Federal Policy for Low-Carbon, High-Renewables Electricity

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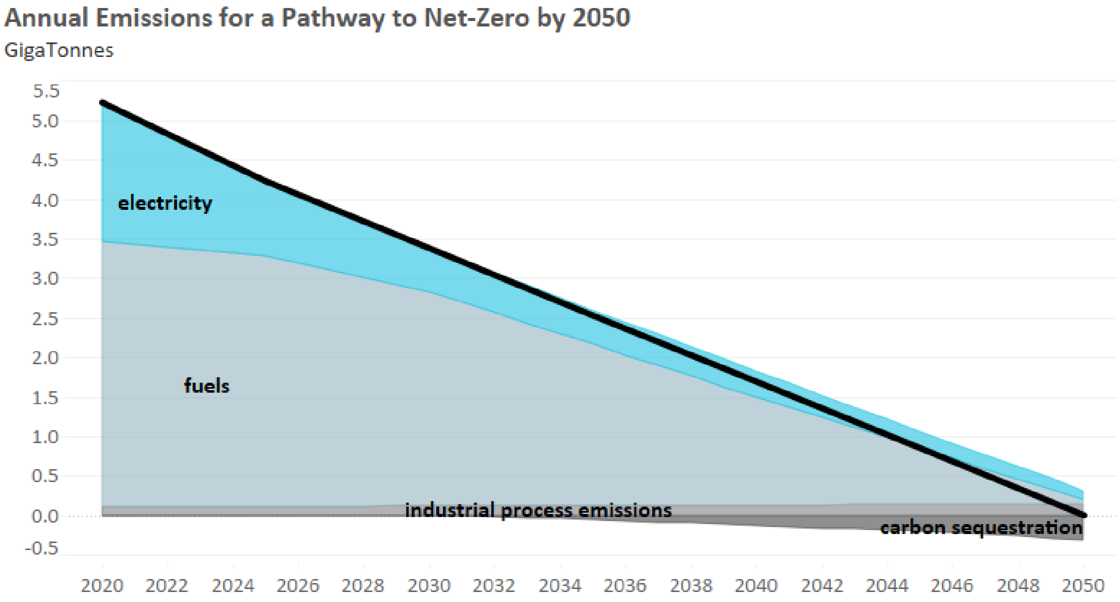
Executive Summary

To minimize the damage from climate change, human emissions of CO_2 must reach net-zero by the middle of this century. Electricity is the key to achieving this goal because decarbonized electricity is the main "fuel" for a net-zero economy. This paper describes the physical transformation of the electricity system required for the United States to reach carbon neutrality by 2050, and analyzes the pros and cons of different federal policy approaches for achieving that outcome, with recommendations for the near term.

This analysis is grounded in rigorous, high-resolution modeling of the technology pathways to net-zero greenhouse emissions for the U.S. economy as a whole.[1] The electricity system transformation we describe is the least-cost portfolio of changes in power generation and transmission needed to enable the U.S. to follow a straight-line path from today's total emissions of more than five billion metric tons of CO_2 to net-zero in 2050 (Figure ES1).

To reach net-zero at the lowest overall cost to the U.S. economy, electricity must set the pace, decarbonizing first, fastest, and most deeply. This is because electricity can be decarbonized more quickly and at a lower cost than fuels, with fewer indirect impacts on the environment, and because electricity decarbonization is synergistic with electrifying buildings and transportation, which are critical steps in the overall decarbonization strategy. The resulting emissions pathway for electricity is a very steep decline in emissions over the next decade, followed by a more gradual decline out to mid-century (Figure ES2).

Figure ES1. Least-cost pathway to net-zero CO_2 emissions from energy by 2050



To be on track to net-zero economy-wide, by 2030, the carbon emissions per unit of electricity must decline by 65%, achieved by retiring all coal power plants and raising the share of zero-

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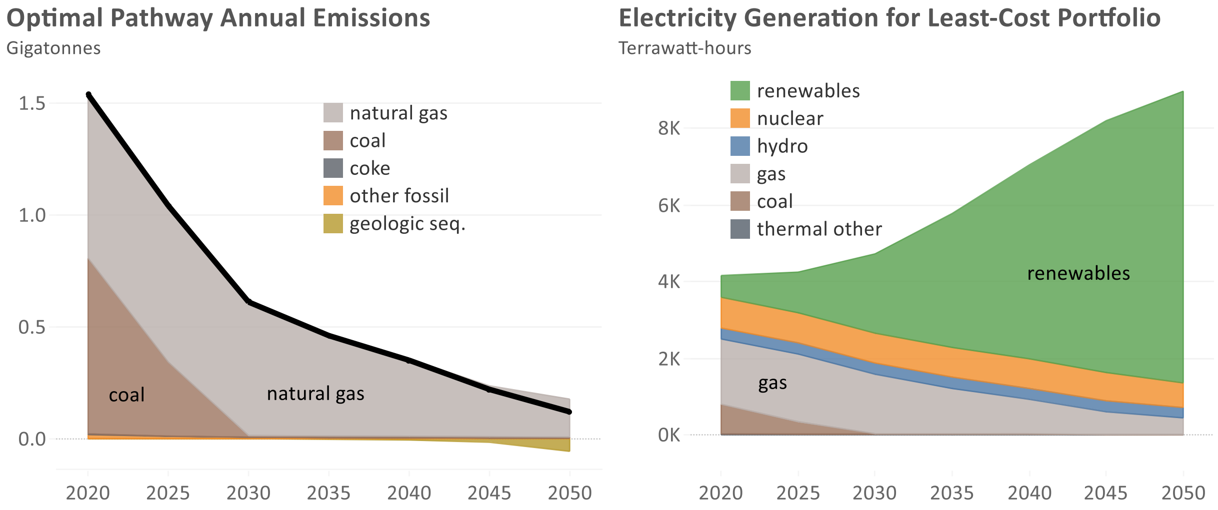
[1] This analysis builds on our recent work on economy-wide decarbonization: J. Williams, R. Jones, B. Haley, G. Kwok, J. Hargreaves, J. Farbes, M.S. Torn, "Carbon-neutral pathways for the United States," article in submission, 2020

carbon generation from renewables, nuclear, or hydro to almost 70%. By 2050, electricity must be nearly emissions free, though it can have small residual emissions offset elsewhere in the energy system by carbon sequestration.

Of the main options for zero-carbon power generation—renewables, nuclear, and fossil fuels with carbon capture and storage (CCS)—it is renewables, primarily wind and solar, that will form the backbone of the decarbonized electricity system. This is because renewables (1) are now the lowest cost form of carbon-free energy; (2) can be sited quickly and more flexibly than the alternatives; and (3) are already expanding much more rapidly than new nuclear or CCS capacity. We found the least-cost portfolio for the U.S. as a whole to be 45% renewables in 2030, and 85% in 2050 (Figure ES2).

Figure ES2. The least-cost electricity pathway (L) steeply reduces emissions in the next decade by (R) rapidly increasing renewable generation and retiring all coal by 2030.



There are challenges in building and operating an electricity system with very high levels of intermittent wind and solar, which is a departure from electricity systems of the past. However, these challenges are eminently solvable using an ensemble of different resources for balancing supply and demand and minimizing system cost. These resources include gas power plants, which are essential for reliability; expanded transmission; energy storage; flexible end-uses ranging from electric vehicle charging to hydrogen production; and, when needed, renewable curtailment. There is the potential for land-use constraints and social acceptance to limit the scale and pace of renewables development, making nuclear and CCS power generation more competitive. In this paper, we explore some of the actions the federal government can take to help address these challenges.

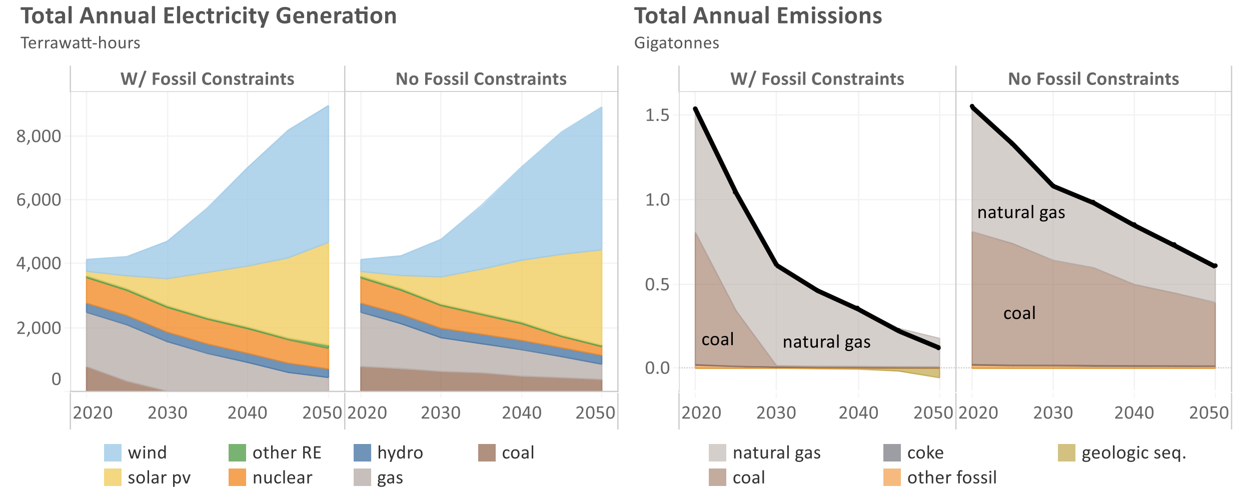
The electricity system must do four things to provide reliable service, keep costs down, and meet decarbonization targets:

- Meet growing demand from the electrification of vehicles, buildings, and industry;
- Rapidly increase zero-carbon generation, primarily from renewables;

- Retire coal power plants; and
- Maintain the gas generation fleet at its current level of capacity for reliability, while reducing how often these plants are operated to limit emissions

The importance of achieving these outcomes in concert is illustrated in Figure ES3. Two electricity systems have the same level of renewable generation and reliability, but one has explicit limits on fossil fuel generation, and one does not. Even though the generation mix is mostly renewable in both cases, the system with fossil limits follows the required decarbonization trajectory for net-zero in 2050, and the other fails dramatically to do so. This is a critical dimension along which to evaluate policy proposals.

Figure ES3. Comparison of two scenarios with the same amount of renewables, one with constraints on fossil generators versus one with no constraints on fossil generators.



There are five main types of federal policy approaches that can enable the transformation to a low-carbon, high-renewables electricity system:

- Direct subsidies, such as tax credits
- Technology mandates, such as clean energy standards
- Carbon pricing, such as a carbon tax
- Carbon caps, such as cap and trade
- Emissions rate standards, such as emissions intensity limits

The advantages and disadvantages of each of these approaches for meeting the electricity system objectives are described in Table ES1, along with additional considerations of implementation challenges.

Table ES1. Comparison of policy approaches for supporting the transition to a low-carbon, high-renewables electricity system.

Policy Approach	Example	Advantages	Disadvantages	Additional considerations
Direct subsidies	Production tax credit	• Directly supports zero-carbon generation • Can be used to catalyze market transformation within the context of broader policies	• Does not directly lead to coal retirements • Policy typically sunsets • Exact emissions reductions are not known • Typically is not technology agnostic	• Direct government subsidy keeps electricity prices low • Subsidy needs to be sustained to meet emissions targets
Technology mandate	Clean energy standard	• Provides long-term clarity on zero-carbon generation • Easy to explain • CO_2 emissions can be known with reasonable certainty if the shift from coal to gas can be accomplished	• Without partial credit for gas generators, will not retire coal by itself • Schemes for partial credit are complex and reduce the clarity of outcomes and ease of explanation	• Can either be technology agnostic or can let society express technology preferences • Policy costs typically remain hidden
Carbon pricing	Carbon tax	• Straight-forward approach for coal to gas switching • Revenue generating	• Zero-carbon procurement incentives are indirect • Exact policy impact on emissions is unknown • Emissions fluctuate with fossil fuel prices	• Long-term price certainty is critical for driving investment, but adjustments in price trajectory are essential for climate outcomes
Carbon caps	Cap and trade	• CO_2 emissions can be known precisely • Can generate revenue • Allows explicit flexibility between regions • Provides direct incentives for coal-to-gas switching and zero-carbon generation	• Zero-carbon procurement incentives are indirect and uncertain • Price ceilings degrade emissions certainty • Adds transactional costs from financial markets	• Uncertainty in the rates of economy-wide electrification make real-world target setting more difficult
Emission rate standard	Annual average emissions rate cap (gram/kWh)	• Emissions can be known with reasonable certainty • Provides incentives for both coal to gas switching and zero-carbon generation	• Difficult to explain to non-experts • Zero-carbon procurement incentives are indirect	• Uncertainty in the rates of economy-wide electrification means exact electricity-sector emissions are unknown

A few general observations can be made on the different policy approaches based on the pros and cons table above:

- Subsidies: Tax credits support the expansion of zero-carbon generation, but with their focus only on new investment, they do not provide the policy needed to drive existing carbon emissions out of the system. Also, tax credits that lapse after a set time do not provide the sustained support required for the full zero-carbon buildout.

- Technology mandates: Clean energy standards (CES) require a steadily increasing percentage of generation to be 'clean'; the key questions are the rate of increase and which resources qualify. We found that when CES qualification requirements were too restrictive, for example, 100% wind, water, and solar (WWS),[2] costs increased dramatically. Conventional CES policies can drive the buildout of renewables and other zero-carbon generation but do not directly affect the operation of fossil fuel plants. We found a CES policy that is not designed to address this issue increases the share of wind and solar side but continues to rely on existing coal generation, resulting in excessive emissions. If federal policy were to rest on a CES alone, it would have to include rules that distinguish between the emissions rates of different thermal plants to retire coal while maintaining gas capacity.

- Carbon prices: The practical questions are setting the initial level and how high to make the subsequent escalation rate. A modest carbon price is effective in driving coal retirement but is a much less robust policy for driving the buildout of zero-carbon generation. This is because a policy based on the difference in costs between fossil fuels and renewable generation is very sensitive to either unexpectedly low fossil fuel prices or unexpectedly high renewables costs. Accordingly, we found that a high initial carbon price was not required ($20/tonne is sufficient) but that the price must increase steadily and predictably to $150/tonne in 2050, given our assumptions about future costs. Even so, there is no guarantee that $150/tonne will be the most efficient price for achieving the necessary emissions reductions when the time comes.

- A critical dimension along which policy options should be compared is the complex relationship between renewables and natural gas. Renewables must continue to grow, and natural gas generation must diminish over time. Rising carbon prices can decrease natural gas generation and increase renewable investment, but are not robust to declines in natural gas prices. In contrast, a CES is robust to falling gas prices for driving renewable build and can ensure a reduction in thermal generation. However, distinguishing between emissions rates for different thermal power plants within a CES policy complicates implementation.

- Even as gas generation is declining, gas capacity must be maintained at levels comparable to today to maintain reliability at the least-cost.[3] Said another way, the number of gas plants should remain the same even though each plant operates for far fewer hours every year. This will require changes in wholesale markets to allow cost recovery for generators that operate infrequently. More broadly, under all policy

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[2] Assumed under the WWS definition is that all thermal power plants must be retired and all electricity balancing is done with hydroelectricity, energy storage technologies, and dispatchable loads.

[3] See the 'Balancing challenges for a high renewable system are significant but solvable' portion of the body of the report for additional details.

approaches, electricity markets and the Federal Energy Regulatory Commission will have a critical supporting role in enabling the necessary changes. They need to update rules and regulations to address the challenges of high levels of renewables and the transition to a system with high fixed and low variable costs.

For comparison, the numerical targets for each approach were adjusted so that the policy produced an emissions trajectory comparable to the optimal pathway shown in Figure ES2. The results of this analysis are shown in Table ES2. The body of the report provides more details on the effects of the different policy options on emissions and costs.

Table ES2. Numerical targets for each policy approach that are needed to reach emissions reductions that are consistent with the least-cost electricity decarbonization pathway.

