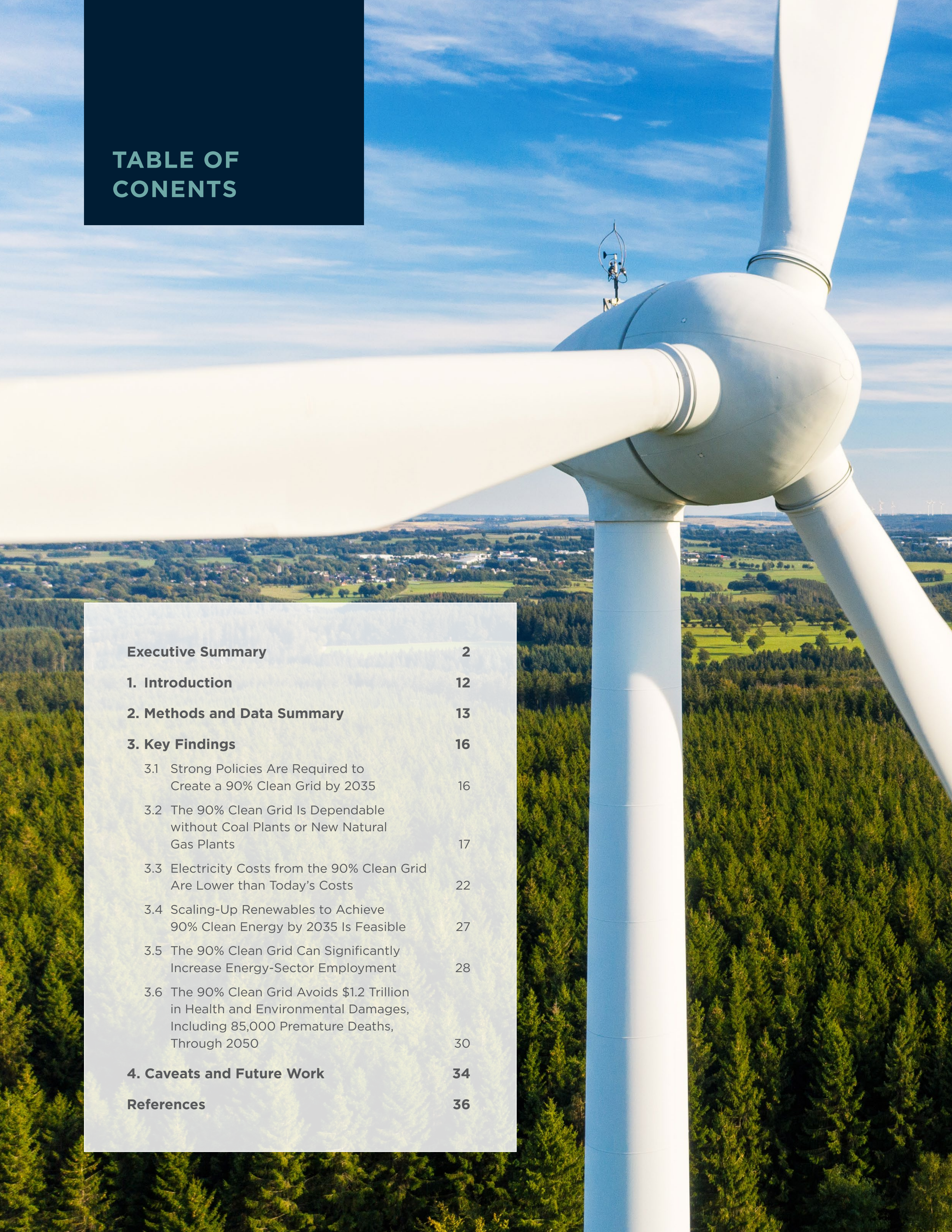


TABLE OF CONENTS

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Appendices, supporting reports, and data visualizations can be found at **2035report.com**

GOLDMAN SCHOOL OF PUBLIC POLICY
UNIVERSITY OF CALIFORNIA BERKELEY

GridLAB

ABOUT UNIVERSITY OF CALIFORNIA BERKELEY GOLDMAN SCHOOL OF PUBLIC POLICY

The Center for Environmental Public Policy, housed at UC Berkeley's Goldman School of Public Policy, takes an integrated approach to solving environmental problems and supports the creation and implementation of public policies based on exacting analytical standards that carefully define problems and match them with the most impactful solutions.

ABOUT GRIDLAB

GridLab is an innovative non-profit that provides technical grid expertise to enhance policy decision-making and to ensure a rapid transition to a reliable, cost-effective, and low-carbon future.

1

INTRODUCTION

In October 2018, the U.N. Intergovernmental Panel on Climate Change (IPCC) reported that global carbon emissions must be halved by 2030 to limit warming to 1.5°C and avoid catastrophic climate impacts (UN IPCC 2018). Most existing studies, however, examine 2050 as the year that deep decarbonization of electric power systems can be achieved—a timeline that would also hinder decarbonization of the buildings, industrial, and transportation sectors through electrification.[2] These studies offer little hope that climate change impacts can be held to a manageable level in this century.

Yet, in light of recent trends, these studies—even those published in the past few years—present overly conservative estimates of decarbonization potential. Plummeting costs and cost projections for wind and solar energy have dramatically changed the prospects for rapid, cost-effective decarbonization (Figure 1). At the same time, battery energy storage has become a viable option for cost-effectively integrating high levels of wind and solar generation into electricity grids.

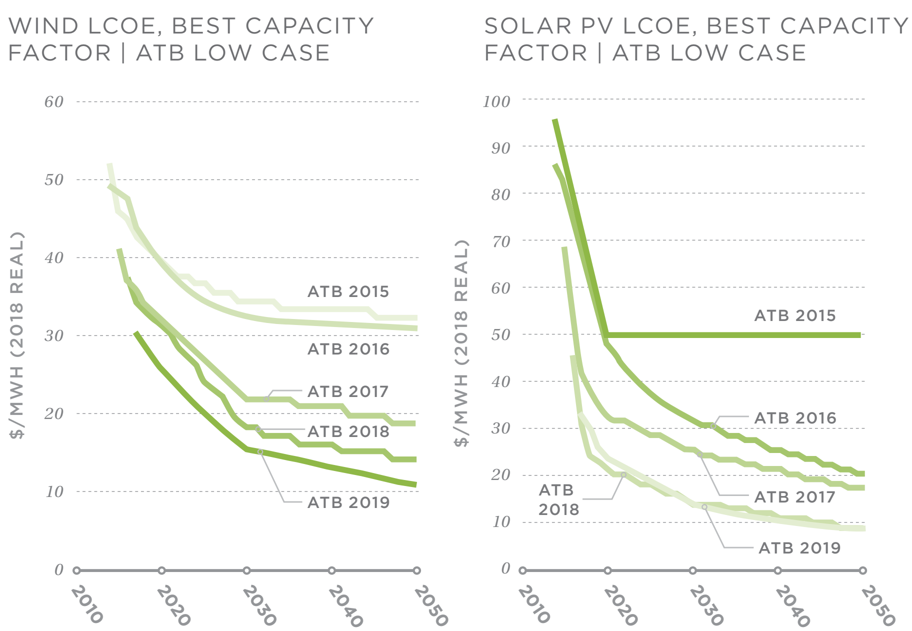

FIGURE 1.

National Renewable Energy Laboratory (NREL) Annual Technology Baseline (ATB) Low-Case Cost Projections Made 2015–2019 for Years Through 2050

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Wind (left) and solar photovoltaic (PV, right) levelized cost of electricity (LCOE) projections are shown by the year that each projection was made in the NREL ATB (NREL 2015; 2016; 2017; 2018; 2019) using ATB low-case assumptions and best capacity factors. LCOE projections were revised downwards in almost every year during this period.

2 Broadly, these studies do not assess near-complete power-sector decarbonization (80% decarbonization or greater) before 2050. The one study (MacDonald et al. 2016) that assesses complete decarbonization of the U.S. power sector by 2030 does not assume a significant role for battery storage, as our report does. Instead, it relies on expansion of the U.S. transmission network, which is technically and economically challenging (Joskow 2004). See Appendix 1 for a brief review of some of these studies.

2

METHODS AND DATA SUMMARY

This report uses the latest renewable energy and battery cost information to demonstrate the technical and economic feasibility of achieving 90% "clean" electricity in the United States by 2035—much more quickly than projected by most recent studies. Generation from any resource that does not produce direct carbon dioxide (CO_2) emissions is considered clean in this analysis, including generation from nuclear, hydropower, wind, solar,[3] biomass, and fossil fuel plants with carbon capture and storage. Consideration of the accelerated 2035 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 90% clean electricity (rather than 100%) by 2035 is also important for envisioning decarbonization at a pace more rapid than considered in previous studies. Achieving almost-complete power sector decarbonization in 2035 may ultimately increase the speed and cost-effectiveness of pervasive, cross-sector decarbonization.

After a brief description of methods and data, the key findings of the 2035 decarbonization report are summarized. The report's appendices provide details of the analyses and results. A companion report from Energy Innovation identifies institutional, market, and regulatory changes needed to facilitate the rapid transformation to a 90% clean power sector in the United States (Energy Innovation 2020).

We performed power-sector modeling in 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

3 The terms "solar" and "PV" are used interchangeably in this report, because essentially all the solar deployed in the simulations is PV; the concentrating solar power deployment is negligible.

based on NREL's ATB 2019 (NREL 2019).[4] 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.[5]
- **90% Clean:** Requires a national 90% clean electricity share by 2035.

We analyzed the sensitivity of the 90% Clean case to periods of extraordinarily low renewable energy generation and/or high demand, to ensure that a system with 90% renewable energy 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 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 90% Clean case on loss of load probability, system inertia, and alternating-current transmission flows.

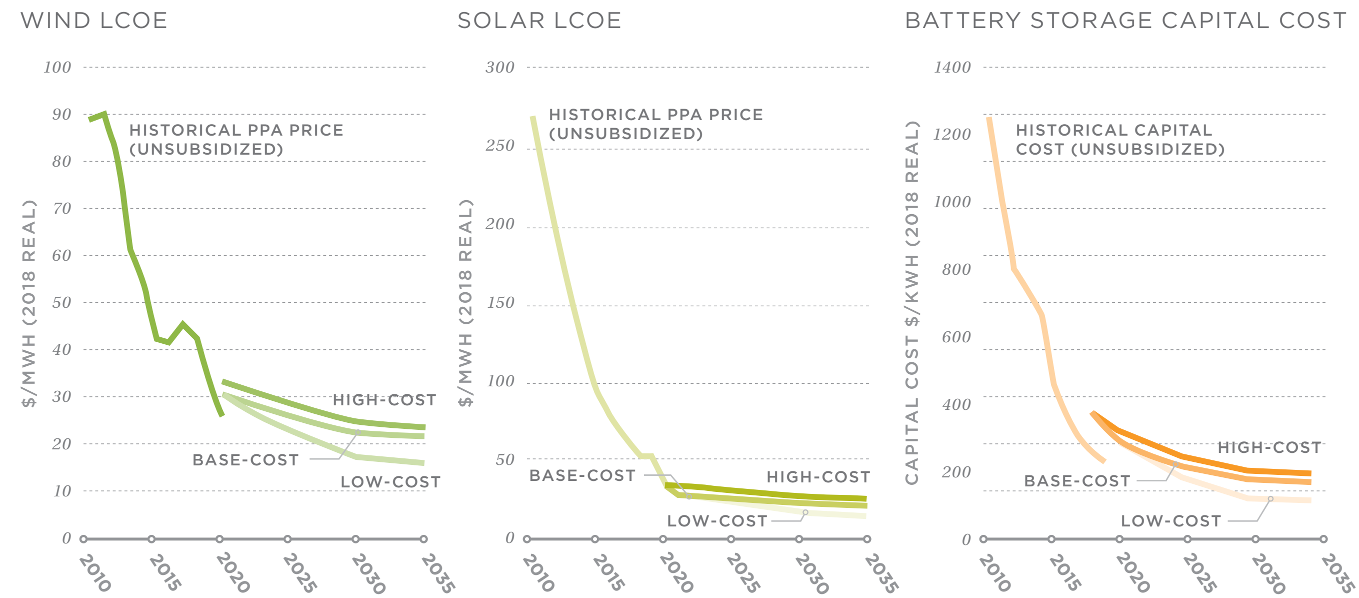
We also considered three primary sets of future renewable energy and battery storage cost assumptions (Figure 2; see Appendix 2 for in-depth cost analyses):

- **Low-Cost:** NREL ATB low-case assumptions, assuming 40% to 50% cost reductions for PV, wind, and storage by 2035 (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.

Appendix 3 details our additional scenario and sensitivity analyses, including a case that seeks to internalize the societal costs of CO_2 emissions. We also evaluated the impact of electrification using the high electrification case from the NREL Electrification Futures Study 2018 (Mai 2018).

4 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 2035, under the 90% Clean case, there are approximately 60 GW of distributed PV, representing approximately 2% of total energy generation. For detail on the renewable capacity breakdown, see Appendix 3.

5 ReEDS considers relevant state and federal policies, such as state Renewable Portfolio Standards, as of early 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, financing costs, and natural gas prices. We considered three primary sets of future renewable energy and battery storage technology costs (described above), two sets of financing costs, and two sets of natural gas prices. The base case financing costs correspond to the assumptions used in NREL (2019) and are in line with today's financing costs. The high financing costs assume that the cost of capital (real) is twice the cost assumed in the base case. The base case natural 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 natural gas prices use New York Mercantile Exchange (NYMEX) future prices until 2023, and beyond 2023 the price of natural gas is kept constant at $2.50/MMbtu (nominal), with a floor of $1.50/MMbtu (2018 real). We evaluate all permutations of these assumptions for the No New Policy and 90% Clean cases (24 cases in total). Refer to Appendix 3 for further sensitivity analyses.

We used the industry-standard IMPLAN model to estimate the job losses and gains associated with each of our cases. We used ReEDS to estimate emissions—CO_2 as well as sulfur dioxide (SO_2) and nitrogen oxides (NO_x)—associated with power generation based on emission factors for each generation technology. We used estimates of the social cost of carbon and damages associated with SO_2 and NO_x from the literature (as dollars and premature deaths per metric ton of pollutant) to estimate the environmental damages associated with each case. Results and assumptions are discussed below and in Appendix 2.

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 (2018a). Future cost projections for all three technologies were based on NREL (2019).