Policy Approach	Description and Caveats	Targets for Equivalent Decarbonization by Year
Direct Subsidies: **Extension of existing federal production and investment tax credits**	Tax credits alone cannot directly drive coal retirements or reduce operations of gas plants at the scale needed to follow the emissions pathway. However, increasing and extending the effective subsidy from these tax credits can drive the necessary renewable deployment.	2020: < 2 cents/kWh 2030: 2.7 cents/kWh 2040: 3.1 cents/kWh 2050: 3.3 cents/kWh
Technology Mandates: **Electricity standard with a 0.4 tonnes/MWh eligibility standard**	A technology mandate in which specified types of generation comprise an increasing share of total generation. The policy includes limited gas generation for reliability.	2020: 39% of all generation 2030: 85% of all generation 2040: 96% of all generation 2050: 99% of all generation
Carbon pricing: **Carbon tax**	A carbon price for the electricity sector that escalates over time.	2020: start at $20/tonne 2030: $50/tonne 2040: $75/tonne 2050: $150/tonne
Carbon cap: **Cap and trade**	A national cap on the electricity sector that limits annual emissions.	2020: < 2,000 million tonnes 2030: 610 million tonnes 2040: 350 million tonnes 2050: 120 million tonnes
Emission Rate Standards: **Generation emission standard**	A mandated average generator emissions intensity for the national generation fleet.	2020: < 500 grams/kWh 2030: 135 grams/kWh 2040: 57 grams/kWh 2050: 16 grams/kWh

In principle, any of these approaches, except for subsidies alone, could be turned into the instrument for driving the transition to a high renewables, net-zero electricity system, if they are designed with sufficient care. That said, hybrid policies that use combined approaches to achieve different objectives, compensating for the shortcomings of each approach as a stand-alone policy, seem more likely to succeed.

Based on our analysis, we recommend a hybrid policy package that includes three elements: (1) a clean energy standard, (2) a policy or regulatory instrument narrowly focused on coal power plants, and (3) direct subsidies for emerging technologies. The rationale for this approach is based on this analysis and political considerations around implementation:

- Clean energy standards are popular and offer long-term clarity for investors, regulators, and the public. It is technology agnostic but can be adjusted to exclude unpopular technologies (e.g., nuclear) based on societal and political requirements. It effectively "hides" the cost of the policy, which becomes subsumed within electricity rates. Finally, because it determines the long-term mix of technologies explicitly, CO_2 emissions can be known with reasonable certainty as long as coal to gas switching is accomplished.

- A separate policy or regulatory approach tailored to signal the need for coal retirements directly and transparently by 2030. Having a separate policy to address coal avoids complicated modifications to the CES policy. A range of approaches could be well suited to drive this outcome, including some form of carbon pricing, either through a cap and trade or a carbon tax, or an emissions intensity standard.

- Direct subsidies are sometimes necessary for supporting promising, but less mature technologies (e.g., small modular reactors) as they compete with more mature options (e.g., onshore wind). The use of subsidies to enable market transformation has an established track record of success and will remain a critical tool for enabling less mature decarbonization technologies to scale. The current solar PV market is the result of this type of transformation, and the technology is now critical to electricity decarbonization. Under this hybrid approach, direct subsidies for mature technologies (e.g., wind and solar PV) can be phased out, as the CES policy will drive the deployment of these market-competitive resources.

List of Terms

AEO – The Annual Energy Outlook a set of modeled results released annually by the U.S. government that forecasts the energy system under current policy for the next three decades.

CCS – Carbon capture and storage (also called carbon capture and sequestration)

CES – Clean Energy Standard, a form of a clean electricity mandate where eligibility rules include renewables and other generators, which could consist of only zero-carbon resources or lower-carbon intensity resources depending on the policy's rules.

CO_2 – Carbon dioxide, the primary greenhouse gas responsible for human-caused warming of the climate

DOE – U.S. Department of Energy

EnergyPATHWAYS – An open-source, bottom-up energy, and carbon planning tool for evaluating long-term, economy-wide greenhouse gas mitigation scenarios.

FERC – Federal Energy Regulatory Commission

Gigatonne –Billions of metric tons, which in the context of this paper is always a mass measurement of CO_2.

GW – Gigawatt (billion watts)

GWh – Gigawatt hour (equivalent to one million kilowatt-hours)

ITC – Investment Tax Credit, an existing federal subsidy that provides a tax credit based on the installed capacity of eligible generation.

MMBtu – Million British thermal units, an energy unit typically applied to natural gas

Optimal Electricity Pathway – The annual emissions budget for the U.S. electricity sector that enables the whole U.S. economy to achieve net-zero CO_2 emissions from energy and industry in 2050 at least-cost.

PTC – Production Tax Credit, an existing federal subsidy that provides a tax credit based on the annual volume of generation for eligible generators.

Quad – Quadrillion British thermal units, an energy unit typically used in energy system models to compare primary and final energy flows.

Renewable curtailment – When grid operators cause renewable generators to produce less energy than they are otherwise capable of generating due to system reliability needs.

RIO – Regional Investment and Operations Platform, an optimization tool built by Evolved Energy Research to explore electricity systems and fuels

RPS – Renewable Portfolio Standard, a common form of a clean electricity mandate where generally only renewable generation, excluding large hydro, is eligible for the policy.

Service demand – Demand for the service which energy consumption enables (e.g., miles traveled, units of hot water, units of refrigeration)

Terawatt-hour (TWh) – Equivalent to one billion kilowatt-hours

Tonne – Metric ton, which in the context of this paper is always a mass measurement of CO_2

WWS – A scenario where only wind, water, and solar resources are allowed by 2050, all thermal resources are retired, but battery energy storage is allowed on the system.

Introduction

Reducing CO_2 emissions in the U.S. economy from today's levels to net-zero in 2050 will require marked but achievable changes throughout all sectors. The electricity sector will have a critical part to play in the transition. This paper explores the role of the electricity sector in an economy-wide, least-cost pathway to carbon neutrality by mid-century and how federal policy can drive the necessary changes to achieve a low carbon electricity system, including a discussion of the pros and cons of different policy approaches. The analysis behind this paper provides insights on the optimal pathway of emission reductions for the electricity sector, including the transformation of the generation fleet and the supporting policies needed to enable the high renewable system that can lead the economy's decarbonization efforts. Results in this paper come from an electricity-focused, economy-wide cost minimization model,[4] and the analysis builds on recent work that examines reducing CO_2 emissions to net-zero in 2050.[5]

This paper explores these topics over five sections: the first section defines the role of the electricity sector within an economy-wide, long-term effort to achieve net-zero CO_2 from energy by 2050; the second explores challenges associated with deploying very high-levels of renewables on an electricity system that can follow the desired emission reduction trajectory; the third section establishes what is necessary from federal policy to transition to a national low-carbon electricity system; the fourth addresses how national policy approaches can follow the least-cost emission reduction trajectory for the electricity sector; and the final section contrasts relative strengths and weaknesses of policy approaches along with a hybrid policy recommendation.

Electricity in Economy-Wide Decarbonization

Energy use in the current U.S. economy predominately comes from the largely unchecked combustion of fossil fuel. The current heavy reliance on these fuels will require a large-scale transformation of the energy infrastructure that powers the economy to achieve carbon neutrality within the next thirty years. This scale of decarbonization will require major increases in carbon-free energy sources, up from the modest levels today. The electricity sector will have a critical role in increasing carbon-free resources and providing the lowest-cost carbon-neutral energy to many portions of the economy.

While most of the existing providers of carbon-free energy are a result of policy, relying on existing policy mechanisms alone will be insufficient to achieve carbon neutrality by mid-century for the whole of the U.S. Some state-level and regional policies have the potential to drive major emission reductions for portions of the country, but federal policy will be needed to enable a

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[4] See the appendix for more details on the modeling platform and methodology

[5] J. Williams, R. Jones, B. Haley, G. Kwok, J. Hargreaves, J. Farbes, M.S. Torn, "Carbon-neutral pathways for the United States," article in submission, 2020

national transition. Numerous recent analyses[6] indicate that this national transition will rely heavily on the electricity sector, with energy use shifting away from the combustion of fuels and toward electricity provided primarily by low-cost renewable generation.

Through a least-cost, economy-wide modeling exercise, we have identified a national annual CO_2 emissions budget for electricity, consistent with an economy-wide straight-line path to net-zero CO_2 emissions by mid-century. Achieving these changes will require differentiated roles for the sectors in the economy, with the electricity sector playing a central part in national decarbonization efforts. With effective planning and coordination across sectors, electricity can provide emission reductions at lower costs than alternatives.

The electricity sector decarbonizes first on an economy-wide pathway to net-zero CO_2 by 2050

The least-cost emission reduction trajectory results in faster emissions declines for the electricity sector in the 2020s than in any other area of the economy. Figure 4 shows emission reductions from electricity, direct combustion of fuels, industrial processes, and carbon sequestration for the least-cost trajectory. Emissions from the electricity sector decline by more than 60% from 2020 to 2030. Despite fuel use outside of electricity making up two-thirds of current-day emissions, these emissions decrease by less than 20% through 2030. The steep emission reductions for electricity are possible over the next decade due to the rapid retirement of coal generation. In other sectors that rely on the combustion of fuels, the adoption of electrified and efficient technologies (e.g., battery electric vehicles and LED lighting) is a slower process than shifting away from coal toward cleaner generation options.[7]

Beyond 2030, continued coordination across sectors drives emission reductions at an accelerating rate for fuels and a roughly linear path for electricity. The pace of electricity emission reductions proceeds at 15% per decade until a greater than 90% reduction in emissions is achieved in 2050. Net emissions from fuels as final energy decline at a faster rate post-2030, achieving a 60% reduction by 2040 and a nearly 100% reduction by 2050. The reductions from fuels are, in large part, due to reduced consumption after efficiency improvements and electrification. After 2035 in our analysis, decarbonized drop-in fuels[8] to

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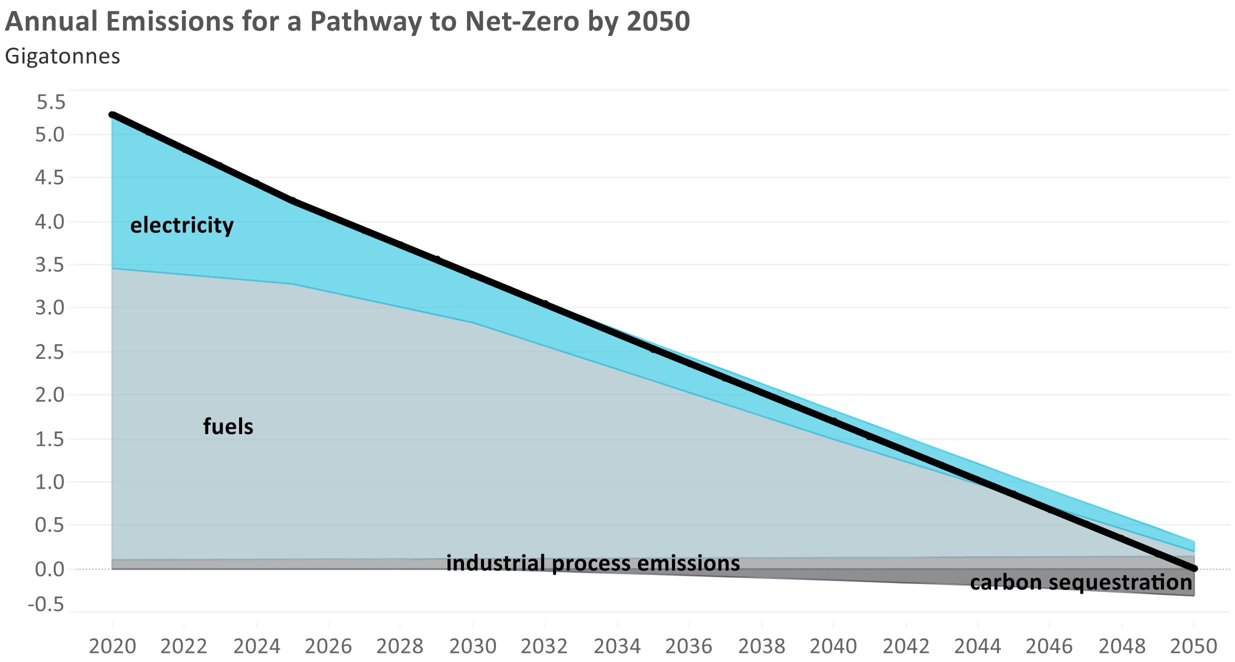
[6] Studies include:
J. Williams, R. Jones, B. Haley, G. Kwok, J. Hargreaves, J. Farbes, M.S. Torn, “Carbon-neutral pathways for the United States,” article in submission, 2020
B. Haley, R. Jones, J. Williams, G. Kwok, J. Hargreaves, J. Farbes, “350 PPM Pathways for the United States,” https://docs.wixstatic.com/ugd/294abc_95dfdf602afe4e11a184ee65ba565e60.pdf
Net-Zero America by 2050, Andlinger Center for Energy & the Environment at Princeton University, forthcoming
J. Williams, R. Jones, J. Farbes, “Achieving Carbon Neutrality in the United States,” SDSN Draft Whitepaper, March 2020, https://irp-cdn.multiscreensite.com/be6d1d56/files/uploaded/SDSN%20Pathways%20Report%20v2.pdf

[7] This trajectory assumes that by 2050, electrified technologies displace their fuel-powered alternatives in key markets, like space heating, water heating, and light-duty vehicles. The analysis assumes there is no early retirement in the turn-over of energy demand technologies, which requires significant lead-times to transform end-use technology markets. For example, transitioning residential heating to heat pump technologies will take time to increase the sales share of heat pumps as furnaces gradually reach their end of life on the order of 15 years.

[8] “Drop-in” fuels are fuels that can be used with no modification to the combustion technology, and can act as a direct replacement for the fossil fuel that is being replaced.

replace fossil emerge as a solution for remaining emissions. The analysis also finds that the least-cost pathway has a small volume of emissions remaining in the electricity sector, which are offset by carbon sequestration in other sectors.

Figure 4 Economy-wide energy CO_2 emissions by category for the least-cost pathway to net-zero emissions by 2050, adapted from J. Williams et al. 2020



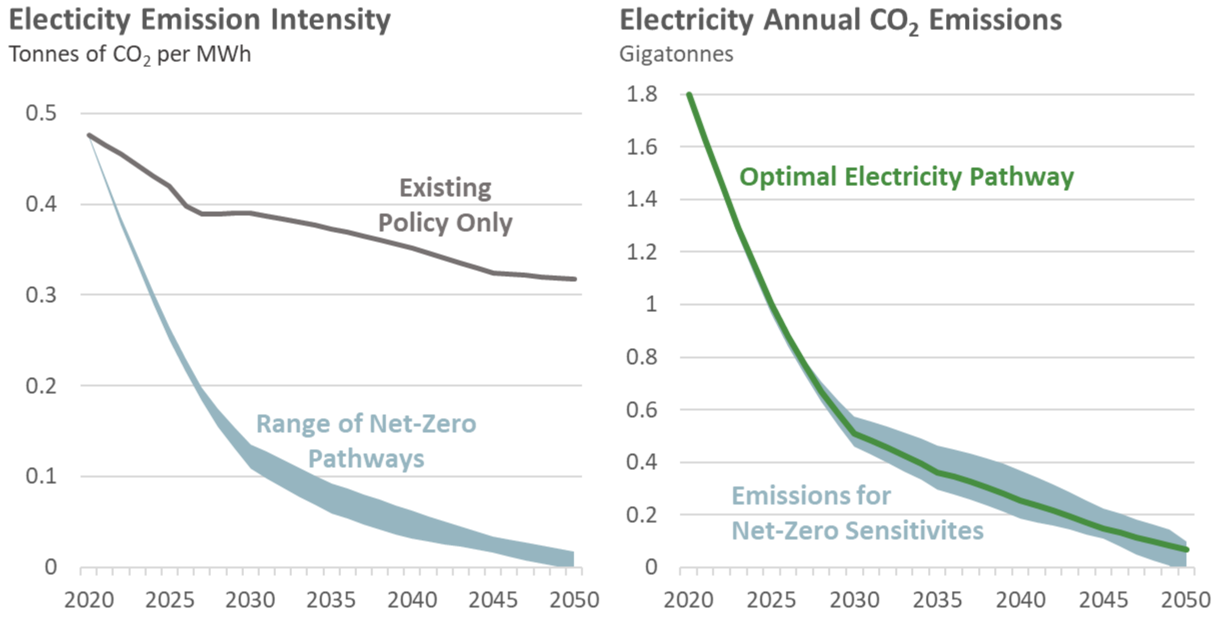
Early decarbonization of electricity combined with large-scale electrification provides a solution for the challenge of reducing emissions from fuels for end-use combustion. Rapid emission reductions for fuels is much more expensive than rapid electricity decarbonization. Achieving a comparable level of early reductions from fuels would require both decarbonized fuels and the early retirement of end-use technologies (such as replacing natural gas furnaces or internal combustion light-duty trucks before the end of their useful life), which is very costly. Relying on biofuels to reduce emissions from fuels will result in energy costs that are two to five times higher than zero-carbon electricity, and supplies of biomass would be insufficient to achieve the emissions reductions.

The paired strategy of clean electricity and electrification avoids the need for significant, near-term investments in new infrastructure to lower the emission intensity of fuels. Many of these investments would sit idle well before the end of their useful life, as demand for fuels will plummet where electrification is an economical alternative (e.g., declining demand for gasoline as light-duty electric vehicles become more cost-competitive). Instead, the least-cost trajectory relies on low-cost renewable electricity generation along with the higher efficiency of electrified technologies. If the pace of adoption of electric and highly efficient technologies is slower than the least-cost trajectory, more significant emission reductions from the electricity sector will be required to stay on a straight-line path to net-zero by mid-century.

Emission intensity falls 65% by 2030 on the Optimal Electricity Pathway

In 2030, the optimal electricity emission reduction pathway ("Optimal Electricity Pathway")[9] has retired all coal generation and produces nearly 70% of its energy from carbon-free sources. Removing the highest emission intensity generation and increasing carbon-free production reduces the grid's emission intensity by 65% compared to 2020, on a trajectory to a 95% reduction by 2050. Figure 5 shows the declines in electricity emission intensity for a range of pathways that achieve economy-wide carbon neutrality by 2050, along with the annual emission trajectory for the electricity sector. Emission intensity declines under the Existing Policy case, primarily due to state-level renewable portfolio policies and the falling costs of renewable energy.

Figure 5 Electricity sector emission intensity and annual emissions for the Optimal Electricity Pathway, based on an adaption of Williams et al. 2020



Coal retirements before 2030 are a critical enabler of these rapid decreases in emission over the next decade. If all coal is not retired, for every 1% of energy generation left as coal, an additional 1% of zero-carbon generation would be needed to follow the emissions reductions of the Optimal Electricity Pathway. Emission reductions after 2030 are slower but occur as electricity load is

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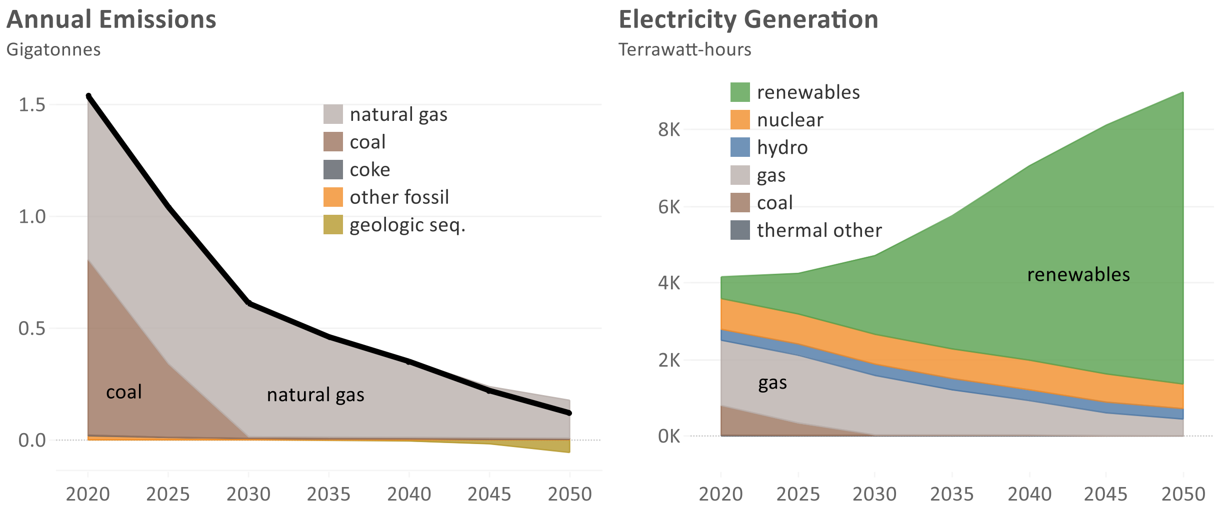
[9] The term "Optimal Electricity Pathway" is used throughout this report to refer to the emission reductions from the collection of actions that achieve electricity emissions reductions consistent with a linear path to net-zero CO_2 emissions in 2050 for the rest of the economy. Throughout the report the capitalization is maintained to make clear that this emissions trajectory represents a single scenario. The Optimal Electricity Pathway is driven by numerous assumptions, and changes to any of these inputs will alter the optimal path. However, across a wide range of inputs, the convex shape of the emissions path was a robust finding. The core policy conclusions of this report are not dependent on the precise trajectory of the Optimal Electricity Pathway shown in the results here.

growing from aggressive electrification, with 10% growth in 2030 on a path to 80% growth in 2050.

Renewables Are the Primary Enabler of the Optimal Electricity Pathway

There is a limited set of options for decarbonizing the electricity system—renewables, nuclear, and CCS—and this analysis finds that renewables, primarily wind and solar, are the principal source of zero-carbon generation in the lowest cost decarbonization portfolio. As shown in Figure 6, renewables[10] account for slightly less than 45% of the total generation in 2030 and 85% in 2050. The Optimal Electricity Pathway eliminates the emissions from coal generation by 2030, and this energy is replaced by new renewables and gas generation. Gas generation progressively declines as more renewables are added to the system.

Figure 6 Annual emissions and electricity generation for the least-cost system on the Optimal Electricity Pathway through 2050.



Balancing challenges for a high renewable system are significant but solvable

Operating a national electricity system with more than 80% wind and solar will present new challenges for the reliable operation of the system.[11] A high renewable electricity system at least cost will rely on a variety of strategies to support balancing: energy storage for short- and medium-duration load balancing, interregional transmission to shift renewable generation from

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[10] In this study, "renewables" and "renewable generation" is used to encompass onshore and offshore wind, solar PV and solar thermal electricity generation technologies as well as geothermal and biomass generation technologies. Large-scale hydro generation is excluded from the definition here.

[11] The analysis that developed the Optimal Electricity Pathway, which is described in the technical appendix, requires that the system meet hourly reliability constraints as the model solves for the least-cost operations and investment portfolio through 2050.

high resource areas to high load areas, industrial-scale energy conversion loads, which can enable longer-duration energy balancing, and thermal generating capacity for reliability. This paper does not address any of these strategies in detail.[12] It does provide an overview of the kinds of balancing services that will be critical enablers of the least-cost, high renewable system that can follow the Optimal Electricity Pathway.

While battery storage will address daily energy imbalances, with the least-cost portfolio adding 300 GW by 2050, a high renewables system requires sustained peaking capability (100's of hours), which will be more expensive to supply with batteries, barring breakthroughs in long-duration storage. During extended periods of excess renewable supply,[13] flexible, industrial-scale energy conversion loads (e.g., electric boilers for steam production or hydrogen electrolysis) can balance the system and also provide zero-carbon final energy to other sectors. Additionally, more interregional transmission will be needed to ensure investments in renewable-rich areas can be delivered to regions with high loads (e.g., high-quality wind from the Midwest reaches load centers along the Atlantic coast).

Thermal generation will play a vital role during extended periods of low renewable production. Whether this generation is nuclear, gas with carbon capture, or gas without carbon capture will depend on societal preferences and the number of hours such resources will be expected to operate every year. Nuclear and gas with carbon capture have high capital costs but relatively low variable costs. By contrast, gas without carbon capture has low capital costs, but has high variable costs after accounting for the need to either burn decarbonized fuels or offset fossil fuel use with a negative emissions strategy (e.g., bioenergy with carbon capture and sequestration).

In a high renewables system, after deploying other available balancing strategies, we find that the average thermal power plant runs less than 10% of the hours every year. In this case, the low utilization of these thermal power plants does not justify the incremental cost of adding carbon capture or building new nuclear. Thus, much of the firm thermal capacity to complement a high renewables system is similar to today's fleet of combined cycle gas plants but operating infrequently. A further advantage of this approach is that it leverages the existing U.S. fleet of nearly 500 GW of gas power plants. This represents a tremendous amount of investment that is already sunk and can be repurposed in support of a high renewable power system without high additional cost.

Land-use constraints and societal acceptance of renewables are major challenges, but federal policy can help address both

Enabling the Optimal Electricity Pathway will entail billions of dollars of new investment with the potential for lasting impacts across the U.S. and its varied ecosystems. Siting of renewables and transmission and potential barriers around social acceptance of these infrastructure changes will

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[12] J. Williams et al. 2020 addresses this topic in greater detail.

[13] This likely to particularly be a challenge in the spring, when electricity demand is low as compared to other seasons, and there is good wind resource potential along with increasing solar isolation moving toward summer.

be critical determinants of whether it is possible to implement a high renewable system capable of following the Optimal Electricity Pathway. Supporting federal policy to address these challenges will be an essential enabler of coordination, planning, and collaboration across stakeholders and systems.

While renewables are the lowest cost form of decarbonized electricity, they do have the potential for significant land impacts if poorly planned. The renewable build for the least-cost portfolio on the Optimal Electricity Pathway is estimated to impact 4.5% of the contiguous U.S. with utility-scale onshore wind and solar PV.[14] That is an area roughly equivalent to the state of Montana, with wind generation accounting for four-fifths of the total renewable footprint.

Where these renewables and their supporting transmission are sited will be a critical consideration. There is a growing body of analysis and recommendations on how to site renewables appropriately.[15,16] The Nature Conservancy has been particularly active in this space by developing the Site Wind Right analysis and dataset to support low-impact siting of wind in the Great Plains.[17] The siting of renewables has already proven to be an issue that can stymie renewable development even in jurisdictions with ambitious renewable deployment goals.[18] Many stakeholders are involved in the siting and permitting processes, and societal acceptance is a critical factor. Greater coordination and collaboration in renewable procurement and development processes will be essential to enable renewable deployment at the scale necessary for the Optimal Electricity Pathway. Failure to achieve this renewable deployment will result in higher costs due to reliance on other zero-carbon resources, principally CCS, nuclear, or wind to solar switching.[19] The emission reduction targets will not be met if these alternative strategies are unavailable.

With the large number of stakeholders involved in siting decisions, and how varied siting and permitting processes are across the country, federal policy will have an essential role in establishing consistent siting and permitting practices and procedures. National legislation that creates a consistent and streamlined siting process within targeted areas of preferable development could enable the necessary acceleration of renewable deployment while pushing siting towards a coherent set of best practices. A national analysis of resource needs and potential should inform this legislation, ensuring the reforms to siting align with the areas of greatest need.

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[14] Land use estimates are based on installed capacity in 2050 and data from the following studies: “WindVision: A New Era for Wind Power in the United States”; S. Ong et al. “Land-Use Requirements for Solar Power Plants in the United States,” National Renewable Energy Lab, June 2013, NREL report # NREL/TP-6A20-56290

[15] G. C. Wu, “ Spatial Planning of Low-Carbon Transitions,” part of the Sustainable Development Solutions Network Deep Decarbonization Pathways Project for the United States, June 2020, https://irp-cdn.multiscreensite.com/be6d1d56/files/uploaded/SDSN_DDPP_SpatialPlanning_GraceWu_final.pdf

[16] https://www.nature.org/en-us/about-us/where-we-work/united-states/california/stories-in-california/clean-energy/

[17] https://www.nature.org/en-us/what-we-do/our-priorities/tackle-climate-change/climate-change-stories/site-wind-right/

[18] A recent analysis by Brookings Institute offers multiple examples of siting challenges stalling or derailing projects: https://www.brookings.edu/research/renewables-land-use-and-local-opposition-in-the-united-states/

[19] Because solar uses less land area than wind, switching from wind to solar will decrease total land use. However, this can result in additional electricity balancing challenges and is expected to increase overall cost.

State-level energy planning entities, which in many cases are the state utility regulatory commissions, will also have an important role in supporting siting and renewable deployment. These planning entities will need to work with state legislatures to advance social acceptance of renewable development, identify new or expanded renewable and transmission corridors with low land impacts, and enable planning processes that produce the highest-value and lowest-impact renewable investments.

Federal Policy Requirements for a Low Carbon Electricity System

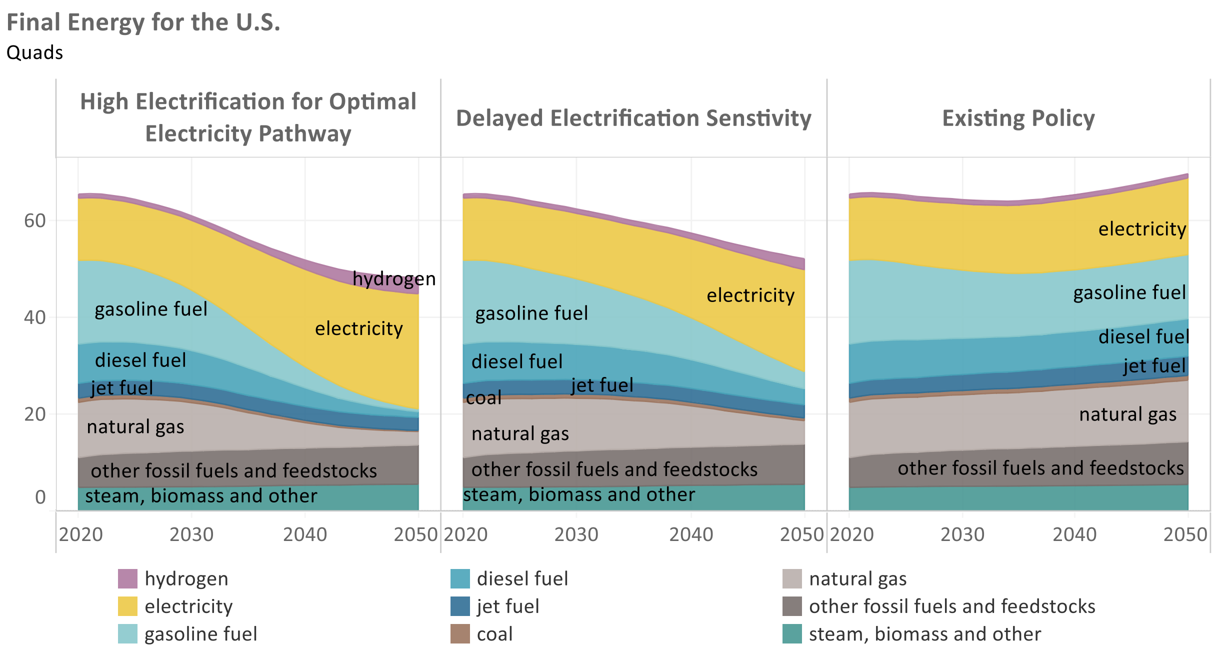
Federal policy that can achieve the lowest cost pathway for the electricity system on a path to an economy-wide, net-zero carbon energy system in 2050 must accomplish three core objectives: (1) meet the growing demand for electricity from electrification; (2) rapidly increase zero-carbon generation; and (3) distinguish between the emission rates of fossil generators. As discussed in the previous section, a large majority of new zero-carbon generation is likely to be renewables, particularly in the next ten years. Policy approaches that cannot accomplish all these objectives will not put the power generation sector on the emissions reduction trajectory that supports the necessary reductions economy-wide.

Meet growing electricity demand from large-scale electrification

Effective policies for achieving the Optimal Electricity Pathway must recognize that electrification to achieve emissions reductions from fuels will significantly grow electricity consumption, increasing the necessary pace and scale of zero-carbon generation. This will be an enormous challenge, and policies will need to support clean energy as it replaces current fossil generation and also meets new load growth from the electrification of vehicles, buildings, and industry.

Rapid electrification shifts final energy demand away from fuels toward electricity, as shown in Figure 7, with electricity demand increasing 85% in 2050 in the high electrification scenario and demand for fuels decreasing by 65%. Improved final energy efficiency from electrified technologies (e.g., electric heat pumps) drives the overall reduction of final energy demand. The delayed electrification sensitivity, which reflects slower adoption of electric technologies, increases load by 60% and decreases fuel use by 50%, which creates greater pressure on the electricity sector to decarbonize. Effective policy formulations will need to meet this load growth with zero-carbon generation, which means the pace of new resource additions driven by policy may be slower than under higher electrification.

Figure 7 The changing final energy demand for the high electrification scenario, delayed electrification sensitivity, and existing policy scenario.[20]



Rapidly increase renewable generation

Achieving the Optimal Electricity Pathway will require rapid increases in zero-carbon generation and sustained growth for these resources through 2050. Renewables make up the vast majority of new zero-carbon generation based on our cost projections. Policy approaches to enable a low carbon system will need to drive significant renewable growth, illustrated in Figure 8. In comparison, 2020 is on pace to see additions of 37 gigawatts of wind and solar combined,[21] up from 11.5 gigawatts in 2019.[22] The existing policy scenario results in roughly 15 gigawatts per year through 2040.