3

KEY FINDINGS

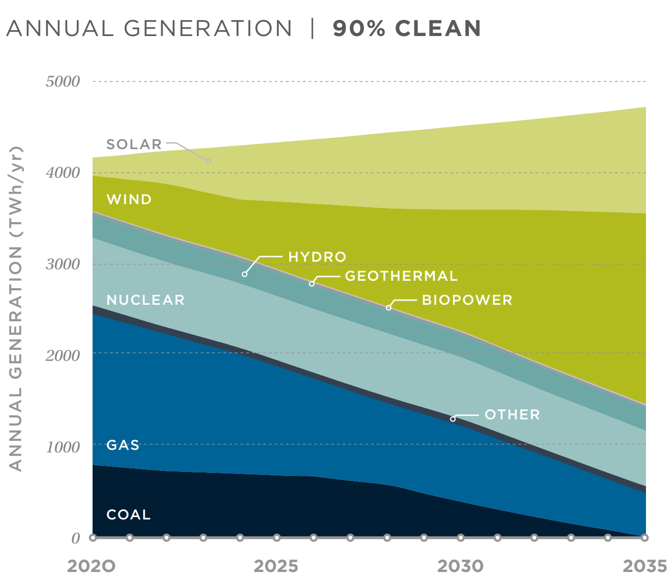
This section highlights the key findings from our analysis. Additional details are provided in the appendices.

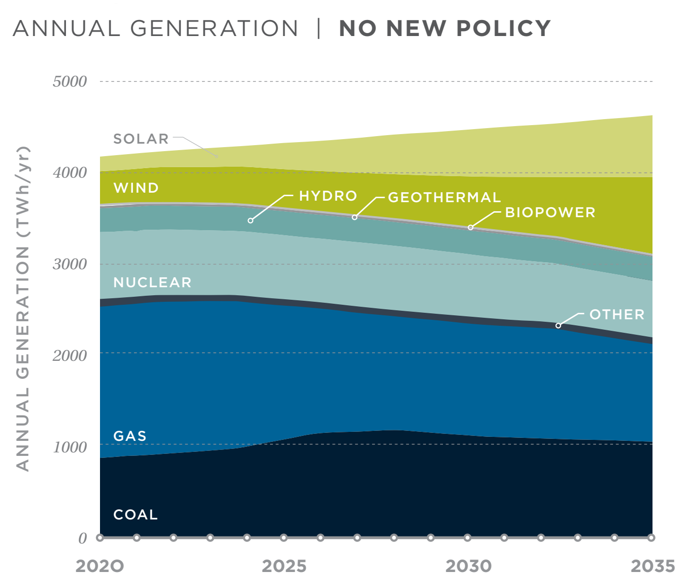
3.1 STRONG POLICIES ARE REQUIRED TO CREATE A 90% CLEAN GRID BY 2035

In our 90% Clean case, we require a 90% clean electricity share by 2035; that is, we set the 2035 grid mix to be 90% clean. In this analysis, clean generation refers to resources that produce no direct CO_2 emissions, including hydropower, nuclear, wind, PV, and biomass. 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 generators only supply 55% of the electricity in the No New Policy case in 2035. Figure 3 compares the grid mixes in the two cases. The 2035 grid mix from EIA's Annual Energy Outlook Reference Case is similar (47% clean generation) to the 2035 mix in the No New Policy case (EIA 2020a).

FIGURE 3.

Generation Mixes for the 90% Clean Case (left) and No New Policy Case (right), 2020–2035





The 90% 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 nominal electricity cost increases under the 90% Clean case are more than offset by the societal benefits provided by that case.

3.2 THE 90% CLEAN GRID IS DEPENDABLE WITHOUT COAL PLANTS OR NEW NATURAL GAS PLANTS

Given the dramatic decline in battery storage prices, we find that significant short-duration storage is cost-effective and plays a critical load in balancing the grid. We estimate that about 600 GWh (150 GW for 4 hours) of storage cost-effectively supports grid operations in the 90% Clean case, representing about 20% of daily electricity demand.[6] 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, about 14% of available renewable energy must be curtailed annually. New long-duration storage technologies might reduce curtailment further.

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.

During 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 94% below rated capacity (about 75 GW of generation from 1,220 GW of capacity) and 80% below the yearly average of wind and solar generation. Solar generation drops to zero in nighttime hours, whereas the lowest hourly period of wind generation is about 90% below

6 Because of modeling limitations, we only consider a 4-hour storage duration in this analysis.

average. The decline in wind and solar generation over days and weeks is progressively lower (Figure 4).

HIGHEST DROP IN WIND/SOLAR GENERATION (% OF AVERAGE)

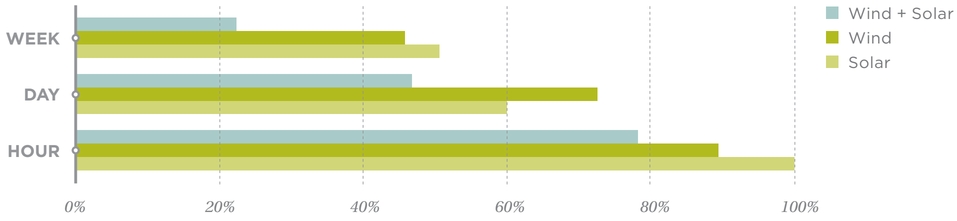


FIGURE 4.

Maximum Drop in Wind and Solar Output Relative to Average Wind and Solar Generation

To highlight the dependability of a 90% 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 needed to compensate for the largest gap between clean electricity generation (including battery generation) and load. The maximum natural gas capacity required is about 360 GW on August 1 in one of the weather years (2007) (Figure 5). At 8:00 pm Eastern Time on that day, solar generation declines to less than 10% of installed solar capacity, while wind generation is 18% below installed wind capacity, resulting in only about 150 GW of wind and solar production (about 55% below the annual average, as indicated in Figures 6 and 7). The total system demand of about 735 GW is met by a combination of other clean resources, such as hydropower and nuclear, approximately 360 GW of natural gas, and 80 GW of battery discharge (Figure 8).

HOURLY DISPATCH DURING THE MAX GAS GENERATION WEEK

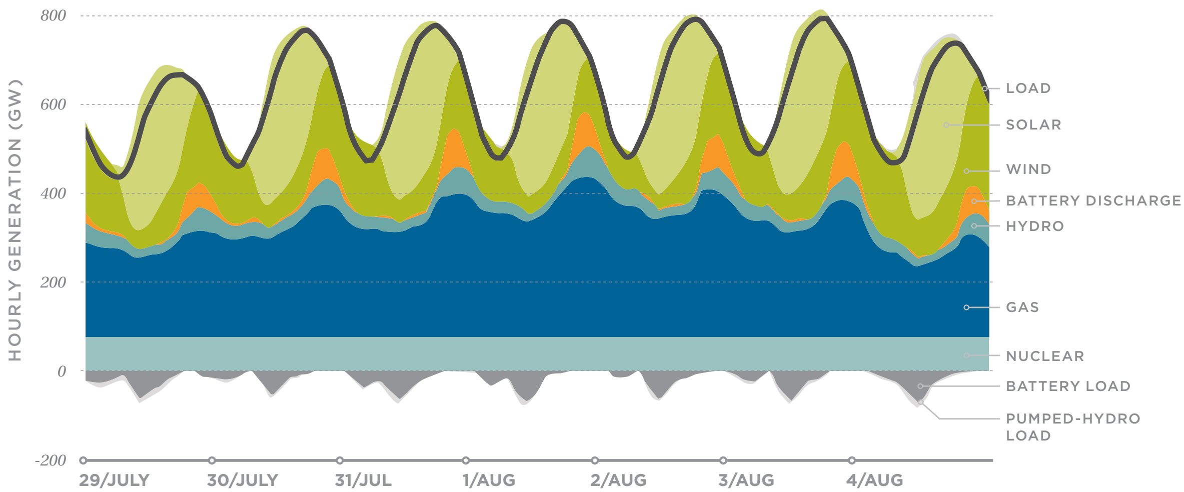


FIGURE 5.