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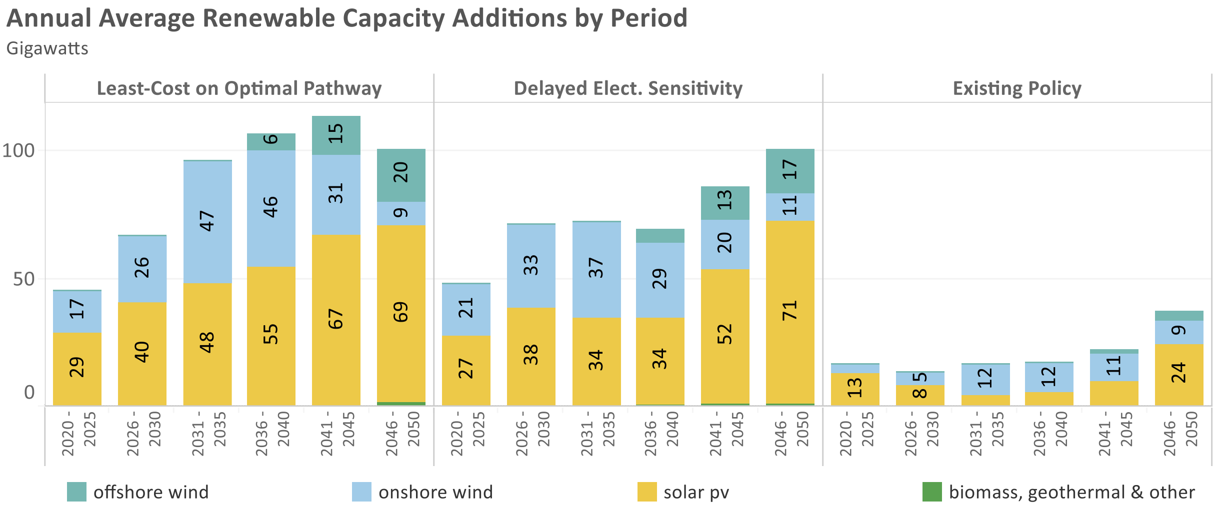
[20] All scenarios meet the same level of service demand, based on EIA's Annual Energy Outlook. Data is adapted from J. Williams et al. 2020.

[21] EIA short-term energy outlook, October 6th 2020: https://www.eia.gov/outlooks/steo/report/electricity.php

[22] FERC Office of Energy Projects Energy Infrastructure Update For December 2019: https://www.ferc.gov/sites/default/files/2020-05/dec-energy-infrastructure.pdf

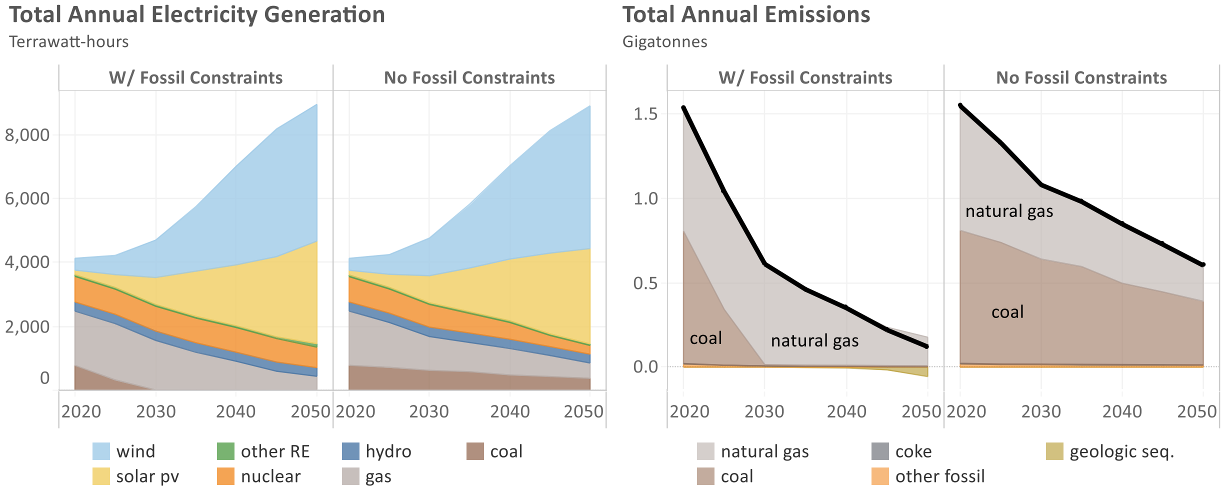
Figure 8 Incremental renewable capacity additions by period for the analysis, with annual average resource additions for the period



Distinguish between the emission rates of fossil generators

Policy that can drive the necessary emissions reductions in the electricity sector will need to differentiate between fossil resources to achieve two objectives: shift from coal toward gas generation in the near-term, and support thermal generation that can complement renewables while still limiting emissions in the long-term. Increasing renewable generation alone will be insufficient to drive emission reductions, particularly when load is growing from electrification. Figure 9 shows a comparison of both generation and annual emissions between two least-cost scenarios with the same share of renewable generation, but one has constraints on fossil generation to follow the Optimal Electricity Pathway ('W/ Fossil Constraints'), and the other has no such constraints ('No Fossil Constraints').

Figure 9 A comparison of two scenarios with the same amount of renewables where one constrains fossil generators to follow the optimal pathway, and the other has no constraints on fossil generators.

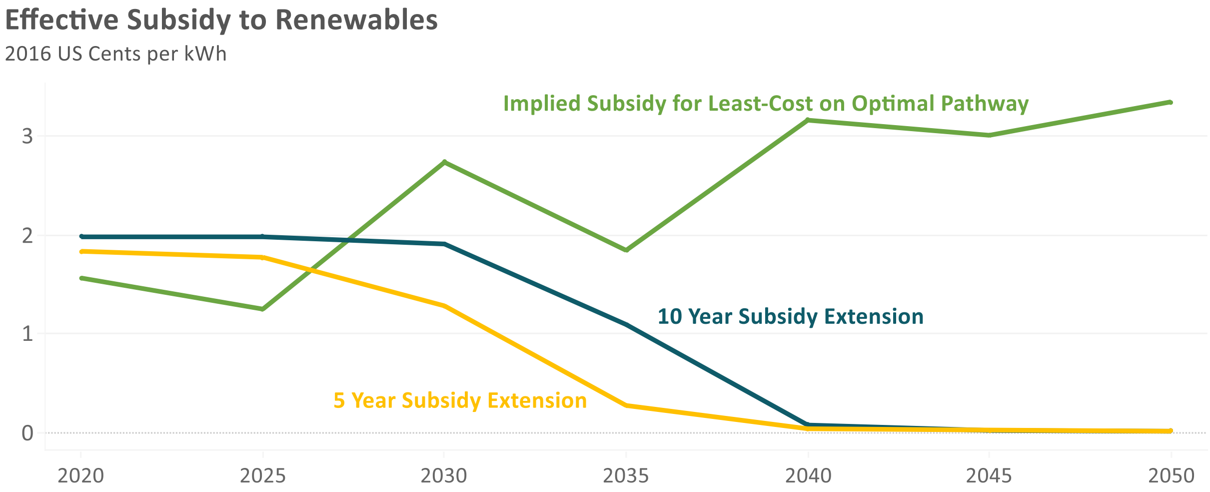


Even with the share of coal generation dropping from roughly 20% to 13% in 2030 and less than 5% by 2050, the No Fossil Constraints scenario has much greater emissions than the scenario with fossil constraints (four times higher in 2050). Policies that can transform the electricity sector to follow the Optimal Electricity Pathway must remove coal generation from the system before 2030 and progressively reduce natural gas emissions to put the whole economy on a trajectory for carbon neutrality.

Extending Existing Renewable Subsidies Will Not Provide the Sustained Policy Support Needed for the Optimal Electricity Pathway

Direct subsidies have been the principal mechanism of federal support for renewables to date. However, this policy approach only addresses the rapid renewable deployment requirement for a low carbon electricity system. Current renewable subsidies were implemented as a part of the Energy Policy Act of 1992 and are a strategy for increasing market penetration. A key argument for subsidies has been that the incentives will result in technology cost declines, eventually reaching the point where they can be phased out because renewables will achieve ‘price parity’ with fossil resources. The two most prominent existing subsidies, the production tax credit (PTC) and investment tax credit (ITC), both include phase-out provisions and have been renewed multiple times in the past. Both subsidies have begun their sunset provisions but with the possibility of further extensions.

Figure 10 Comparison of subsidy levels from an extension of existing subsidies to the level of subsidy that would be needed to achieve the level of renewable deployment for the least-cost system on the Optimal Electricity Pathway.[23]



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[23] The values for the subsidy extension scenarios are based on a translation of all federal subsidies into annual cents per kWh estimates, representing the total subsidy divided by the kWh produced by subsidized resources. Investment tax credits are translated into an energy basis by assuming that subsidy is equally divided over every year of the lifetime of the asset.

The implied subsidy from the least-cost portfolio on the Optimal Electricity Pathway incorporates sunsetting federal subsidies and the shadow price of a renewable portfolio standard policy that results in the same level of renewable generation as the Optimal Electricity Pathway.

Figure 10 contrasts the subsidy to renewables under a five-year and ten-year extension of existing PTC and ITC policies with the implied subsidy needed to deploy the level of renewable generation in the least-cost portfolio for the Optimal Electricity Pathway. The subsidy extension scenarios have a higher effective subsidy before 2030, which results in higher deployment of renewables through 2025.[24] However, both subsidy extensions decline over time, reflecting their phase-out, while the implied subsidy for the Optimal Electricity Pathway rises as more renewables are added to the system.

The declining marginal value of renewable resources is one major factor leading to an increase in the necessary subsidy to stay on the Optimal Electricity Pathway. While wind and solar technologies will continue to drop in price as deployment increases, their marginal benefit to the power system declines as penetration increases. The declining marginal value of these resources bucks the conventional wisdom that once 'price parity' has been reached for renewables supporting policies (e.g., PTC and ITC) can be removed. In an Existing Policy only scenario, the least-cost portfolio includes renewable additions beyond the levels required by state renewable portfolio standards alone, suggesting some amount of renewables do achieve 'price parity.' However, following the Optimal Electricity Pathway will require sustained policy intervention over decades to continue to drive the necessary level of renewable deployment.

Extensions of existing renewable subsidies can rapidly increase renewables in the near-term, potentially even outpacing the modeled Optimal Electricity Pathway, but will fall behind the necessary renewable trajectory in the long run if those policies end. Additionally, since these policies only incentivize renewables, they cannot directly distinguish between fossil generator emission rates, nor ensure load growth is met with zero-carbon resources. Prolonging existing subsidies could play a supporting role for the appropriate federal policy, but relying solely on direct subsidies will result in significantly higher annual and cumulative emissions.

However, direct subsidies can have an important and lasting contribution to electricity decarbonization by accelerating market transformation. When viewed historically, all forms of energy, including fossil fuels, have undergone periods with direct government subsidization.[25] In many cases, technological learning from evolving markets resulted in cost declines that would have been previously unimaginable. Both solar and wind are recent examples of the power of market transformation. For still nascent technologies (e.g., long-duration storage) to enjoy the same technological learning process, they will likely need direct subsidies to compete with the incumbents. In some cases, the technology in question will remain marginal, while in others, cost declines and performance improvements will mean it becomes a critical part of a decarbonized power system.

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[24] The ten year extension scenario deploys more wind than the five year extension, and wind has a higher effective subsidy, which explains why the ten year policy subsidy level is higher than the five year policy in the near term.

[25] For an anlaysis and overview of the historical role of energy subsidies, see N. Pfund, B. Healey, "What Would Jefferson Do? The Historical Role of Federal Subsidies in Shaping America's Energy Future," September 2011. http://i.bnet.com/blogs/dbl_energy_subsidies_paper.pdf

FERC and electricity markets must take steps to prepare for high renewable systems with high fixed costs and low variable costs

The rules that establish the structure of wholesale electricity markets, which serve approximately two-thirds of all U.S. electricity demand, will enable investment and reliable operation of the high renewable system. The Federal Energy Regulatory Commission (FERC) is mainly responsible for those rules. As FERC's regulations evolve, the entities that serve the remaining third of U.S. electricity demand are likely to adopt similar rules. Markets and FERC will face multiple challenges in the transition to a high renewable system, including:

- Evolving reliability standards and energy services;
- Allocating a greater share of fixed costs across market participants while variable costs decrease;
- Make updates to market operations that can improve renewable forecasting, allow for enough revenue certainty to incentivize long-term investments, and better integrate flexible loads.

Evolving reliability standards and energy services

With major increases in the volume of variable energy resources like wind and solar, the conditions that will stress electricity systems in the future and define reliability needs will shift as compared to today. The defining metric of reliability will move from capacity for peak load to capacity *and energy* for peak *net* load (load minus renewables generation). Periods with low renewable output will increasingly drive the greatest reliability need, even if these periods do not align with peak gross load (load without consideration of renewables). Increasing renewable deployment will be accompanied by energy storage with limited discharge durations, making reliability an issue of both capacity and energy.

These shifts will likely leave a vital role for existing thermal generation in maintaining reliability. Existing thermal generators will need to stay available,[26] but will produce much less energy every year. The Optimal Electricity Pathway modeled here results in average capacity factors for fossil plants falling to less than 10% in 2050. These sizable declines in hours of operation may lead to lower revenues from wholesale energy markets for these resources—and if not lower revenue, certainly more variable revenue that is concentrated in a handful of hours each year. In such a scenario, new compensation mechanisms may lead to higher efficiency through more certainty.

FERC and markets will need to revise rules to track the changes in key reliability metrics.[27] Resources that have a reliability role today will play a similar role in enabling the Optimal Electricity Pathway. However, the value they provide to the system will be based on different

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[26] By 2050, the least cost portfolio that can achieve the Optimal Electricity Pathway sees only a 10% decline in total thermal capacity, however gas capacity replaces coal capacity.

[27] The North American Electric Reliability Council (NREC) will also have a role to play in shaping requirements for stability and reliability of a future, high renewable electric system, but the nature of the reliability challenges NERC addresses change in different and less fundamental ways than these other entities. The fundamental metrics NERC uses to assess reliability largely will not change, but rules around what type of resources can support reliability, including inverter-based resources, are likely to need updating.

metrics, including potentially the length of time that a resource can reliably deliver energy. For some markets, shifting reliability metrics and a need to keep existing thermal generation online may result in restructuring the suite of products transacted in some wholesale markets. Energy-only organized markets are likely to face pressure as electricity generation from thermal resources decreases while renewable generation increases. For these markets, capacity-style products may better align compensation with the reliability-services these resources provide to the system. These market updates will be critical to ensure that reliability requirements enable rather than impede the deployment of renewables and decarbonization.

Allocating rising fixed costs as variable costs decline

In today's electricity grid, most of the total system costs, including generation, transmission, and distribution, are fixed, meaning they don't change with the volume of electricity produced. A high renewable system will result in the proportion of costs that are fixed to increase further because fuel costs in today's system are almost entirely displaced by renewable generation with little variable cost. With fixed costs representing a greater share of total cost, more of the system's revenue requirement must be collected regardless of how, when, or whether electricity gets used.

The allocation of fixed costs is a challenging and contentious process today. It will become more difficult as the share of fixed costs increases, and inter-state and inter-regional power flows increase. The cost of balancing resources, including existing thermal generation and new electric conversion loads, will increase the complexity of cost allocation. Burden-sharing on a high renewable system will need to ensure these resources can stay online to enable the system to operate reliably, at least-cost, and on a path to net-zero CO_2.

FERC, in its role as a regulator of rate-setting processes, along with state utility regulatory commissions, will have a central role in addressing the allocation questions of which parties should pay for which fixed costs. Existing approaches for cost allocation may result in the disproportionate distribution of burdens and cross-subsidies that could ultimately undermine decarbonization efforts. Rate-making principals from the 20th century can still provide the structure to which modifications can be made to equitably allocate fixed costs from new balancing services and a greater reliance on fixed-cost dominated supply resources. As more rate setting exercises are conducted with more of these types of resources, FERC and regulators can develop best practices around equitable burden-sharing for high renewable, low-carbon energy systems.