Hourly U.S. Power-System Dispatch for Extreme Weather Days in the 90% Clean Case in 2035

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Figure 5 details the dispatch for the period of maximum natural gas generation, one week in late July and early August. Approximately 360 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 system operations.

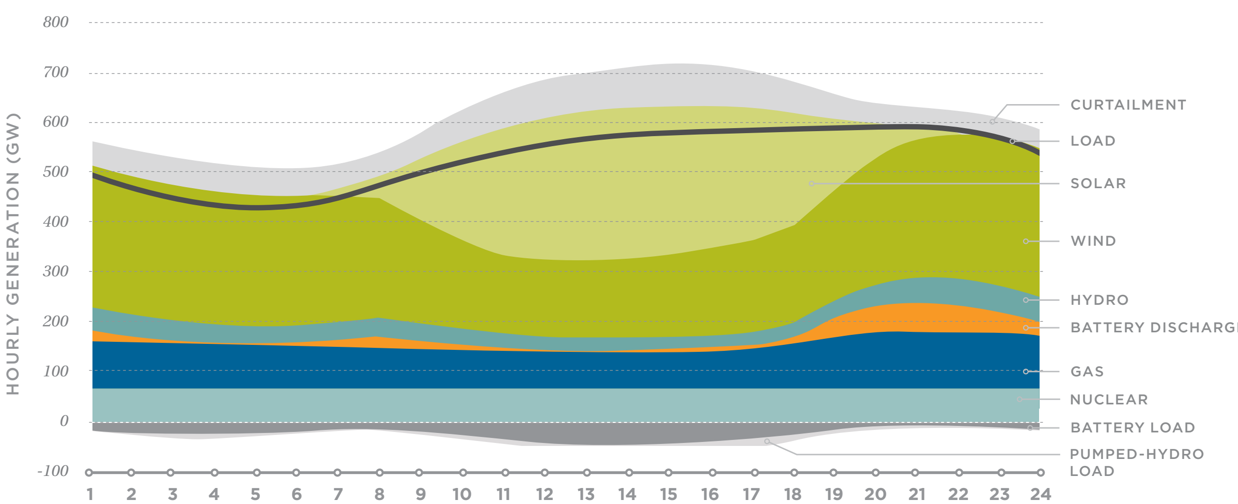

FIGURE 6.

Hourly U.S. Power-System Dispatch for an Average Weather Day in the 90% Clean Case in 2035

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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.

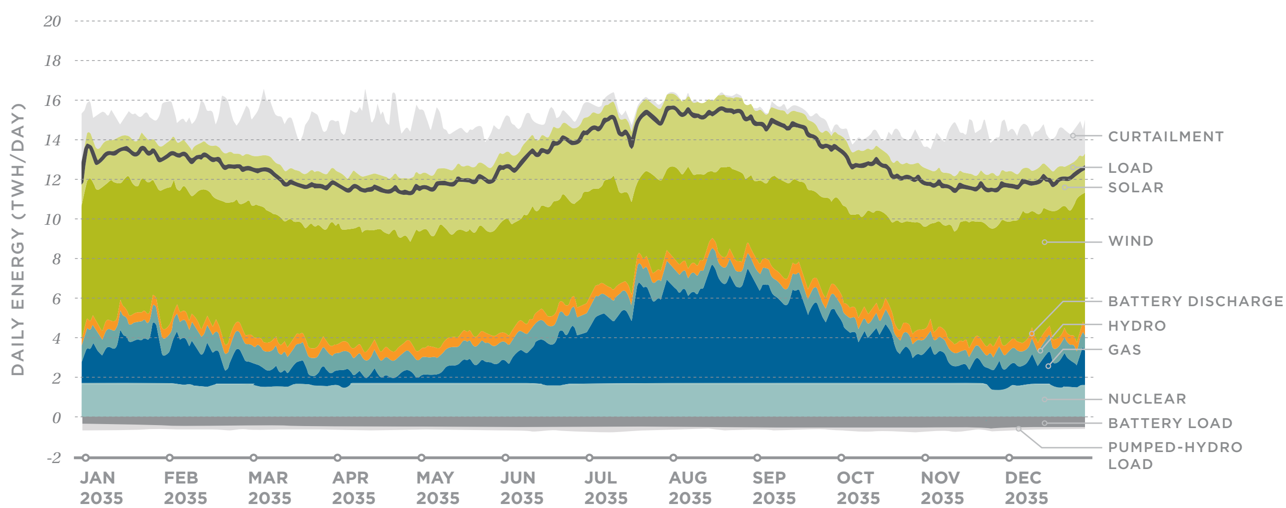
For all weather years, the natural gas capacity requirements are highest in August, when wind generation falls significantly (Figures 7 and 8). Natural gas generation above 300 GW is required for fewer than 45 hours per year over the 7-weather-year simulation. Of the 360 GW of natural gas dispatch in 2035 under the 90% Clean case, 70 GW has a capacity factor below 1%. Other technology alternatives not considered in this analysis, such as demand response, energy efficiency, or flexible load, may be more cost-effective for system balancing in those hours.

We also find that increased electrification of the U.S. economy reduces the amount of battery storage required, and results in slightly lower wholesale power costs than the 90% Clean Case (see Appendix 3).

FIGURE 7.

Daily U.S. Power System Dispatch Averaged Over 7 Weather Years in the 90% Clean Case in 2035

DAILY ENERGY BALANCE



GAS GENERATION IN 2035 FOR SEVEN WEATHER YEARS

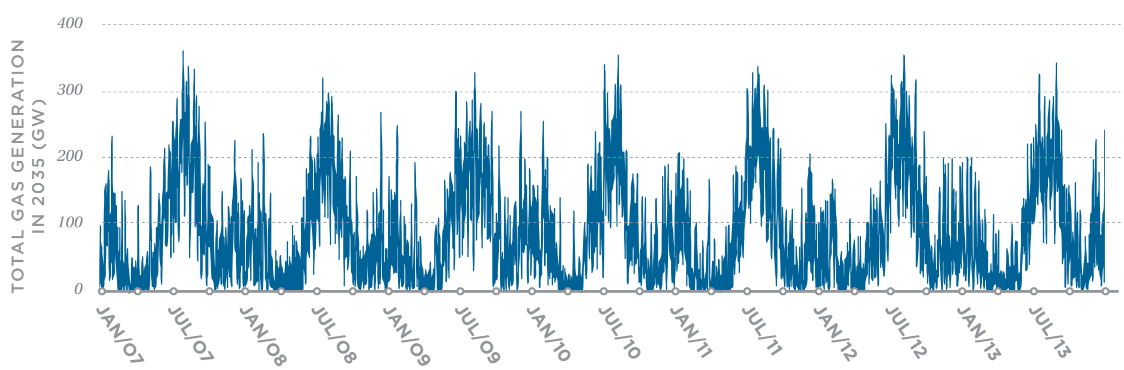


FIGURE 8.

Hourly U.S. Natural Gas Dispatch over 7 Weather Years in the 90% Clean Case in 2035

Figure 8 details the hourly natural gas generation in 2035 for 7 weather years. The maximum natural gas generation required is 360 GW.

The 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), although they may underestimate the variation in wind generation compared to that seen in our data, as Shaner et al. considers significantly lower spatial resolution than our study. Our analysis does not consider 35 weather years owing to lack of data. Further, our simulation includes adequate natural gas and battery storage capacity to meet residual load (load minus clean energy generation) that is up to 113% of average load and 70% 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, retaining existing hydropower capacity and nuclear power capacity (after accounting for planned retirements) and about half of existing fossil fuel capacity, combined with 150 GW of new 4-hour battery storage, is sufficient to meet U.S. electricity demand with a 90% clean grid in 2035, even during periods of low renewable energy generation and/or high demand. Under the 90% Clean case, all existing coal plants are retired by 2035, 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 70% of total annual generation, while hydropower and nuclear provide 20%. During periods of high demand and/or low renewable generation, existing natural gas plants (primarily combined-cycle plants) cost-effectively compensate for remaining mismatches between demand and renewables-plus-battery generation—accounting for about 10% of total annual electricity generation, which is about 70% lower than their generation in 2019.

Although the capacity-expansion modeling (ReEDS) required that clean resources contribute 90% of annual generation in 2035, the hourly operational model (PLEXOS) simulated roughly 85% clean generation, primarily due to 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 a 90% clean energy constraint, as modeled in our 90% Clean Case, clean energy may bid negative prices in certain hours in order to get dispatched and meet the 90% constraint. We utilize ReEDS to effectively model this 90% 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 90% 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 90% clean energy. Various complementary approaches could help achieve this deep decarbonization, with potential for even lower system costs and accelerated emissions reductions. Demand-side approaches include demand response and flexible loads, such as flexible electric vehicle charging and flexible water heating—which could play a large role if building and vehicle electrification occurs more rapidly than envisioned in our core cases. 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. Firm, low-carbon resources could include electricity generation from gases (such as hydrogen or methane) produced via excess clean electricity, small modular nuclear reactors, long-duration storage, or other emerging technologies. Such alternative approaches to balancing generation and demand could cost less than retaining significant natural gas capacity that is rarely used.

3.3 ELECTRICITY COSTS FROM THE 90% CLEAN GRID ARE LOWER THAN TODAY'S COSTS

Wholesale electricity (generation plus incremental transmission) costs are lower in 2035 under the 90% Clean case than they are today (Figure 9).[8] The base wholesale electricity cost under the 90% Clean case is 4.6 cents/kWh, about 10% lower than the 5.1 cents/kWh in 2020. Wholesale costs in the 90% Clean case in 2035 are 4.2–5.6 cents/kWh across all cost sensitivities. The only sensitivity case in which those costs are marginally (10%) higher than costs in 2020 assumes both high technology costs and high financing costs (see Appendix 3 for details). Lower wholesale costs would translate into lower retail electricity prices, assuming electricity distribution costs do not change significantly in the 90% Clean case.[9]

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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 2019.

9 We assume distribution costs do not rise faster than inflation in the next 15 years. Because the 90% 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 2035, under the 90% Clean case, there are approximately 60 GW of distributed PV, representing approximately 2% of total energy generation.

These findings are similar to the findings of power-system studies conducted in the past 1–2 years, but the clean power system target date for most of those studies is 15 years later than 2035 (Jayadev et al. 2020, Bogdanov et al. 2019). Our findings contrast sharply with the findings of studies completed more than 5 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%–70% above 2010 prices, for a system with 90% 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.

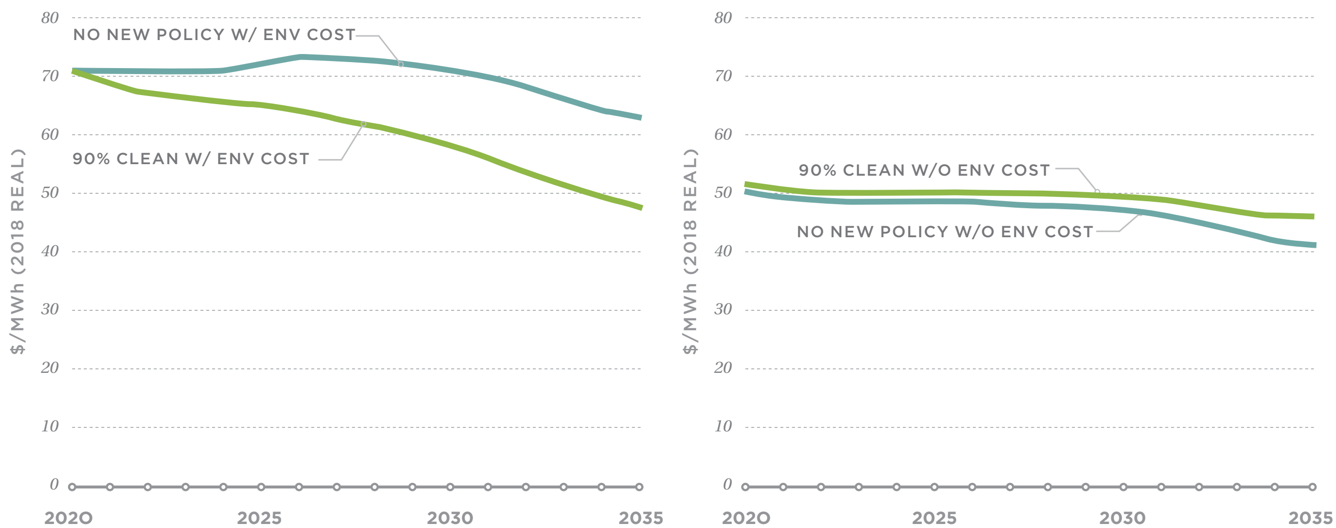

FIGURE 9.

Wholesale Electricity Costs (Costs of Generation and Incremental Transmission) with (left) and without (right) Environmental (Air Pollution and Carbon Emissions) Costs, for the 90% Clean and No New Policy Cases

If environmental costs are included, wholesale electricity costs are about 33% lower in 2035 under the 90% Clean case than they are in 2020, and they are 25% lower in 2035 under the 90% Clean case than they are in 2035 under the No New Policy case. Without considering environmental costs, wholesale electricity costs are 10% lower in 2035 under the 90% Clean case than they are in 2020, but they are 12% higher in 2035 under the 90% Clean case than they are in 2035 under the No New Policy case.

Low renewable energy and storage costs are the primary reason that electricity costs decline under the 90% Clean case. Section 2 shows the dramatic national 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.

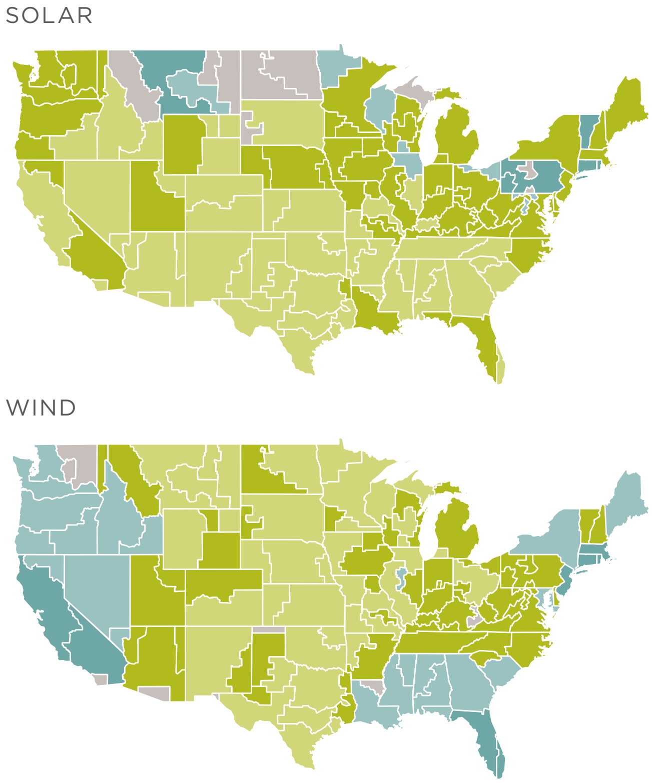

FIGURE 10.