Market updates for better renewable forecasting, improving flexible load participation, and enabling more investment certainty

Adding large volumes of intermittent resources into the existing organized market designs will create challenges that could engender opposition to further renewable deployment. These challenges may include sustained negative electricity spot market prices after unanticipated oversupply or price spikes after unanticipated renewable generation deficits. Market updates will be needed to mitigate these challenges and support continued investment in renewable additions.

Improvements in renewable forecasting will increase the efficiency of system operations and reduce system costs, particularly as penetrations of variable energy resources like wind and solar increase.[28,29] System operators inside organized markets are the direct consumers of these forecasts and have a central role in driving improvement and adoption of better forecasts. Greater transparency around the performance of current forecasts can enable research and development on advancements in forecasting. FERC and state utility regulatory commissions have a role in encouraging these entities to increase transparency and seek out better forecasts. Improved renewable forecasts should also improve energy trading rules in these markets. Stakeholders in the market, including potential investors in generation assets, will have a critical role in pushing for these revisions, and depending on the scope of changes, FERC may play an instrumental role as well.

Market updates will also be needed to fully enable balancing services to support the high renewable system that can deliver the Optimal Electricity Pathway. Future balancing services may take on many forms (e.g., flexible end-uses like electric vehicles, battery energy storage, renewable curtailment, industrial-scale flexible energy conversion loads) and could target shorter or longer duration balancing. Enabling greater participation of flexible loads in bulk system operations will require a restructuring of demand bids, including who can submit them and how they are submitted. Organized markets will need to allow flexible loads to submit demand curves into the market, analogous to the supply curves generators bid today, either as aggregations of smaller loads or as large individual users.[30] FERC will need to be involved in these market updates to enable the potential of large flexible loads like fleets of electric boilers or electrolysis for hydrogen production.

Market rules will also need to allow for long-term contracting mechanisms, similar to renewable power purchase agreements, which can support the range of long-lifetime capital assets required to enable the Optimal Electricity Pathway. In organized markets, if these new investments depend solely on uncertain future market prices, they will face higher financing costs or the potential for underinvestment. These contracting mechanisms will be needed to pool the risks surrounding many of these new technologies, including large energy conversion loads, and mitigate the impacts of uncertain market prices on long-term financing rates. State utility commissions, along with utilities, will have a central role in defining and contracting around these arrangements, providing stability in future revenue streams and enabling long-term decarbonization goals. Market procurement mechanisms, including reverse auctions, should be employed to bring the lowest cost solutions online. These approaches can allow regulators to

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[28] Q. Wang, C. B. Martinez-Anido, H. Wu, A. R. Florita and B. Hodge, "Quantifying the Economic and Grid Reliability Impacts of Improved Wind Power Forecasting," in IEEE Transactions on Sustainable Energy, vol. 7, no. 4, pp. 1525-1537, Oct. 2016, doi: 10.1109/TSTE.2016.2560628.

[29] C. B. Martinez-Anido, B. Botor, A. R. Florita, C, Draxl, S. Lu, H. F. Hamann, and B. Hodge, “The value of day-ahead solar power forecasting improvement,” in Solar Energy, volume 129, pp. 192-203, 2016, doi: 10.1016/j.solener.2016.01.049.

[30] A technical challenge remains for how to most effectively bid or schedule flexible load or energy storage with state of charge. There are market testing different approaches today, but currently most large-scale energy limited resources like hydro or energy storage, self-schedule generation (bid as price-takers). Failure to address this challenge will result in a greater dependence on thermal generation

remain technology neutrality, and instead, define the technical characteristics or services that new resources must provide.

Multiple Policies Could Address the Low Carbon Requirements

Multiple policy approaches, if appropriately designed, can help address the core policy requirements for a low carbon system:

- Direct subsidies, such as tax credits
- Technology mandates, such as clean energy standards
- Carbon pricing, such as a carbon tax
- Carbon caps, such as cap and trade
- Emissions rate standards, such as emissions intensity limits

For comparison, Table 3 shows numerical targets for each approach. All policies except for the direct subsidy approach are, in theory, able to achieve the Optimal Electricity Pathway. The direct subsidy does not result in the necessary reductions in coal and gas generation. For the electricity standard, which is analogous to some forms of clean energy standards, a system of partial credit for gas is needed to distinguish between coal and gas resources enabling the policy to achieve emissions reduction goals. This system of partial credit is discussed more in the following sections that summarize some of the critical considerations for policy approaches that have been of particular interest in the current session of the U.S. Congress (the 116th Congress).

Table 3 Numerical targets for each electricity policy approach that are needed to reach emissions reductions that are consistent with the Optimal Electricity Pathway.

Policy Approach	Description and Caveats	Targets for Equivalent Decarbonization by Year
Direct Subsidies: **Extension of existing federal production and investment tax credits**	Tax credits alone cannot directly drive coal retirements or reduce operations of gas plants at the scale needed to follow the emissions pathway. However, increasing and extending the effective subsidy from these tax credits can drive the necessary renewable deployment.	2020: < 2 cents/kWh 2030: 2.7 cents/kWh 2040: 3.1 cents/kWh 2050: 3.3 cents/kWh

Technology Mandates: **Electricity Standard with a 0.4 tonnes/MWh eligibility standard**[31]	A technology mandate in which specified types of generation comprise an increasing share of total generation. The policy includes limited gas generation for reliability.	2020: 39% of all generation 2030: 85% of all generation 2040: 96% of all generation 2050: 99% of all generation
Carbon pricing: **Carbon Tax**	A carbon price for the electricity sector that escalates over time.	2020: start at $20/tonne 2030: $50/tonne 2040: $75/tonne 2050: $150/tonne
Carbon cap: **Cap and Trade**	A national cap on the electricity sector that limits annual emissions.	2020: < 2,000 million tonnes 2030: 610 million tonnes 2040: 350 million tonnes 2050: 120 million tonnes
Emission Standards: **Generation Emission Standard**	A mandated average generator emissions intensity for the national generation fleet.	2020: < 500 grams/kWh 2030: 135 grams/kWh 2040: 57 grams/kWh 2050: 16 grams/kWh

Carbon prices to achieve the Optimal Electricity Pathway need to reach $50/tonne by 2030 and steadily increase to $150/tonne by 2050

Modeling suggests that carbon pricing policies that achieve the Optimal Electricity Pathway do not need to start high but need to increase through 2050 steadily. While carbon cap policy approaches directly limit emissions to achieve the target, indirectly creating carbon prices in the process, carbon tax policies rely on rising prices to drive lower emissions. This makes the trajectory of carbon prices the central issue for designing these policies to achieve emission reduction targets.

Figure 11 compares the implied carbon price in the Optimal Electricity Pathway to two carbon pricing scenarios that are broadly representative of two different high-level approaches taken by carbon tax bills put forward in the 116th Congress.[32] One approach starts at a lower carbon tax and escalates at a higher rate, $20/tonne escalating at a real 5.5%, while the other starts at a higher carbon tax and increases more slowly, $40/tonne escalating at a real 2.2%. The carbon pricing scenarios achieve comparable levels of annual emissions in 2030 as the Optimal Electricity Pathway.[33] However, the carbon prices in these scenarios fall behind the implied

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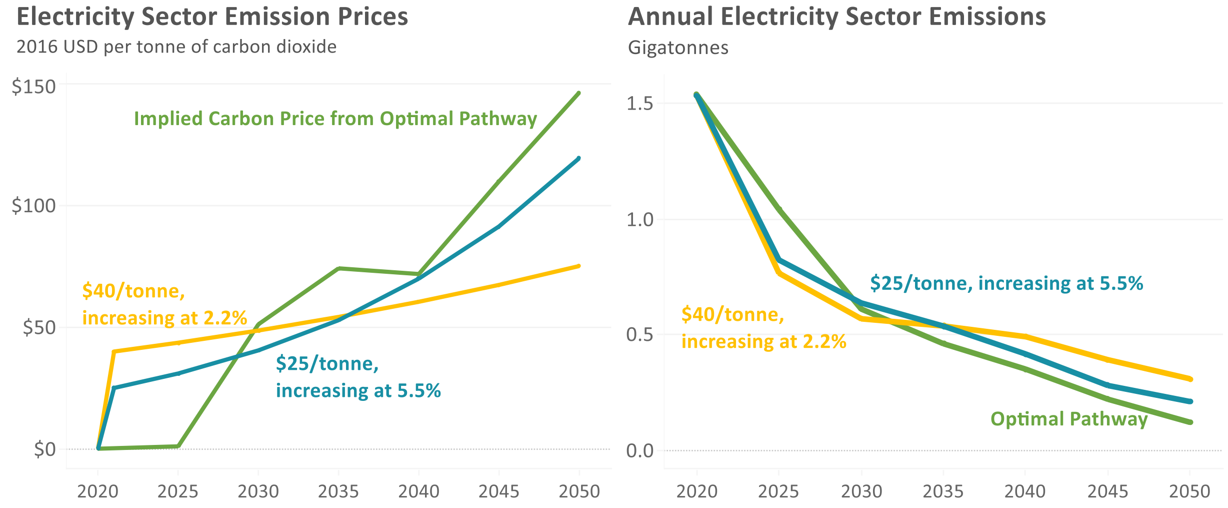
[31] The portion of generation which is credited toward the technology mandate is calculated by 1 – (tonnes of CO2 per MWh for the resource)/ 0.4 tonnes of CO2 per MWh. This means only efficient gas resources are eligible. For example, a natural gas combined cycle plant with a heat rate of 7.1 mmbtu per MWh will receive 6% credit for each MWh generated (1 - [7.1 mmbtu per MWh* 0.053 tonnes per mmbtu]/0.4 = 0.058). This concept is explored further in a section below.

[32] For a summary of carbon pricing proposals in the 116th Congress see: https://www.c2es.org/document/carbon-pricing-proposals-in-the-116th-congress/

[33] The carbon pricing scenarios have lower emissions in 2025 than the Optimal Electricity Pathway, driven by early carbon prices that are high enough to prompt switching coal to gas, particularly with the model used for the analysis having perfect foresight of the continued rise of future carbon prices.

prices of the Optimal Electricity Pathway, resulting in lower renewable additions and insufficient emission reductions.

Figure 11 Comparison of emission prices (L) and annual emissions (R) for carbon pricing scenarios and the Optimal Electricity Pathway.



Significant differences in carbon pricing levels before 2030 (one of the scenarios starts 60% higher than the other) do not lead to meaningfully different outcomes for renewables or annual emission reductions over the first 15 years of the policies.[34] Beyond 2035, the differences in escalation rates make a material difference, with the higher escalation rate more closely trailing behind the Optimal Electricity Pathway.

For carbon pricing policies to stay on the optimal trajectory, they need the ability to increase prices at a faster rate beyond 2040 than either the $25/tonne or $40/tonne scenarios explored here. An effective carbon pricing policy that can follow the Optimal Electricity Pathway will need to roughly follow the implied carbon prices through 2040 and allow for much faster growth beyond 2040 to 2050.

Proper design of technology mandate policies is crucial for following the Optimal Electricity Pathway at least cost

Effective design of technology mandate policies needs to focus on the two core components of the policy: how resource eligibility is defined, and the trajectory of the mandate for eligible resources. The most common formulations of technology mandates are the renewable portfolio standard (RPS) and the clean energy standard (CES), which differ from one another in the qualification of resources like nuclear, CCS, and large hydroelectric plants. Most RPS policy implementations to date have excluded qualification of any resources except wind, solar, small hydro, and a handful of other renewable technologies (biomass, tidal, wave, etc.). While

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[34] The lower emissions before 2030 for the carbon pricing scenarios leads to lower cumulative emissions than the Optimal Electricity Pathway until after 2045. Early carbon pricing at comparable levels is an effective approach for policy that is focused cumulative emission goals, which more directly addresses the challenge of mitigating climate change, rather than the typical annual emission goals.

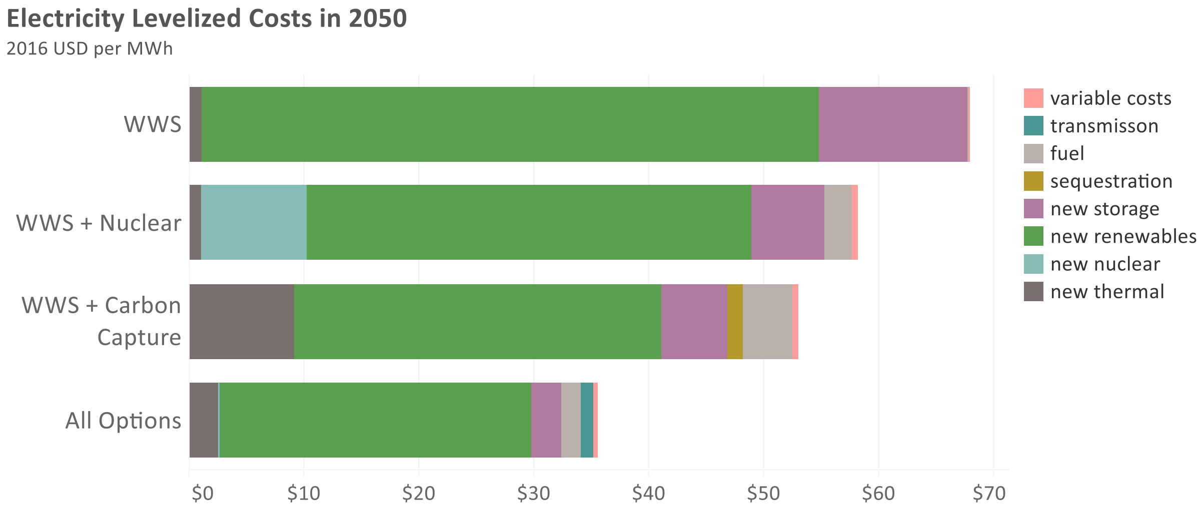
technology mandates share a number of attributes with emission rate standards, the critical distinction between them is mandates focus on decarbonizing a portion of all generation to decrease total emissions rather than setting a standard to address the entire fleet.

Technology mandates ensure that clean generation will keep pace with electrification; however, proper design is critical for guaranteeing these policies can rapidly deploy zero-carbon generation and also distinguish between emission rates of fossil resources. In the discussion below, we implicitly assume that no supporting policies beyond existing subsidies are in place and explore what it would take to achieve the Optimal Electricity Pathway using a technology mandate alone. Also explored are the tradeoffs between CES and various RPS policy definitions.

Less restrictive resource eligibility requirements will enable emission reductions at lower costs

While the RPS approach to technology mandates has helped popularize the concept, mandate policies with broader low- and zero-carbon eligibility rules will enable decarbonization at lower costs. Figure 12 compares the levelized costs of electricity for four scenarios, each of which has the same mandate trajectory but differs in eligibility rules. The wind, water, and solar (WWS) scenario retires all thermal generation and balances the system using batteries alone. The WWS + Nuclear scenario has the same eligibility as the WWS scenario but allows for new nuclear resources. The WWS + Carbon Capture scenario allows thermal generators that incorporate carbon capture (thermal without carbon capture must retire) in addition to WWS resources. And in the all options scenario, all zero-carbon generation (including renewables, existing nuclear, carbon capture, and thermal plants burning zero-carbon fuels) is eligible for the policy. Fewer restrictions on resource eligibility simplifies meeting reliability and operational constraints and lowers overall cost. The WWS scenario has the highest electricity levelized cost in 2050. Nuclear eligibility lowers costs by 15%, while carbon capture eligibility reduces costs by more than 20%. Expanding eligibility to allow all zero-carbon generation options reduces costs by almost 50%.

Figure 12 Comparison of electricity levelized costs between scenarios with the same compliance requirement but different resources eligibility: a wind, water, and solar (WWS) scenario; WWS with nuclear; WWS with carbon capture; and a scenario with all zero-carbon options.



Partial crediting of thermal generation under a CES can retire coal generation and increase zero-carbon generation

A clean energy standard that allows partial crediting for thermal generation must define two parameters: (1) the percentage of generation covered by the policy (and must qualify for credit), and (2) the emissions threshold that determines the credit each resource's generation receives toward meeting the standard. The reason for partial crediting of gas generation is that reaching high penetrations of renewables is not enough alone to drive emissions out of the system (as illustrated above in Figure 9). In particular, if coal is not retired in preference for gas in the near term, the fraction of generation that must be carbon-free increases and costs along with it. Since the mandate cannot directly impact generation that is outside the policy,[35] generation outside the mandate can continue to come from the most emission-intensive plants. Partial crediting gas resources better positions CES approaches to meet the policy requirement of distinguishing between fossil plant emission intensity, which enables them to drive coal retirements and reduce emissions from gas plants.