Average Solar (top) and Wind (bottom) LCOE by Region in the 90% Clean Case in 2035

The maps show capacity-weighted average LCOE for the least-cost portfolio to meet the 90% 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 3.5 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 90% Clean case, most transmission investments are in new spurline transmission rather than bulk transmission (Figure 11).[10] Although the 90% Clean case requires about three times more spurline investment than the No New Policy case does, the total transmission requirements in the 90% Clean case add only 0.2 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] 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 90% Clean case, limited new bulk transmission investments are necessary.

NEW TRANSMISSION INVESTMENT, 2020-2035

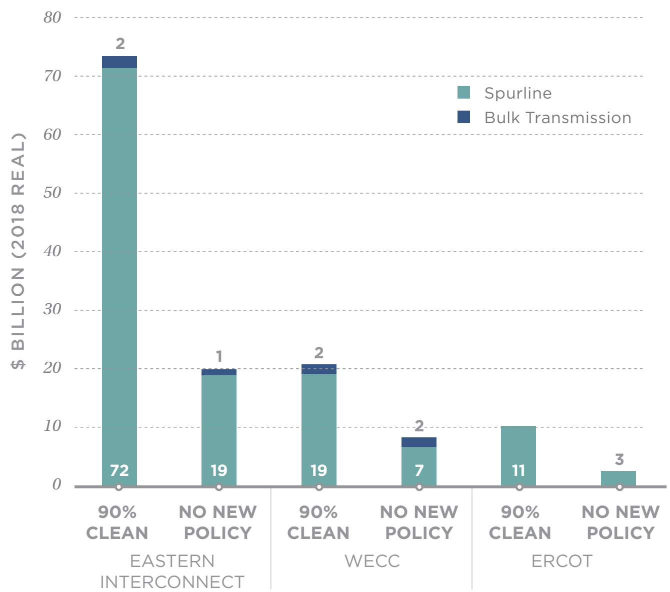

FIGURE 11.

Additional Spurline and Bulk Transmission Investments by Interconnect under the 90% Clean and No New Policy Cases, 2020–2035

The vast majority of transmission investments are spurline investments as opposed to bulk transmission system investments. Total transmission investments add only 0.2 cents/kWh to system costs in the 90% Clean case. ERCOT = Electric Reliability Council of Texas, WECC = Western Electricity Coordinating Council.

Low electricity costs in the 90% Clean case are also facilitated by the limited use of fossil fuel generators; all coal plants are retired by 2035, and no new natural gas plants are built (see Section 3.2). Thus, the 90% Clean case avoids large amounts of fuel and large investments in generating capacity that is used infrequently. In addition, using a 2035 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 1,000 GW of U.S. fossil fuel generation capacity operating today, 800 GW will be at least 30 years old in 2035 (Figure 12) (Jell 2017). At this time, a high percentage of the coal and older natural gas units will be fully 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, as discussed in an accompanying report from Energy Innovation (Energy Innovation 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 accompanying report from Energy Innovation for further discussion of stranded assets (Energy Innovation 2020).

UNDEPRECIATED VALUE OF EXISTING FOSSIL ASSETS ($ BILLION)

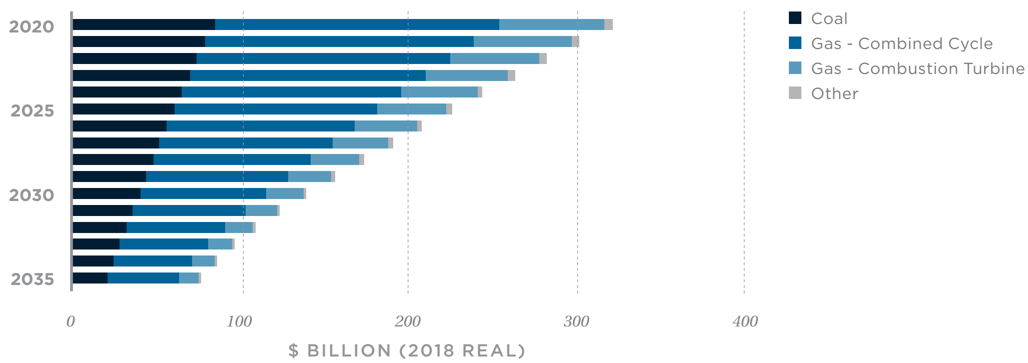

FIGURE 12.

Undepreciated Value of Existing U.S. Fossil Fuel Capacity, 2020–2035

By 2035, the remaining undepreciated value of fossil fuel generating plants is minimal, suggesting a transition to 90% clean energy can be accomplished with minimal stranded assets.

Conversely, using existing natural gas capacity to meet about 10% of electricity demand avoids the need to build excess renewable energy and long-duration storage capacity—helping accelerate the timeline for 90% clean electricity while keeping costs down. Further decarbonization could then build on this mostly clean electricity system; several pathways to 100% clean electricity have been identified. See Appendix 1 for a brief literature review on many of these analyses.

Although electricity costs are lower in 2035 under the 90% Clean case than they are today, they are 0.46 cents/kWh (12%) higher than they are under the No New Policy case in 2035 (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 90% Clean case than they are under the No New Policy case (see Section 3.6). In addition, the 90% Clean case supports additional jobs in the electricity sector compared with the No New Policy case (Section 3.5). Finally, significant natural gas capacity is built under the No New Policy case, which likely will result in future stranded costs, whereas no new fossil fuel capacity is built under the 90% Clean case.[14]

14 If there still are a few coal units owned by regulated utilities that, in 2035 (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 90% CLEAN ENERGY BY 2035 IS FEASIBLE

To achieve the 90% Clean case by 2035, 1,100 GW of new wind and solar generation must be built, averaging about 70 GW per year (Figure 13). 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. For example, 65 GW of U.S. natural gas generation were built in 2002 (Ray 2017).

CUMULATIVE NEW CAPACITY ADDITIONS

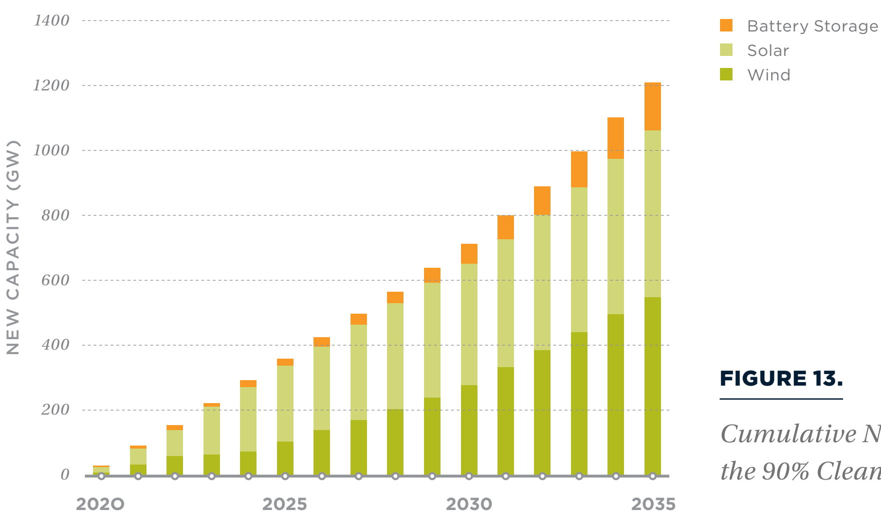

FIGURE 13.

Cumulative New Capacity Additions in the 90% Clean Case, 2020–2035

Historical and planned U.S. renewable energy deployments also suggest that annual deployments of 70 GW are possible. In 2016, 15 GW of PV were installed, and EIA suggests that 19.4 GW of wind will be deployed in 2020 (EIA 2020b). Interconnection queues in the United States currently include 544 GW of wind, solar, and standalone battery storage, roughly half of the 1,100 GW required (Bolinger et al. 2019a, 2019b). 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, as highlighted in an accompanying report from Energy Innovation (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% 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%).

3.5 THE 90% CLEAN GRID CAN SIGNIFICANTLY INCREASE ENERGY-SECTOR EMPLOYMENT

The COVID-19 pandemic has taken a heavy human and economic toll. In just 6 weeks, the pandemic wiped out over 40 million American jobs. In a slack labor market, such as the one that Americans may experience in the coming years owing to a contracting economy, a clean energy buildout could be a key part of the economic recovery.

The 90% Clean case supports approximately 29 million job-years cumulatively during 2020–2035. Employment related to the energy sector increases by about 8.5 million job-years as increased employment from expanding renewable energy and battery storage more than replaces lost employment related to declining fossil fuel generation (Figure 14). The No New Policy case requires one-third fewer jobs, for a total of 20 million job-years over the study period. These jobs include direct, indirect, and induced jobs related to construction, manufacturing, operations and maintenance, and the supply chain.[15] In the 90% Clean case, an increase in construction- and manufacturing-related jobs outweighs a smaller decrease in jobs related to operations and maintenance. Fossil fuel power-sector jobs are dominated by fuel handling, operations, and maintenance activity. Solar, wind, and storage plants require less daily maintenance and no fuel handling, but they do require far more labor-intensive construction jobs.[16]

15 A job-year represents one full-time job held for one year.

16 There is uncertainty about where clean energy manufacturing might occur in a 90% Clean case. The employment factors modeled in IMPLAN assume most PV, wind, and battery component manufacturing occurs in the United States. This assumption potentially overstates the resulting domestic jobs in all scenarios; those results should be considered as upper bounds of employment potential. Supporting federal policy can drive employment in these sectors and ensure jobs in manufacturing and the supply chain remain in the United States, as indicated in a supporting report from Energy Innovation (2020).

CUMULATIVE JOB-YEARS ('000), 90% CLEAN COMPARED TO NO NEW POLICY

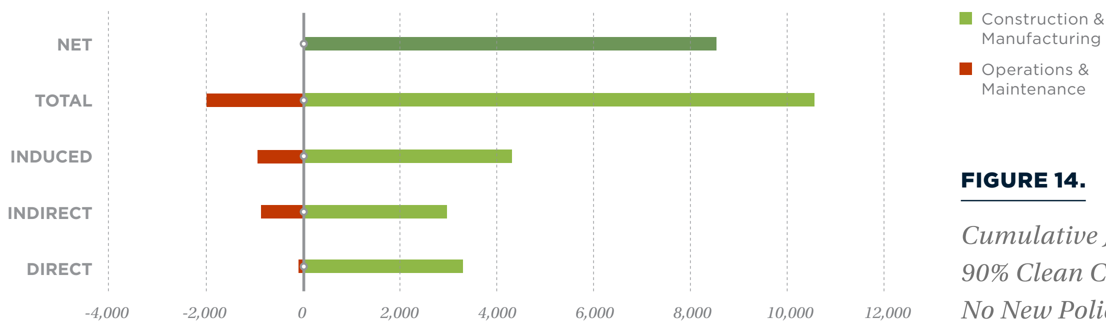

FIGURE 14.

Cumulative Job-Years 2020–2035, 90% Clean Case Compared to the No New Policy Case

Overall, the 90% Clean case supports over 500,000 more jobs each year compared to the No New Policy case. A loss of about 100,000 fossil fuel operations and maintenance jobs is more than offset by growth in wind and solar construction of over 600,000 jobs per year.

The 90% Clean case supports about 1.8 million ongoing jobs, or a total of approximately 29 million job-years from 2020–2035. About 1.1 million jobs, or 18 million job-years, are related to the construction, manufacturing, and supply chain of the electricity system (including induced jobs). The additional 700,000 jobs (11 million job-years) are related to operations and maintenance.

In contrast, the No New Policy case supports approximately 1.3 million ongoing jobs, or 20 million job-years from 2020–2035. Approximately 460,000 ongoing jobs (7.4 million job-years) are related to construction, manufacturing, and supply chain industries, while another 813,000 (13 million job-years) are related to operations and maintenance.

Although economic models such as IMPLAN are useful in determining the upside potential of job creation, the results are only realized through significant policy support. The extraordinary economic downturn resulting from the COVID-19 pandemic presents an opportunity to drive job creation in the near term through accelerated renewable energy deployment. The 2009 American Reinvestment and Recovery Act can serve as a model for effective stimulus spending (Mundaca and Luth Richter 2015).

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. A supporting report from Energy Innovation highlights key policy drivers to support coal community services, health, and employment during the energy transition (Energy Innovation 2020).

Appendix 4 reports the employment results in detail.

3.6 THE 90% CLEAN GRID AVOIDS $1.2 TRILLION IN HEALTH AND ENVIRONMENTAL DAMAGES, INCLUDING 85,000 PREMATURE DEATHS, THROUGH 2050

The 90% Clean case nearly eliminates emissions from the U.S. power sector by 2035 (Figure 15), resulting in environmental cost savings as well as reduced mortality related to electricity generation. Further, achieving 90% clean electricity by 2035 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, SO_2, and fine particulate matter ($PM_{2.5}$) emissions using an established method from the literature.[17] Compared to the No New Policy case, in the 90% Clean case CO_2 emissions are reduced by 1,300 million metric tons (88%) through 2035, while NO_x and SO_2 emissions are reduced by 96% and 99%, respectively (Figure 15). See Appendix 4 for details of the analysis.

17 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 SO_2, NO_x, and $PM_{2.5}$ are based on state-by-state damage factors provided by Maninder Thind based on Thind et al. (2019).

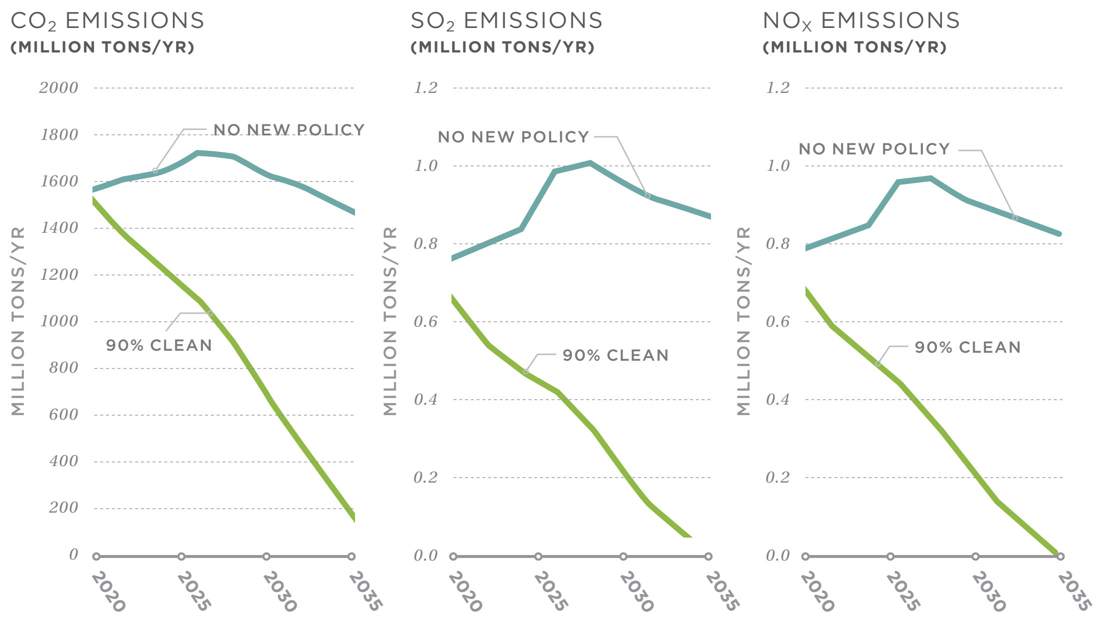

FIGURE 15.