The following example calculations help to illustrate how the emission threshold translates into partial credit for gas resources. These examples use an eligibility standard of 0.4 tonnes of CO_2 per MWh to determine credit toward compliance with CES. This threshold comes from the Clean Energy Standard Act of 2019 introduced in the 116th Congress (S.1359). Credit for resources is calculated by dividing the emission intensity of the resource by 0.4 tonnes per MWh and subtracting that value from one. The threshold implies the following credits for different types of generators:

Zero-carbon renewables

$$1 - \frac{0\,\frac{tonnes}{MWh}}{0.4\,\frac{tonnes}{MWh}} = 100\%\ credit$$

Gas generator without carbon capture with an efficiency of 50%

$$1 - \frac{0.36\,\frac{tonnes}{MWh}}{0.4\,\frac{tonnes}{MWh}} = 9.6\%\ credit$$

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[35] Once a mandate reaches a high enough level, it can influence generation which is not considered eligible for compliance. For example, if the eligibility of a CES is set at 1.0 tonnes per MWh then a generator with an emission intensity of 0.9 tonnes per MWh (equivalent to a coal plant with a heat rate of roughly 9.4 MMbtu per MWh) will have 10% of its generation credited toward the mandate. If 20% of the entire generation fleet has an emission intensity of 0.9 tonnes per MWh, these resources can only contribute toward the mandate as long as it covers less than 82% of all generation. Once the mandate reaches 82%, all other generation must be zero-emissions for these plants to continue to run, as the 90% of their generation which is not credited toward the mandate will account for the entire 18% of generation that is not subject to the mandate. This "crowding out" effect can be used to distinguish between generator emission rates when compliance levels are high enough.

Gas generator with 90% capture and an efficiency of 45%

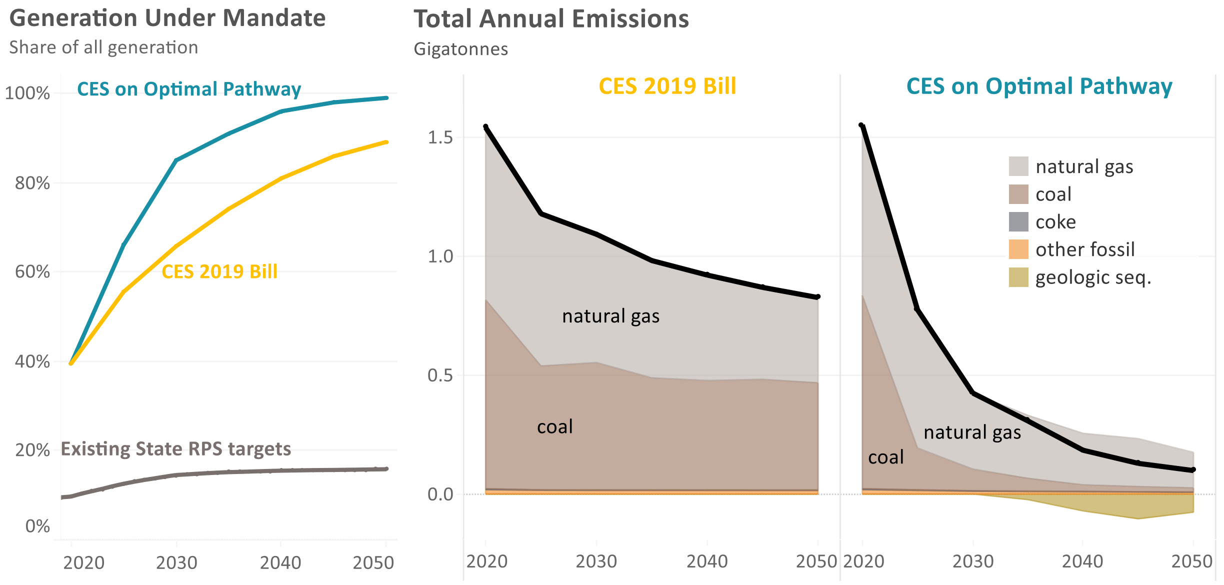
$$1 - \frac{0.04\,\frac{tonnes}{MWh}}{0.4\,\frac{tonnes}{MWh}} = 90\%\ credit$$

Coal generator with an efficiency of 40%

$$1 - \frac{0.81\,\frac{tonnes}{MWh}}{0.4\,\frac{tonnes}{MWh}} = 0\%\ credit$$

With a crediting and eligibility system in place, the pace that the mandate increases is the primary driver of emission reductions for the policy. The slower the policy moves toward requiring all generation to comply with the mandate, the less ability it has to distinguish between emission rates of fossil plants and decrease coal emissions. Figure 13 illustrates how differences in the share of generation that must meet the mandate impacts emissions reductions. The CES 2019 Bill scenario is a representation of the Clean Energy Standard Act of 2019, and the CES on the Optimal Pathway scenario achieves the emission reduction targets of the Optimal Electricity Pathway. As noted above, both scenarios use an eligibility standard of 0.4 tonnes of CO_2 per MWh to determine credit toward compliance with the mandate. Alternative compliance is ignored.

Figure 13 Comparison of the CES 2019 Bill scenario with a CES policy with the same resource eligibility rules but a faster increase in the compliance requirement that allows it to follow the Optimal Electricity Pathway.



Both scenarios have somewhat stringent resource eligibility requirements, where the only eligible fossil thermal plants have low emission intensities. However, the CES 2019 Bill has significantly higher emissions, driven by the high share of generation that remains outside the policy's mandate and comes from coal generation. This contrasts with the CES on Optimal Pathway scenario, where the level of the mandate increases much faster to generate emission reductions even with the same resource eligibility. The faster increases in the share of generation under the policy are necessary to achieve these emission reductions, shifting away from coal to gas and eventually pushing coal generation out of the fleet. In summary, under a system of partial crediting, technology mandate policy design should focus on achieving close to 100% targets as quickly as feasible to crowd out non-compliant generation.

Pros and Cons of Different Policy Approaches

In principle, any of the policy approaches discussed, with the exception of subsidies alone,[36] could be used as a single policy mechanism to drive the Optimal Electricity Pathway. However, each option has advantages and disadvantages from an implementation perspective, summarized in Table 4, that make certain approaches preferable to others.

Table 4 Comparison of policy approaches for supporting the transition to a low-carbon, high-renewables electricity system

Policy Approach	Example	Advantages	Disadvantages	Additional considerations
Direct subsidies	Production tax credit	• Directly supports zero-carbon generation • Can be used to catalyze market transformation within the context of broader policies	• Does not directly lead to coal retirements • Policy typically sunsets • Exact emissions reductions are not known • Typically is not technology agnostic	• Direct government subsidy keeps electricity prices low • Subsidy needs to be sustained to meet emissions targets
Technology mandate	Clean energy standard	• Provides long-term clarity on zero-carbon generation • Easy to explain • CO_2 emissions can be known with reasonable certainty if the shift from coal to gas can be accomplished	• Without partial credit for gas generators, will not retire coal by itself • Schemes for partial credit are complex and reduce the clarity of outcomes and ease of explanation	• Can either be technology agnostic or can let society express technology preferences • Policy costs typically remain hidden
Carbon pricing	Carbon tax	• Straight-forward approach for coal to gas switching • Revenue generating	• Zero-carbon procurement incentives are indirect • Exact policy impact on emissions is unknown • Emissions fluctuate with fossil fuel prices	• Long-term price certainty is critical for driving investment, but adjustments in price trajectory are essential for climate outcomes

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[36] In order for direct subsidy to drive the transition alone, it would need to incentivize gas generation in order to achieve coal retirements, which would then work at cross purposes to the subsidies for zero-carbon generation.

Carbon caps	Cap and trade	- CO$_2$ emissions can be known precisely - Can generate revenue - Allows explicit flexibility between regions - Provides direct incentives for coal-to-gas switching and zero-carbon generation	- Zero-carbon procurement incentives are indirect and uncertain - Price ceilings degrade emissions certainty - Adds transactional costs from financial markets	- Uncertainty in the rates of economy-wide electrification make real-world target setting more difficult
Emission rate standard	Annual average emissions rate cap (gram/kWh)	- Emissions can be known with reasonable certainty - Provides incentives for both coal to gas switching and zero-carbon generation	- Difficult to explain to non-experts - Zero-carbon procurement incentives are indirect	- Uncertainty in the rates of economy-wide electrification means exact electricity-sector emissions are unknown

A more nuanced discussion of strengths and weaknesses from an implementation perspective must focus separately on the near-term and long-term policy objectives. While there is a range of critical considerations in advancing a federal policy, including political economy, regional impacts to employment and political palatability, this discussion focuses on insights that differentiate policy approaches in terms of implementation.

Near-term policy objectives

Through 2030 the necessary actions of an effective policy are well defined: quickly switch from coal-fired to gas-fired generation, encouraging all coal capacity to retire, and rapidly expanding renewable deployment. Over the next decade, load growth from electrification is expected to be small, making the other two policy requirements the central focus of effective policies. There is a high degree of certainty around these near-term objectives, and while the scale of changes for the electricity system is significant, the impacts should be manageable. The reliability impacts of coal resources leaving the system are minor, given that gas resources play a critical role in replacing these resources in the near-term. Renewable additions accelerate quickly, but most jurisdictions will be able to integrate these new resources with modest changes to market rules and operating practices.

Only a modest carbon price at the beginning of this decade is necessary to drive the needed coal to gas transition, starting around $20/tonne. A major strength of the carbon pricing approach is that increasing pressure to reduce emissions from an escalating tax will send a clear signal to incentivize coal retirements. A potential weakness of these policies is their ability to signal the need for dramatically more investment in renewables when the price of carbon is mediated through electricity markets. Investors facing long-term and large-scale capital investment decisions are likely to find that carbon prices are a weak price signal for investment in wholesale electricity markets.

For example, a potential wind energy developer facing only a carbon price and selling into a wholesale electricity market must make a very complicated investment and return calculation.

That calculation must account for the many factors that influence electricity markets, including long-term forecasts of carbon prices, natural gas prices, construction of other renewable and non-renewable generation to estimate system-level curtailment, development of transmission to estimate local curtailment, cost uncertainty about siting and permitting, etc. These uncertainties impose additional risks on investors and will be reflected in a higher premium on the cost of capital, which could limit the pace of deployment of renewables and potentially lag well behind what is needed to follow the Optimal Electricity Pathway at least-cost.

This contrasts with a technology mandate policy approach that can send clear signals to ramp up renewable investment and deployment that does not need to be mediated through energy markets. The mandate and the fact that its trajectory is known well into the future incentivizes investment and can support lower capital costs for these investments. A comparative weakness of the technology mandate approach is that a CES or RPS policy would require a high mandate level within the next few years to drive the shift from coal to gas by 2030. In practice, a CES policy would be needed to allow much of the existing generation fleet to be eligible, and the policy would increase the stringency of eligibility through time.

A carbon emission intensity standard or carbon cap could be very effective at retiring coal generation; however, neither sends the same transparent investment signal for renewables as a CES or RPS policy. From an analytical perspective, all forms of mandates, be it an RPS or an emission standard, are at their core the same policy structure, just with different eligibility rules and compliance trajectories. A CES policy can be structured to achieve the same results as a declining emission standard; however, this design flexibility comes at the cost of complexity, which could lead to significant implementation challenges.

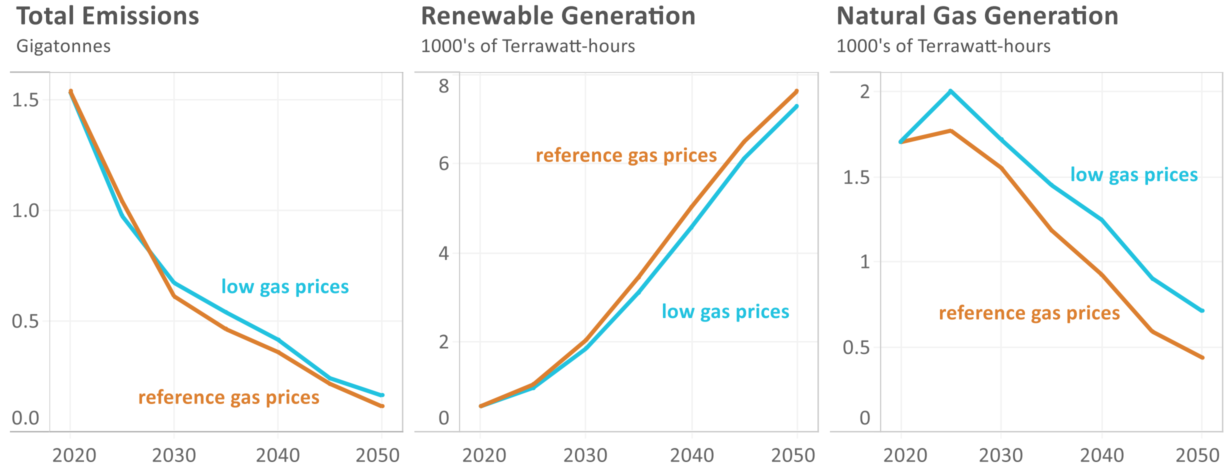
Long-term policy objectives

Beyond 2030, the central policy goals shift to continually reducing emissions from natural gas and keeping pace with electrification as load begins to grow much more quickly. If it is possible to address the siting challenges for renewables to continue their deployment at a large-scale, the reductions in emission from gas generation will come from lower utilization of these resources rather than relying on carbon capture. With long-term goals, there is inherently less certainty of precisely what is needed as compared to near-term goals. However, there is high certainty around the role of the electricity sector in enabling emission reductions in other sectors. The Optimal Electricity Pathway is the critical enabler of achieving net-zero emissions by 2050 for the economy, and effective electricity policy will need to build on the near-term objectives to meet the long-term needs.

The near-term strengths of carbon pricing are less apparent when considering the long-term needs of the system. A fundamental weakness of a carbon pricing approach is that it is not robust to declining natural gas prices or higher than expected zero-carbon generation prices. With more renewables on the electricity system and rising electrification, demand for natural gas will fall, and commodity prices should decrease.[37] As a price-based policy, carbon tax approaches depend on the relative economics of zero-carbon generation and their fossil competitors. Declining natural gas prices can upend the economics for additions of renewables and zero-carbon generation, which can undermine the effectiveness of this policy approach.

Figure 14 shows how low gas prices impact a carbon pricing approach. Initially, lower natural gas prices increase gas generation, which displaces coal and decreases emissions. But once coal is off the system, more gas generation crowds out renewable additions and drives higher emissions. In this analysis, carbon prices eventually rise high enough to encourage greater adoption of gas with carbon capture, which begins to offset the higher emissions from increased natural gas use. Nonetheless, this sensitivity illustrates how lower fuel prices can blunt the effectiveness of the policy.

Figure 14 Comparison of low natural gas prices to reference prices for a carbon tax policy that follows the Optimal Electricity Pathway under reference gas prices.



The advantage of technology mandate or carbon cap policies in the long-term is their certainty of the outcome and clarity in its communication. As volume-based policies, each is robust to potential declines in natural gas prices, enabling the policy to stay at or below the desired emission trajectory even with growing load. Emission rate standards can offer the same long-run advantage of greater emissions certainty in the face of uncertain natural gas prices. These policies cannot guarantee emission outcomes due to the uncertainty of load growth, but as they become more stringent in the long run, the impact of this uncertainty decreases as emission rates become very low.

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[37] This analysis does not directly address how major declines in demand for fuels (see Figure 7) impacts their prices, rather it considers low natural gas prices, which when burned in efficient gas-fired generators is the primary fossil fuel competitor to new renewables, influences the least-cost portfolio. This analysis uses a lower price natural gas sensitivity based on AEO 2020 prices, which is about 19% lower than reference prices in 2030 and 27% lower in 2050.

Concluding Recommendations

As outlined above, the various policy approaches each have strengths and weaknesses when considering the required electricity transformation in the coming decades. A hybrid policy package can overcome the shortcomings of each option as a stand-alone policy and increases the chances of successfully decarbonizing at low cost and high reliability.

Based on our analysis, we recommend a hybrid policy package that includes three elements: a clean energy standard, direct subsidies for emerging technologies, and a targeted policy or regulatory approach focused on transparently driving the retirement of coal power plants. The rationale for this approach is based on this analysis and political considerations around implementation:

- Clean energy standards are popular and offer long-term clarity for investors, regulators, and the public. It is technology agnostic but can be adjusted to exclude unpopular technologies (e.g., nuclear) based on societal and political requirements. It effectively "hides" the cost of the policy, which becomes subsumed within electricity rates. Finally, because it determines the long-term mix of technologies explicitly, CO_2 emissions can be known with reasonable certainty as long as coal to gas switching is accomplished.
- A targeted policy or regulatory approach tailored to signal the need for coal retirements directly and transparently by 2030. Having a separate policy to address coal avoids complicated modifications to the CES policy. A range of approaches could be well suited to drive this outcome, including some form of carbon pricing, either through a limited cap and trade program or carbon tax policy, or an emissions intensity standard. The best policy will be the one that can be enacted and implemented quickly.
- Direct subsidies are sometimes necessary for supporting promising, but less mature technologies (e.g., small modular reactors) in competing with more mature options (e.g., onshore wind). The use of subsidies to enable market transformation has an established track record of success and will remain a critical tool for enabling less mature decarbonization technologies to scale. The current solar PV market is the result of this type of transformation, and the technology is now critical to electricity decarbonization. Under this hybrid approach, direct subsidies for mature technologies (e.g., wind and solar PV) can be phased out, as the CES policy will drive the deployment of these market-competitive resources.

Appendix

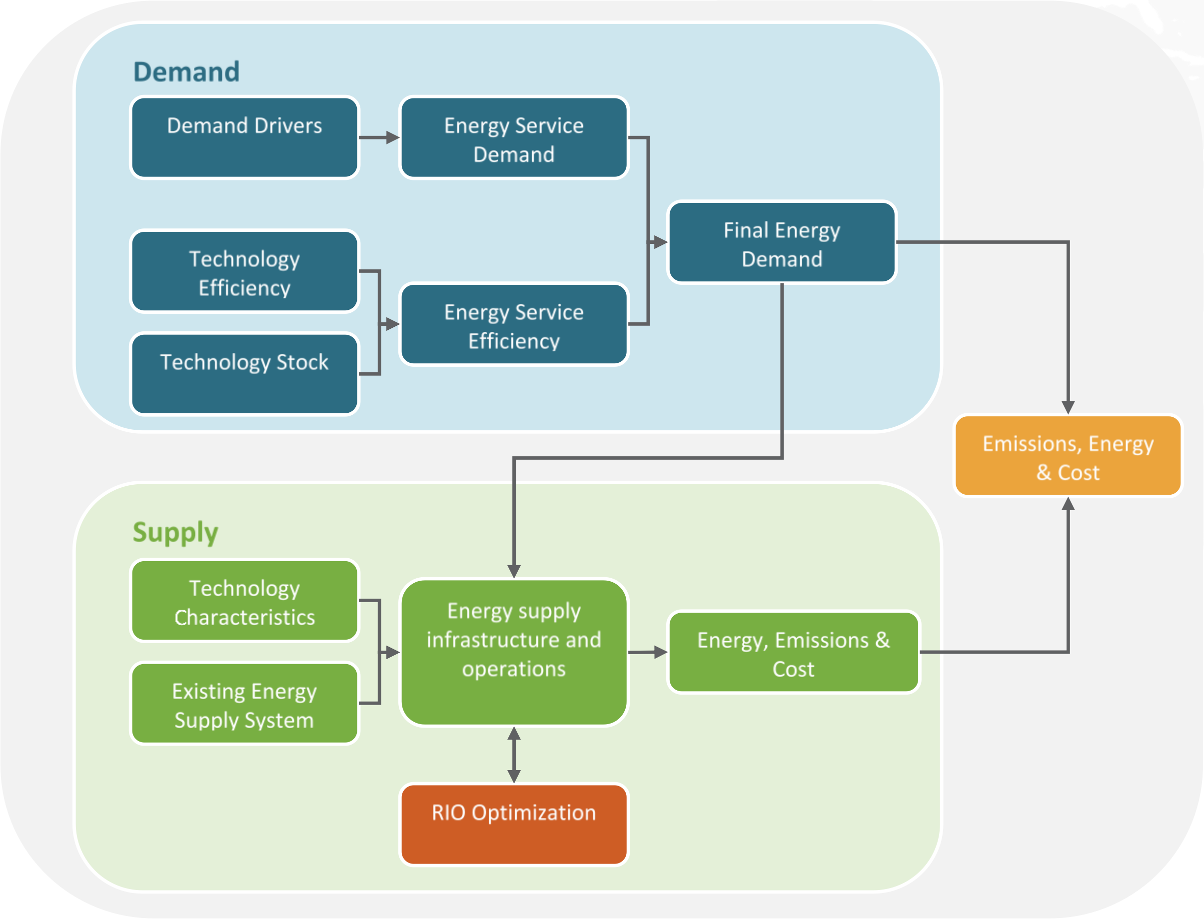
Structure of the Analysis

This analysis models the electricity system's transition from high-carbon to low-carbon within a broader economy-wide effort to achieve net-zero energy CO_2 emissions by 2050. The analysis explores scenarios to understand the lowest-societal cost approach to meeting the emission reduction target for the electricity sector as well as to assess the performance of potential federal policies for increasing deployment of renewables. This study utilizes sophisticated analytical tools for the electricity system, EnergyPATHWAYS and RIO, which are addressed below.

Modeling platforms

The modeling work was performed using RIO and EnergyPATHWAYS (EP), numerical models with high temporal, sectoral, and spatial resolution. Final-energy demand scenarios were developed in EP, a bottom-up stock accounting model. EP outputs including time-varying electricity and fuel demand were input into RIO, a linear programming model that combines capacity expansion and sequential hourly operations to find least-cost supply-side pathways. RIO has unique capabilities for this analysis because it models interactions among electricity generation, fuel production, and carbon capture, allowing it to accurately evaluate the economics of coupling these sectors; tracks storage state of charge over an entire year, allowing it to accurately assess balancing requirements in electricity systems with very high levels of variable renewable energy (VRE); and solves for all infrastructure decisions on a five year time-step to optimize the entire energy system transition, not only the endpoint. RIO finds technology configurations that minimize the net present value of the sum of all energy system costs over the full 30-year modeling period, 2020 – 2050. The steps of the modeling analysis are framed at a high level by the flow chart in Figure 15.

Figure 15 demand-side & supply-side model flow chart



Scenario framework

The scenarios for this analysis are structured to explore how potential policy approaches performs relative to one another and against a scenario that follows the Optimal Electricity Pathway at the lowest total societal cost, *Least-Cost on Optimal Pathway* case. Scenarios with different policies are contrasted on how they perform in terms of renewable deployment, emission reductions, and total societal cost for operating the U.S. electricity system. These federal policy scenarios are grouped into three categories: direct subsidies, technology mandates, and carbon pricing. Table 5 summarizes the categories of scenarios, describing what each set of scenarios explores, the underlying drivers of emission reductions, the assumed level of electrification, and the minimum required share of renewable generation.

All scenarios are required to meet the same demand for energy services for daily life as a business-as-usual reference case based on the Department of Energy's Annual Energy Outlook (AEO) long-term forecast. All scenarios use AEO assumptions for population, GDP, and service demand. The modeling assumes only technologies that are commercial or have been demonstrated at a large pilot scale. The study is on a national level and models the 48 contiguous states in 14 zones. While distributed solar generation is included as a potential resource in this modeling, the focus of the analysis is on utility-scale renewables, which have received the bulk of federal support historically and are likely to be a primary focus for future policy. Economic repowering of existing nuclear generation is allowed in all scenarios, but no new nuclear generation is permitted. All scenarios are subject to the same resource constraints, infrastructure buildout rates, and costs unless otherwise noted.

Table 5 Overview of the categories of scenarios

	Description	Driver of Emissions Reductions	Level of Electrification	Minimum Renewable Share
Existing Policy Only	Defines the no additional policy case beyond state and federal policies on the books through 2019.	Emissions only decrease if it's economic with a carbon price of 0.	Reference	Existing state policy
Least-Cost on Optimal Pathway	Defines the least-cost system that follows the optimal electricity pathway by constraining (capping) emissions and otherwise placing no policy driven constraints on resource eligibility or selection.	Emissions capped at on the optimal electricity pathway	High	Existing state policy
Direct Subsidies	Tests direct renewable subsidy policies for the level of renewables and emission reductions	Higher renewable deployment from subsidies	High	Existing state policy
Technology Mandates	Tests mandate policies that require clean or renewable energy for the level of renewable deployment and emission reductions	Mandate's requirement for clean generation	High	Varies by eligibility rules
Carbon Pricing	Tests carbon pricing policies for the level of renewable deployment and emission reductions	Pricing of emissions	High	Existing state policy

The direct subsidy scenarios consider a five-year extension of the existing federal ITC[38] and PTC along with a ten-year extension of these tax credits. Historically, the subsidies have lapsed, and renewals have extended the programs for periods shorter than five years, but the most recent extension of the PTC in 2015 was for five years.[39] Given the potential for stimulus to support economic recovery in response to the COVID-19 pandemic, a five-year extension to both the ITC and PTC is a potential policy response that could support renewable deployment. A ten-year extension represents a higher level of ambition for direct subsidies and is a useful comparison for understanding the scale of renewable deployment and emission reductions under a more aggressive policy.

The technology mandate scenarios assess the performance of a representation of the Clean Energy Standard Act of 2019,[40] a variation on the CES 2019 bill which follows the optimal electricity pathway, and a set of scenarios that illustrate how eligibility rules impact the cost of

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[38] The current ITC is assumed to cease entirely in 2030, and the subsidy scenarios include a comparable assumption of the remaining 10% credit going away ten years after the ITC begins to decline.

[39] https://fas.org/sgp/crs/misc/R43453.pdf

[40] S.1359 in the 116th Congress

CES policies. The CES 2019 bill scenario incorporates the 0.4 tons of CO_2 per MWh benchmark emission intensity from the bill for determining credits for compliance with the policy, as well as a state-level representation of the compliance targets, which increases year over year rather than at the retail electricity supplier level compliance in the bill. However, our analysis does not include the bill's alternative compliance mechanism, nor the ability to bank excess compliance credits for the future.

The carbon pricing scenarios are representative of high-level approaches taken by different carbon tax bills put forward in the 116th Congress;[41] one approach starts at a lower carbon tax and escalates at a higher rate, the other starts at a higher carbon tax and escalates more slowly. Regional differences in fuel and operating costs along with renewable resource quality can lead to differences in the relative cost competitiveness of renewables at a given carbon price. Exploring different trajectories for a carbon price can provide insights into how policy design decisions may impact the performance of a carbon tax policy.

Our analysis includes a range of sensitivities to support insights into areas with significant or irreducible uncertainty. The key sensitivities for this study are:

- *Lower natural gas prices*: energy from efficient gas-fired generation burning low-cost natural gas is typically the primary fossil fuel competitor to new renewables. A lower price natural gas sensitivity, based on AEO 2020 prices, offers insights on how the least-cost portfolio changes when renewables face a more competitive fossil alternative.
- *Delayed electrification:* As a foundational strategy of decarbonization, electrification has a critical role in controlling the costs of decreasing emissions. While the high electrification assumption in the core scenarios is feasible and would require no early retirement of technologies, consumer adoption decisions are multifaceted and can be difficult to influence with policy. This sensitivity explores changes that would result from the rate of electrification lagging roughly a decade behind what is assumed in the high electrification case.[42]
- *Constrained renewable resource potential:* siting of renewables represents a significant challenge for the large-scale deployment needed for deep decarbonization of the economy at the lowest cost. This sensitivity incorporates substantial constraints on the land available to site new renewables.[43]
- *Delayed coal plant retirements*: Declining coal generation and coal retirements are the principal sources of very rapid declines in emission through 2030. Decisions to retire

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[41] For a summary of carbon pricing proposals in the 116th Congress as of Sept 2019 see https://www.c2es.org/site/assets/uploads/2019/09/carbon-pricing-proposals-in-the-116th-congress.pdf

[42] Slower electrification creates additional pressure to decarbonize other sectors, and this sensitivity incorporates a more aggressive emission reduction trajectory for the Decarbonization case to reflect a new balance in emission reductions between decarbonization of fuels and electricity.

[43] Utility-scale solar PV is limited to 0.5% of U.S. land area and wind is limited based on TNC Site Wind Right dataset

coal plants are not always grounded in economics, and this sensitivity explores how policies are impacted by coal plants remaining online longer.

Supplemental Results

Figure 16 Comparison of total installed generation capacity between the existing policy scenario (L) and the least-cost portfolio that follows the Optimal Electricity Pathway (R).

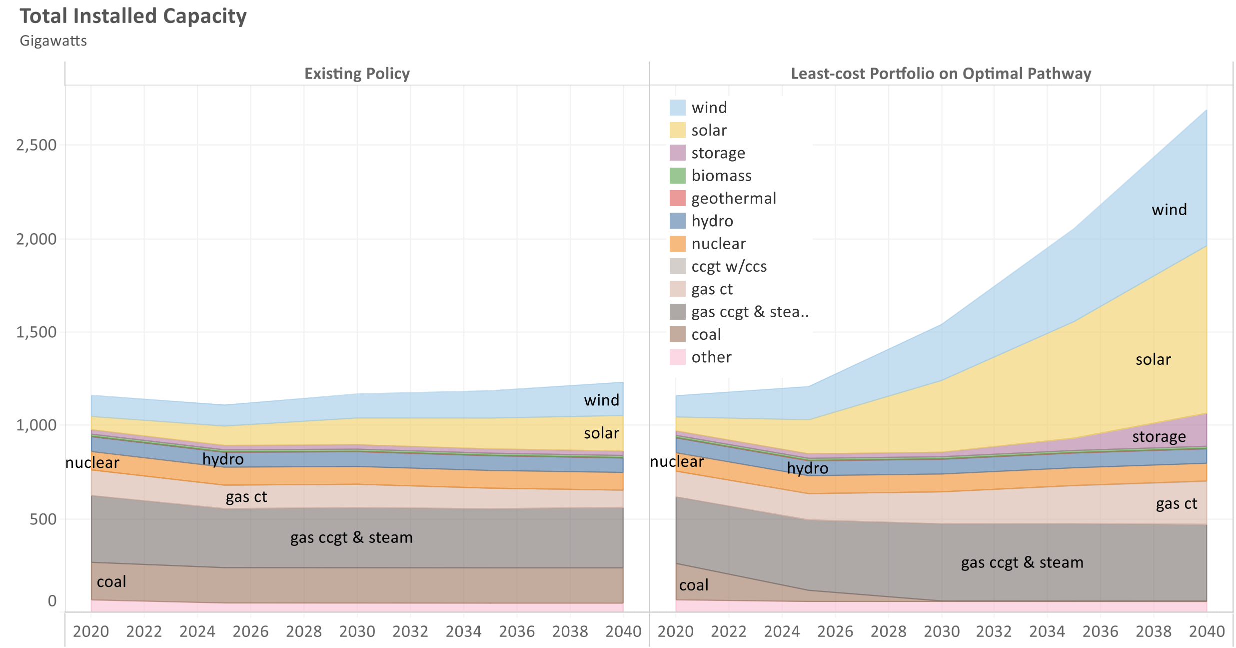


Figure 17 Comparison of annual generation between the existing policy scenario(L) and the least-cost portfolio that follows the Optimal Electricity Pathway (R).

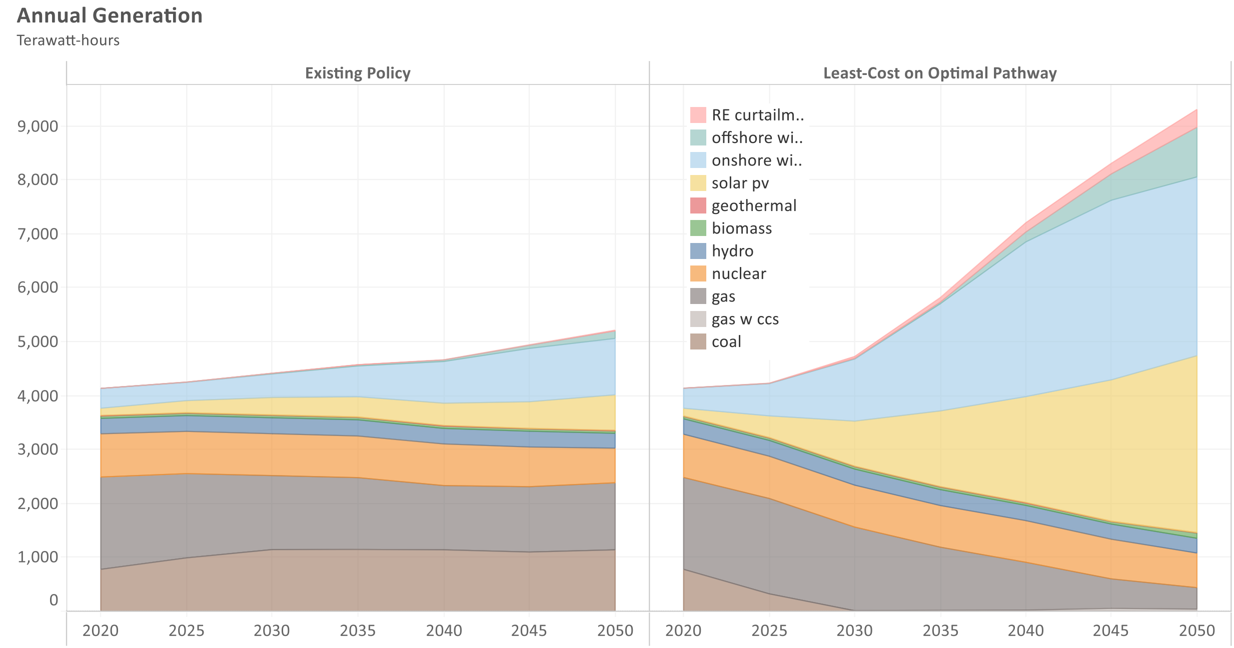


Figure 18 Comparison of the regional generation mix between the existing policy scenario(T) and the least-cost portfolio that follows the Optimal Electricity Pathway (B).