Emissions of CO_2, SO_2, and NO_x in the 90% Clean and No New Policy Cases, 2020–2035

As a result, the 90% Clean case avoids about $1.2 trillion (in 2018 dollars) in environmental and health costs through 2050, including approximately 85,000 premature deaths, largely due to avoided SO_2, NO_x, and CO_2 emissions from coal plants (Figure 16) (Holland et al. 2019).[18] The environmental cost savings from the 90% Clean case roughly equate to 2 cents/kWh of wholesale electricity costs. Avoided premature deaths are primarily because of reduced exposure to $PM_{2.5}$, driven by reductions in SO_2 emissions, a precursor to $PM_{2.5}$, from coal plants.[19] About 60% of the avoided environmental costs are from avoided CO_2 emissions, with the remainder associated with reduced exposure to $PM_{2.5}$.

18 Coal power generation accounted for about 90% of air pollution related premature deaths and about 60% of CO_2 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). This fact, and the very low capacity factors predicted for coal plants in 2035, led us to assume that all coal power plants retire after 40 years of life (which allows them to recover most of their fixed costs). In 2035, we find that about 10% of the coal capacity will be 40 years old or younger.

19 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% of premature deaths due to $PM_{2.5}$ exposure.

CUMULATIVE PREMATURE DEATHS

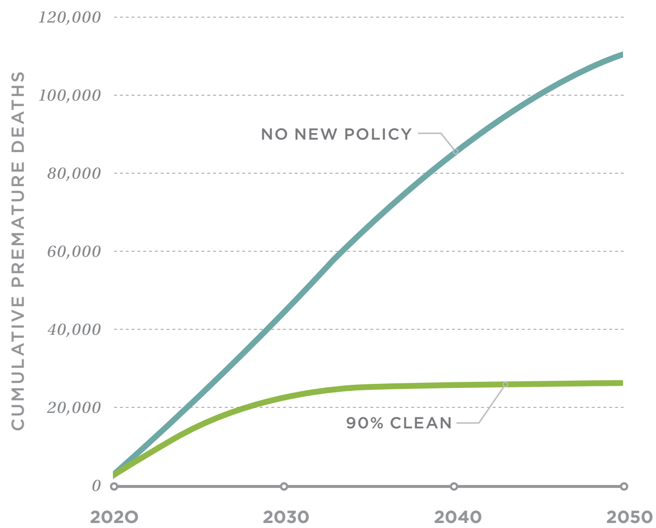

FIGURE 16.

Cumulative Premature Deaths Due to SO_2 and NO_x Pollution, 2020–2050

THE 90% CLEAN CASE AVOIDS ABOUT 85,000 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. 2019). Our estimate of premature deaths (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 premature deaths.[20] Our assumptions regarding the social cost of carbon are based on the lower range of estimates of national social cost of carbon calculations.

Important milestones can be achieved before 2035 as well. This report shows that, by 2030, the United States can reach over 70% zero-carbon electricity on the grid at no additional cost. The IPCC states that global economy-wide emissions must be reduced 45% by 2030 from 2010 levels to limit warming to 1.5° (UN IPCC 2018). Using a 2010 baseline, reaching over 70% zero-carbon electricity in the United States by 2030 would contribute an 18% reduction in U.S. economy-wide emissions, and reaching 90% zero-carbon electricity would contribute a 27% reduction by 2035. This is a meaningful contribution to the overall

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

requirements outlined by the IPCC, and a clean electricity system can help reduce emissions from transportation and buildings via conversion to electric vehicles and appliances.

Refining the estimates of benefits from the 90% Clean case is an important area for future work. Appendix 4 provides analysis of two particular impacts of expanding renewable energy technologies and shrinking fossil fuel generation: reduced water use and increased land use related to electricity generation.

ACHIEVING A 100%-CLEAN U.S. POWER SECTOR

This report's target of 90% clean electricity (rather than 100%) by 2035 is important for envisioning decarbonization at a pace more rapid than considered in conventional policymaking and academic research. The use of currently available, cost-effective technology to accelerate near-complete power-sector decarbonization provides additional time and resources to pursue complete power-sector decarbonization. Significant uncertainties surround the economic and operational viability of potential technologies and strategies needed to achieve 100% power-sector decarbonization, and these approaches are subject to considerable debate. Research and development needs and policies to scale up the technologies needed for 100% clean electricity are detailed in Energy Innovation's companion policy report (2020).

The major contribution of our report is its demonstration of a path to near-complete power-sector decarbonization that is readily available and cost-effective—only concerted policy action is required to ramp-up affordable clean generation and stop the construction of unnecessary fossil fuel plants. Achieving this near-complete power-sector decarbonization in 2035 may ultimately increase the speed and cost-effectiveness of pervasive, cross-sector decarbonization.

SOCIAL COST OF CARBON CASE

We analyze a scenario in which the social costs of CO_2 emissions are embedded into the wholesale generation cost of fossil fuel plants. The CO_2 price begins at $10/metric ton in 2020, ramps up by 5% until 2025, and then increases 1.5% each year thereafter, reaching $50/metric ton in 2035.

This case rapidly accelerates the early retirement of coal power and dramatically scales up early investments in new renewable energy resources. Although this case is slightly more expensive than the No New Policy case, the reductions in CO_2 emissions, air pollutants, and associated environmental costs are extraordinarily large. See Appendix 2 and 3 for details.

4

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 a 90% 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 90% 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 a 90% 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 (Energy Innovation 2020). Further study limitations and a more robust narrative of detailed results can be found in the appendices.

The 2035 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 90% clean energy by 2035 without increasing consumer bills or impacting the operability of the electric grid. In doing so, the U.S. power sector can inject over $1.7 trillion in clean energy investments into the U.S. economy, support employment equivalent to about 29 million job-years cumulatively during 2020–2035, and largely eliminate planet-warming and air pollution emissions from electricity generation. This 90% clean electricity grid can provide clean, dependable power without the construction of new fossil fuel plants. However, the 90% clean grid cannot be achieved without concerted policy action, and business-as-usual could lead to over $1.2 trillion in cumulative health and environmental damages, including 85,000 premature deaths.

Perhaps most importantly, this report shows that the timeline for near-complete decarbonization of the electric sector can be accelerated from 2050 to 2035. 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 regions and countries. More research is needed to identify the potential for near-complete decarbonization in the 2035 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.

This report's target of 90% clean electricity (rather than 100%) by 2035 is also important for envisioning decarbonization at a pace more rapid than considered in previous studies. This target allows some existing natural gas generation capacity to be used infrequently to meet demand during periods of low renewable energy generation, which otherwise require major additional investments in renewable energy and energy storage, increasing costs dramatically.

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