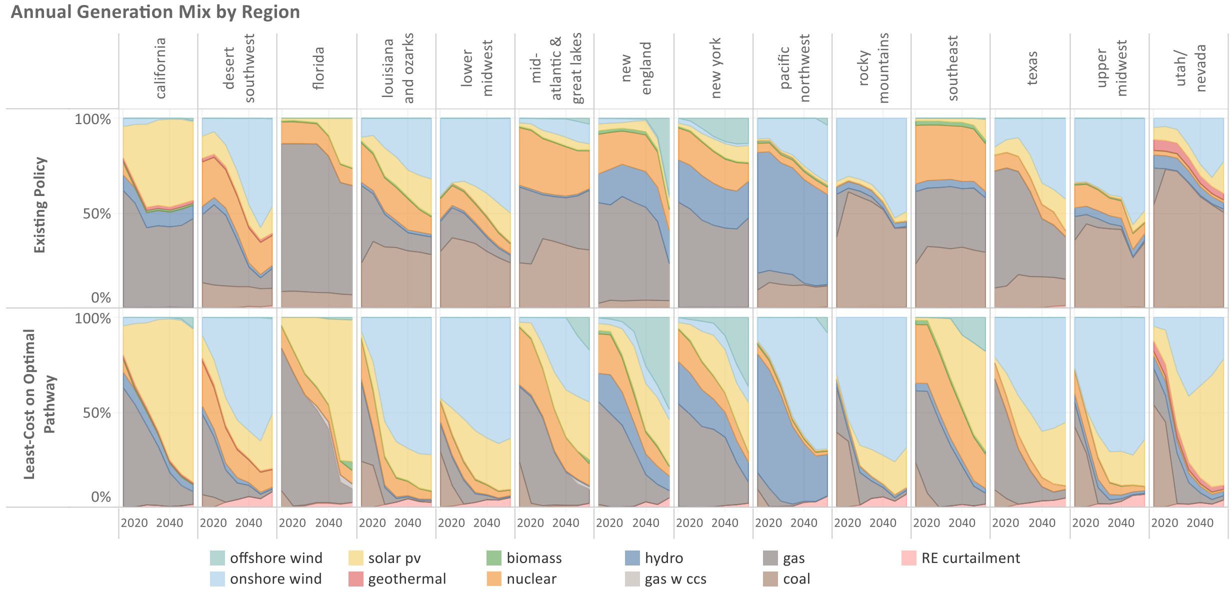


Figure 19 Hourly operations for a representative summer day in 2050 for the least-cost system on the Optimal Electricity Pathway, illustrating generation (T) and load (B).

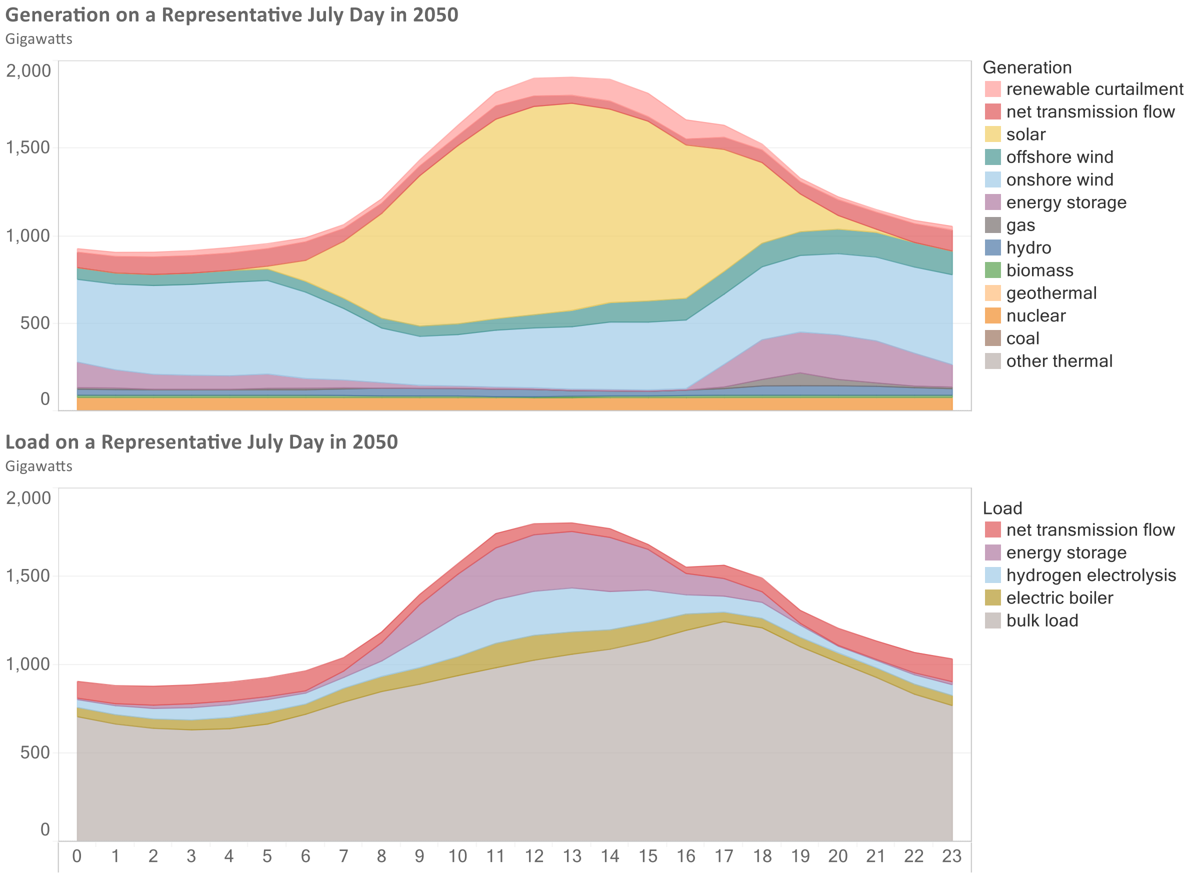


Figure 20 Zonal hourly operations averaged across days in 2050 for the least-cost system on the Optimal Electricity Pathway, illustrating generation (T) and load (B).

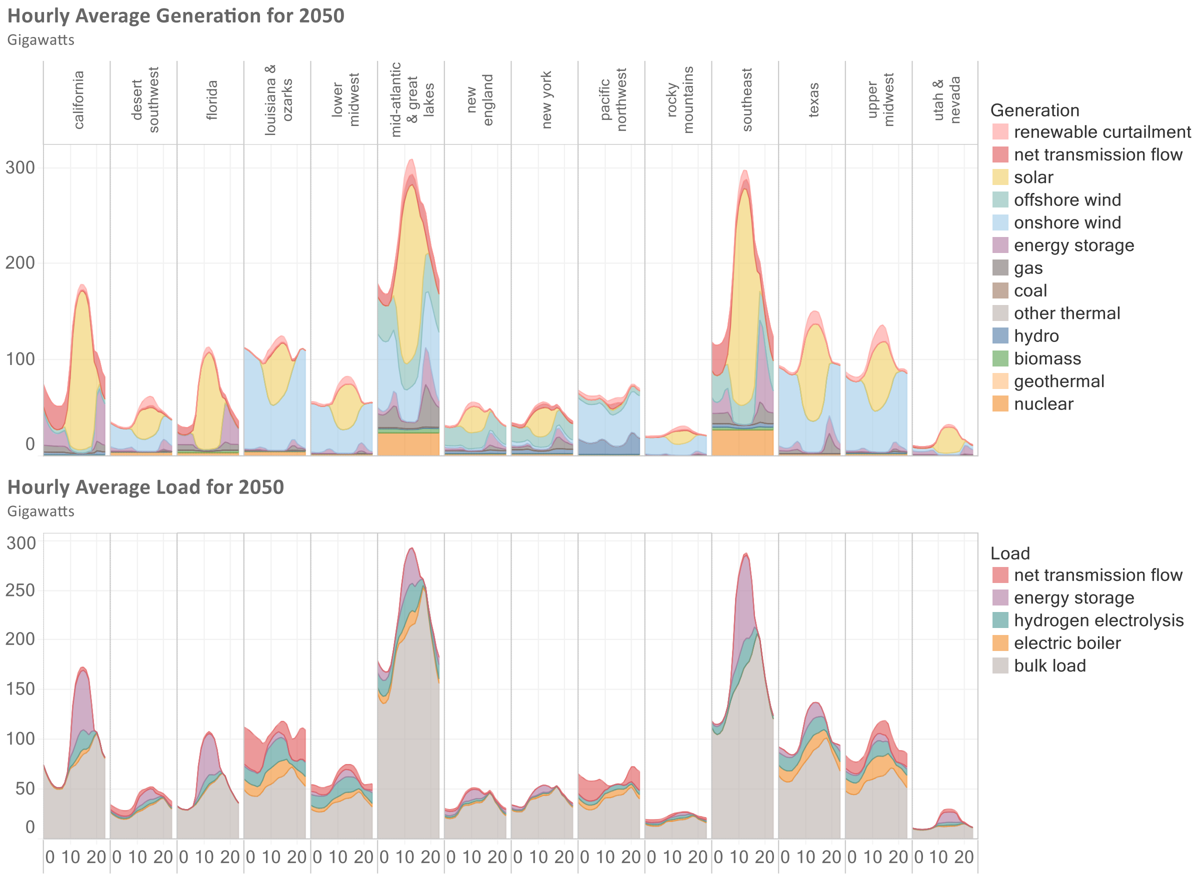
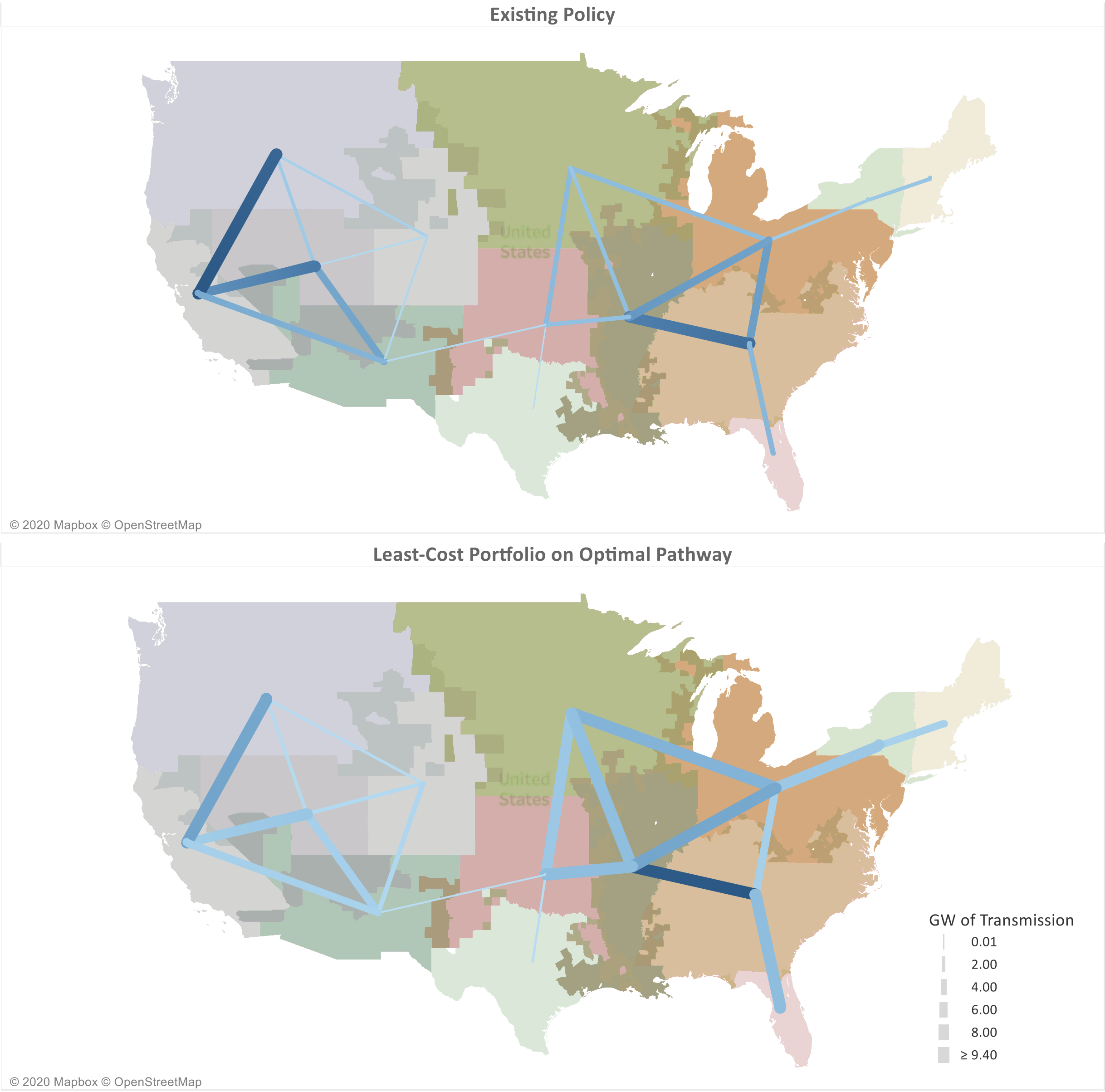


Figure 21 Total inter-zonal transmission capacity in 2050 for the existing policy scenario (T) and the least-cost system on the Optimal Electricity Pathway (B).



Considerations for Policy to Support Electrification

Electrification has a critical role in supporting decarbonization and determines the Optimal Electricity Pathway for an economy-wide transition to net-zero CO_2. In this analysis, electrification is assumed to increase electric loads by 80% in 2050, almost eliminating gasoline demand and significantly decreasing demand for diesel and natural gas. To enable this major shift away from fuels towards electricity will require a dramatic increase in the sale of electrified alternatives to existing technologies (e.g., electric vehicles rather than internal combustion vehicles, or air source heat pumps rather than natural gas furnaces). While many of these electric technologies are cost-competitive on a lifecycle basis, technology adoption is not always driven by lifetime economics, this particularly true for consumer adoption decisions. A range of barriers may slow the adoption of electric technologies, which could raise the cost of achieving carbon neutrality by 2050.

The drivers of the adoption of electrified technologies vary by purchaser, which means policies or actions to accelerate adoption will likely need to be tailored for particular market segments. For purchasers that are sensitive to lifecycle costs of investments, typically commercial or industrial concerns (e.g., operators of commercial transportation fleets), their decision may be motivated by the potential cost savings of adopting electrified technologies, but they may face barriers related to making the change. These barriers could include a lack of knowledgeable vendors to support their investment or high upfront transition costs. For these purchasers, targeted direct subsidies and technical assistance may be all that is needed to significantly accelerate adoption.

For purchasers who are not sensitive to lifecycle costs, particular end-use consumers, their preferences can be thought of as multifaceted decision-making criteria. These complex decision-making processes typically cannot be swayed with blanket incentive policies, and policy approaches will need multiple prongs to accelerate adoption beyond only addressing upfront or operational costs. Impactful efforts to address these barriers will need to be grounded in findings from consumer preference research for particular market segments. Electric vehicles are one example where there is a range of academic literature and polling on barriers to adoption, which suggests several factors influence consumer decision making. Under circumstances where policies to encourage adoption are unlikely to drive adoption that lowers total societal cost, technology standards may prove to be a better approach to driving market transformation.

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